

Decoding Imprints of Black Hole Accretion: Investigations through X-ray Timing and Spectro-Polarimetry

*A thesis submitted for the award of the degree of
Doctor of Philosophy in Physics
by*

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To my father, who has come this far, displaced from his roots, yet kept hope alive...

In the same spirit, this thesis is dedicated to all refugees who crossed horizons in search of a better life.

And finally, to the innocent people of Palestine, slaughtered in one of the most shameful genocides in human history—an atrocity the world must never forget.





“It always seems impossible until it’s done.”

—Nelson Mandela



Declaration



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I hereby declare that the work presented in the thesis entitled “**Decoding Imprints of Black Hole Accretion: Investigations through X-ray Timing and Spectro-Polarimetry**” has been carried out by me under the supervision of Dr. Santabrata Das (IIT Guwahati) and Dr. Anuj Nandi (URSC, Bangalore) at the Department of Physics, Indian Institute of Technology Guwahati, India. The thesis has not been submitted anywhere else for any degree. Works presented in the thesis are all my own unless referenced to the contrary in the thesis.

Date: 17-10-2025

Seshadri Majumder



Certificate



This is to certify that the work presented in the thesis entitled **“Decoding Imprints of Black Hole Accretion: Investigations through X-ray Timing and Spectro-Polarimetry”**, submitted by Mr. Seshadri Majumder (Roll No. 196121111), a Ph.D. student of the Department of Physics, Indian Institute of Technology Guwahati, has been carried out under our supervision and has not been submitted elsewhere for the award of any other degree.

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providing valuable suggestions, and patiently listening to my countless setbacks on numerous occasions.

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List of Publications

(A) Publications Pertaining to Thesis

1. **Seshadri Majumder**, Sreehari Harikesh, Nafisa Aftab, Tilak Katoch, Santabrata Das, Anuj Nandi; *Wide-band view of high-frequency quasi-periodic oscillations of GRS 1915+105 in ‘softer’ variability classes observed with AstroSat*; Monthly Notices of the Royal Astronomical Society, 512, 2508 (2022) [**Chapter 3**]
2. **Seshadri Majumder**, Santabrata Das, Anuj Nandi; *Possible detection of HFQPOs associated with ‘unknown’ variability class of GRS 1915 + 105*; Publications of the Astronomical Society of Australia; Accepted for publication, arXiv:2508.08594 [**Chapter 3**]
3. Anuj Nandi, Santabrata Das, **Seshadri Majumder**, Tilak Katoch, H. M. Antia, Parag Shah; *Discovery of evolving low-frequency QPOs in hard X-rays (~ 100 keV) observed in black hole Swift J1727.8–1613 with AstroSat*; Monthly Notices of the Royal Astronomical Society, 531, 1149 (2024) [**Chapter 3**]
4. **Seshadri Majumder**, Santabrata Das, Vivek K Agrawal, Anuj Nandi; *First detection of X-ray polarization in thermal state of LMC X–3: spectro-polarimetric study with IXPE*; Monthly Notices of the Royal Astronomical Society Letters, 527, L76 (2023) [**Chapter 4**]
5. **Seshadri Majumder**, Ankur Kushwaha, Swapnil Singh, Kiran M. Jayasurya, Santabrata Das, Anuj Nandi; *Probing the accretion geometry of black hole X-ray binaries: A multi-mission spectro-polarimetric and timing study*; Monthly Notices of the Royal Astronomical Society; Under Review, arXiv:2506.03774v1 [**Chapter 4**]
6. **Seshadri Majumder**, Santabrata Das, Vivek K Agrawal, Anuj Nandi; *Unveiling the accretion scenario of BH-ULXs using XMM–Newton observations*; Monthly Notices of the Royal Astronomical Society, 526, 2086 (2023) [**Chapter 5**]
7. **Seshadri Majumder**, Santabrata Das, Anuj Nandi; *Long-term evolution of BH-ULX candidates: An ‘unusual’ $L_{disc} - T_{col}$ correlation associated with spectral states*; Monthly Notices of the Royal Astronomical Society, 539, 2064 (2025) [**Chapter 5**]

(B) Publications Not Pertaining to Thesis

1. Santabrata Das, Anuj Nandi, Vivek K Agrawal, Indu Kalpa Dihingia, **Seshadri Majumder**; *Relativistic viscous accretion flow model for ULX sources: a case study for IC 342 X–1*; Monthly Notices of the Royal Astronomical Society, 507, 2777 (2021)
2. **Seshadri Majumder**, Rwitika Chatterjee, Kiran M. Jayasurya, Santabrata Das, Anuj Nandi; *First Detection of X-Ray Polarization in Galactic Ultraluminous X-Ray Pulsar Swift J0243.6+6124 with IXPE*; The Astrophysical Journal Letters, 971, L21 (2024)
3. Sreehari Harikesh, **Seshadri Majumder**, Santabrata Das, Anuj Nandi; *Evidence of*

oscillating ‘compact’ Comptonized corona in GRS 1915 + 105: Insights into HFQPOs with AstroSat; Monthly Notices of the Royal Astronomical Society, 540, 2965 (2025)



Conferences/Workshops Attended

Conference & Academic Visit Presentations

15. Participated in the “**REcent Trends in the study of Compact Objects (RETCO-VI): Theory and Observation**” held at the Indian Institute of Technology Indore, India, during 10 – 12 March 2025, and delivered an oral presentation titled “*Unveiling the disc-corona-wind driven accretion scenarios of BH-ULXs with XMM-Newton Observations*”.

14. Attended the “**North East Meet of Astronomers (NEMA)-X**” held at Tezpur University, Assam, India, during 23 – 25 October 2024, and delivered an oral presentation titled “*Discovery of X-ray polarization in Galactic ULX pulsar Swift J0243.6+6124 with IXPE*”.

13. Presented a seminar on “*Polarimetric insights of X-ray binaries with IXPE*” during an academic visit to the Department of Astronomy, Xiamen University, China, on September 2, 2024.

12. Participated in the “**45th COSPAR Scientific Assembly**” held at Busan, South Korea, during 13 – 21 July 2024, and presented three oral talks:

- (a) “*Exploring the accretion scenario of BH-ULXs with XMM-Newton*”
- (b) “*First IXPE view of ULX pulsar Swift J0243.6+6124: Polarimetric results and detection of pulsation*”
- (c) “*AstroSat and IXPE view of black hole transient Swift J1727.8–1613: Detection of LFQPO up to 100 keV and polarization*”

11. Delivered an oral presentation entitled “*Polarimetric properties of black hole sources with IXPE and XPoSat prospects*” at the “**2nd XPoSat User Meet**”, ISRO Headquarters, Bengaluru, India, during 18 – 19 December 2023.

10. Participated in the “**10th International Conference on Gravitation and Cosmology (ICGC-2023)**” at the Indian Institute of Technology Guwahati, India, during 6 – 9 December 2023 and delivered an oral presentation titled “*A deeper insight into the accretion scenario of BH-ULXs with XMM-Newton*”.

9. Presented an oral talk titled “*A deeper insight into the accretion scenario of BH-ULXs with XMM-Newton*” at the “**North East Meet of Astronomers (NEMA)-IX**” held at Mizoram University, Mizoram, India, during 20 – 22 November 2023.

8. Participated in “**Advances in Relativistic Astrophysics (AReA-2023)**”, held at ARIES, Nainital, India, during 2 – 4 November 2023, and delivered an oral talk titled “*A deeper insight into the accretion scenario of BH-ULXs with XMM-Newton*”.

7. Attended the “**REcent Trends in the study of Compact Objects (RETCO-V): Theory and Observation**” at Kodaikanal Solar Observatory, Kodaikanal, India, during 3 – 5 April 2023, and presented an oral presentation titled “*Revealing the accretion scenarios of BH-ULXs with XMM-Newton*”.

6. Delivered an oral presentation titled “*Spectro-temporal correlation studies of BH-ULXs with XMM-Newton and possible accretion scenario*” at the “**32nd meeting of Indian Association for General Relativity and Gravitation (IAGRG32)**” held at Kolkata, India, during 19 – 21 December 2022.
5. Participated in the “**44th COSPAR Scientific Assembly**” at Athens, Greece, during 16 – 24 July 2022, delivering an oral presentation titled “*A deeper insight into the HFQPOs of GRS 1915+105 with AstroSat*”.
4. Attended the 40th meeting of the “**Astronomical Society of India**” remotely during 25 – 29 March 2022, organized by IIT Roorkee and ARIES Nainital.
3. Participated remotely in the “**North-East Meet of Astronomers (NEMA)–VII**”, held during 27 – 29 January 2022 at Rajib Gandhi University, Arunachal Pradesh, and presented an oral presentation titled “*Wide-band view of High Frequency QPOs of GRS 1915+105 in ‘softer’ variability classes observed with AstroSat*”.
2. Attended remotely the “**XII Biennial National Conference of Physics Academy of the North East (PANE)**” during 15 – 17 December 2021 and presented an oral talk entitled “*Wide-band view of High Frequency QPOs of GRS 1915+105 in ‘softer’ variability classes observed with AstroSat*”.
1. Participated remotely in the “**North-East Meet of Astronomers (NEMA)–VI**” held at IIT Guwahati, Assam, India, from 10 – 13 November 2020.

Workshops

3. Participated in the “**I-HOW COSPAR Workshop 2024**” focused on “high-resolution X-ray spectroscopy” at Fudan University, China, during 19 – 30 August 2024, and delivered a presentation based on the carried-out project “*A search for winds in NGC 247 ULX1 with XMM-Newton*”.
2. Participated in the workshop on “**Introduction to Machine learning with Python**” held at the Indian Institute of Technology, Guwahati, during 25 – 26 March 2023.
1. Attended in the online workshop on “**Advanced AstroSat Data Analysis**” organized by the AstroSat Science Support Cell during June 21–30, 2021.

List of Abbreviations

ADAF	Advection Dominated Accretion Flow
AGN	Active Galactic Nuclei
AO	Announcement of Opportunity
ARF	Ancillary Response File
BAT	Burst Alert Telescope
BH	Black Hole
BH-LMXB	Black Hole Low Mass X-ray Binary
BH-ULX	Black Hole Ultra-Luminous X-ray Source
BH-XRB	Black Hole X-ray Binary
BLF	Bump Like Feature
CCD	Charge Coupled Device
CENBOL	CENtrifugal pressure supported BOundary Layer
CdZnTe	Cadmium Zinc Telluride
CM	Center of Mass
CPM	Charged Particle Monitor
CZTI	Cadmium Zinc Telluride Imager
CV	Cataclysmic Variables
DEC	Declination
DFT	Discrete Fourier Transform
DU	Detector Unit
EA	Event Analysis
EPIC	European Photon Imaging Camera
FC	Fast Counter
FFT	Fast Fourier Transform
FOV	Field of View
FPM	Focal Plane Module
FTN	Flat-topped Noise
FW	Fast Window
FWHM	Full Width at Half Maxima
GSC	Gas Slit Camera
GT	Guaranteed Time
GTI	Good Time Interval
HID	Hard Intensity Diagram
HMXB	High Mass X-ray Binary
HFQPO	High Frequency Quasi-periodic Oscillation
HIMS	Hard-Intermediate State
HR	Hardness Ratio
HSS	High-Soft State
IAU	International Astronomical Union
IMBH	Intermediate Mass Black Hole
IMXB	Intermediate Mass X-ray Binary
ISCO	Innermost Stable Circular Orbit
ISM	Inter-stellar Medium
ISRO	Indian Space Research Organization
ISSDC	Indian Space Science Data Centre

IXPE	Imaging X-ray Polarimetry Explorer
LAXPC	Large Area X-ray Proportional Counter
LFQPO	Low Frequency Quasi-periodic Oscillation
LHS	Low-Hard State
LMC	Large Magellanic Cloud
LMXB	Low Mass X-ray Binary
MAXI	Monitor of All-Sky X-ray Imaging
MCMC	Markov Chain Monte Carlo
MDP	Minimum Detectable Polarization
MJD	Modified Julian Date
MMA	Mirror Module Assembly
MOS	Metal Oxide Semiconductor
MPU	Measurement Power Unit
NASA	National Aeronautics and Space Administration
NICER	Neutron star Interior Composition Explorer
NS	Neutron Star
NS-XRB	Neutron Star X-ray Binary
NuSTAR	Nuclear Spectroscopic Telescope Array
ObsID	Observation ID
ODF	Observation Data File
OM	Optical Monitor
PA	Polarization Angle
PC	Photon Counting
PCA	Proportional Counter Array
PD	Polarization Degree
PL	Power-Law
PDS	Power Density Spectrum
QPO	Quasi-periodic Oscillation
RA	Right Ascension
RGS	Reflection Grating Spectrometer
RMF	Redistribution Matrix File
RMS	Root Mean Square
RXTE	Rossi X-ray Timing Explorer
SAA	South Atlantic Anomaly
SIMS	Soft Intermediate State
SPL	Steep Powerlaw State
SSC	Solid-state Slit Camera
SSM	Scanning Sky Monitor
SMBH	Supermassive Black Hole
StMBH	Stellar Mass Black Hole
SXT	Soft X-ray Telescope
TCAF	Two Component Advective Flow
TOO	Target of Opportunity
TOV	Tolman-Oppenheimer-Volkoff
ULX	Ultra-Luminous X-ray Source
UVIT	Ultra-Violet Imaging Telescope
UVOT	Ultra Violet Optical Telescope
WT	Windowed Timing

XRB	X-ray Binary
XRT	X-ray Telescope
XTI	X-ray Timing Instrument
XMM	X-ray Multi-Mirror Mission
XPoSat	X-ray Polarimeter Satellite
XRISM	X-Ray Imaging and Spectroscopy Mission
ZCL	Zero-centred Lorentzian





List of Notations

r_g	Schwarzschild radius
G	Gravitational constant
M_{BH}	Mass of black hole
c	Speed of light
m_p	Mass of proton
v_{ff}	Free-fall velocity
M	Mass of compact object
r	Radial distance
R	Radius of compact object
η	Energy efficiency of accretion
L_{acc}	Accretion luminosity
$\dot{m}$	Mass accretion rate
$M_{\odot}$	Solar mass
M_1	Mass of primary star
M_2	Mass of secondary donor star
m_1, m_2	Scaling constants
b	Binary separation
P_0	Orbital period in binary system
M_3	Summed mass of primary and secondary stars
Ω	Angular speed of a binary system
Φ_R	Roche potential
$\mathbf{r}$	Position vector
q_0	Mass ratio of the primary to secondary star
L_i	Lagrange points in binary system with $i = 1, 2, 3, 4, 5$
v_w	Wind speed of secondary star
v_{es}	Escape velocity
R_d	Radius of donor star
v_{co}	Speed of compact star in binary orbit
v_{rel}	Relative speed of donor wind near primary star
r_{acc}^w	Wind accretion radius
f_g	Gravitational force
m_e	Mass of electron
F	Photon flux
σ_T	Thomson scattering cross section
f_{rad}	Radiation force
L_{Edd}	Eddington luminosity
$\dot{m}_{\text{Edd}}$	Eddington accretion rate
P	Gas pressure
K	Constant
γ	Adiabatic index
ρ	Specific density
r_s	Sonic point
r_{acc}	Bondi accretion radius
c_s	Sound speed
$\mathcal{M}$	Mach number

H	Vertical scale height of accretion disc
Ω_k	Keplerian angular speed
v_ϕ	Azimuthal component of velocity
$t_{r\phi}$	Viscous stress
r_{ISCO}	Innermost stable circular orbit radius
α_s	Viscosity parameter
P	Thermal pressure
T_{eff}	Effective Temperature
σ_S	Stefan-Boltzmann constant
v_r	Radial velocity
r_{sh}	Shock location
L_ν	Luminosity per unit frequency range
L_{bol}	Bolometric luminosity
F_{bol}	Bolometric flux
ν	Frequency of X-ray emission
I_ν	Monochromatic specific intensity
α_ν	Absorption coefficient
j_ν	Emission coefficient
τ	Optical depth
l_ν	Mean free path
h	Planck's constant
k_B	Boltzmann constant
λ	Wavelength
B_ν	Planck's spectrum
r_{in}	Inner extent of accretion disc
r_{out}	Outer extent of accretion disc
F_{disc}	Disc blackbody flux
D	Source distance
ϵ	Energy
I_B	Intensity of Bremsstrahlung emission
G_0	Gaunt factor
T_p	Plasma temperature
Z	Charge of a ion
n_e	Number density of electron
n_i	Number density of ion
B	Magnetic field strength
r_0	Classical radius of charge particle
α_p	Pitch angle
β	Velocity normalized with speed of light
P'	Synchrotron radiation power
γ_0	Lorentz factor
U_B	Magnetic energy density
q	Electric charge
m_q	Mass of a charged particle
ω	Angular frequency
ω_c	Critical frequency
$K_{5/3}$	Modified Bessel function of order 5/3
Ω_s	Solid angle

θ	Angle between incident and scattered photon direction
λ_c	Compton wavelength of electron
σ_{KN}	Klein-Nishina cross section
U_{ph}	Photon energy density
y_{par}	Compton y-parameter
T_e	Electron temperature
n	Photon phase space density
z	Dimensionless photon energy
t_c	Time measure in units of mean time between scatterings
$\mathbf{E}$	Electric field vector
$\mathbf{B}$	Magnetic field vector
$\hat{a}_1, \hat{a}_2$	Unit vectors
$\mathbf{k}$	Electromagnetic wave vector
ϕ_1, ϕ_2	Phase of electric fields
$E, \mathcal{E}$	Magnitudes of electric field vectors
ψ, χ_p	Angles to define polarization
I, Q, U, V	Stokes parameters
S	Variance of light curve
$\overline{\sigma_{err}^2}$	Mean squared error of light curve
F_{var}	Fractional variability amplitude
N	Number of bins
x_k	Photon count in k^{th} bin
$\bar{x}$	Mean photon count
C_s	Photon counts in soft energy band
C_h	Photon counts in hard energy band
a_j	Fourier transform of x_k
P_j^{Leahy}	Leahy normalized power in j^{th} bin
N_{ph}	Number of detected photons
P_j^{rms}	Power in rms normalization for j^{th} bin
Δt	Time resolution of light curve
τ_d	Deadtime of detector
r_{obs}	Observed count rate
r_t	Deadtime corrected count rate
N_{det}	Number of detector units
L_{lor}	Lorentzian function
N_{lor}	Lorentzian normalization
err_{neg}	1σ negative error in Lorentzian normalization
Δ_F	Full width at half maxima of Lorentzian function
f_{cen}	Centroid frequency of Lorentzian function
$Q-fac$	Quality factor of QPO feature
σ_{QPO}	Significance of QPO feature
ν_{QPO}	QPO centroid frequency
ν_{har}	Centroid frequency of QPO harmonic
σ_{har}	Significance of QPO harmonic
rms_{har}	rms amplitude of QPO harmonic
rms_{QPO}	QPO rms amplitude
rms_{total}	Total rms amplitude
$\Delta\chi_{dof}^2$	Change in model-fitted χ^2 per degrees of freedom

$\Delta\chi_{\text{obs}}^2$	Change in model-fitted χ^2 obtained from real observed data
$\Delta\chi_{\text{sim}}^2$	Change in model-fitted χ^2 obtained from simulated data
Γ_{PL}	Powerlaw photon index
$norm_{\text{PL}}$	Powerlaw normalization
f_{pcfabs}	Dimensionless covering fraction in pcfabs
$\sigma(\epsilon)$	Photoelectric absorption cross-section
T_{in}	Inner disc temperature
N_{diskbb}	Normalization of diskbb
T_{col}	Color corrected inner disc temperature
L_{disc}	Disc luminosity
$C(I)$	Detected photon counts in channel I
$S(\epsilon)$	Intrinsic source spectrum
$R(I, \epsilon)$	Detector response function
$A(\epsilon)$	Effective area of the detector
$C_{\text{m}}(I)$	Model predicted X-ray spectrum
$\sigma(I)$	Uncertainty in $C(I)$
R_{in}	Apparent inner disc radius in kilometers
D_{10}	Source distance in units of 10 kpc
θ_{inc}	System inclination
f_{h}	Spectral hardening factor
ξ	Geometric correction factor
ζ	Torque at inner disc boundary
a_*	Spin of black hole
f_{scatt}	Scattered seed photon fraction
Γ_{simpl}	Photon index of simpl
Γ_{nth}	Photon index of nthcomp
$norm_{\text{nth}}$	Normalization of nthcomp
F_{nth}	Photon flux of nthcomp component
F_{th}	Photon flux of thcomp component
F_{PL}	Photon flux of powerlaw component
cov_{frac}	Covering fraction of thcomp
Γ_{th}	Photon index of thcomp
ϕ_k, ψ_k	Azimuthal angle of electric field
$f(\psi)$	Modulation function
μ	Modulation factor of detector
$\mathcal{Q}, \mathcal{U}$	Normalized Stokes parameters
p_r	Polarization fraction
ψ_r	Polarization angle
P_c	Probability of getting polarization more than p_r
N_0	Number of detected events
n_{H}	Hydrogen column density
A_{fe}	Iron abundance
$A_{\odot}$	Solar iron abundance
R_{f}	Reflection fraction parameter
F_{relxill}	Flux of relxill component
$\log \xi$	Ionization of the accretion disc
σ_{pol}	Significance of polarization detection
MDP_{99}	Minimum detectable polarization at 99% confidence level

A_{norm}	Normalization of energy dependent polarization degree in polpow
A_{index}	Powerlaw index of energy dependent polarization degree in polpow
ψ_{norm}	Normalization of energy dependent polarization angle in polpow
ψ_{index}	Powerlaw index of energy dependent polarization angle in polpow
A_{slope}	Slope of the polarization fraction in pollin
ψ_{slope}	Slope of the polarization angle in pollin
χ^2	Chi-square statistics
χ^2_{red}	Reduced chi-square
$\text{PD}_{\text{polpow}}$	Polarization degree from polpow
$\text{PA}_{\text{polpow}}$	Polarization angle from polpow
$\text{PD}_{\text{polconst}}$	Polarization degree from polconst
$\text{PA}_{\text{polconst}}$	Polarization angle from polconst
P_{null}	Null hypothesis probability
$F_{\text{disc}}^{\text{soft}}$	Low temperature diskbb flux
$F_{\text{disc}}^{\text{hard}}$	High temperature diskbb flux
$d.o.f$	Degrees of freedom
$T_{\text{in}}^{\text{soft}}$	Softer inner disc temperature
$T_{\text{in}}^{\text{hard}}$	Hotter inner disc temperature
$HR1$	Soft X-ray color
$HR2$	Hard X-ray color
E_{gauss}	Gaussian line energy
$norm_{\text{gauss}}$	Normalization of Gaussian line
t_{infall}	Infall time scale
v_{sh}	Post-shock velocity
$\mathcal{G}$	Gravitational redshift factor
Q_c	Cooling rate
r_{sp}	Spherization radius
f_{Nyq}	Nyquist frequency



Abstract

Accretion is a fundamental astrophysical process that powers a large fraction of the energy output observed in the X-ray sky. In accretion powered binary systems, known as X-ray binaries (XRBs), a compact object accretes matter from a companion star, leading to X-ray emission. Among these, black hole systems are of particular interest due to their extreme gravitational fields, which make direct observation of their interiors impossible. As a result, black hole XRBs serve as natural laboratories for probing strong gravity through indirect observations. Their high accretion efficiency leads to substantial X-ray output, detected by space-based observatories. From this, X-ray photons recorded in time and energy bins reveal the temporal and spectral properties of the emission, while the orientation of their electric fields carries polarimetric information. This thesis analyzes such observational data from various X-ray observatories (*AstroSat*, *NICER*, *NuSTAR*, *IXPE*, *MAXI*, *Swift*, *XMM-Newton*) to investigate the accretion dynamics of various galactic and extragalactic black hole sources.

Chapter 1 focuses on the accretion process as a primary energy source in astrophysical systems and discusses various mass transfer mechanisms in XRBs, such as Roche lobe overflow and stellar winds. We review the types of accretion-powered XRBs, including ultra-luminous X-ray sources (ULXs), and outline the key aspects of the theoretical models of accretion processes. The fundamentals of the radiative processes relevant in such extreme environments are then discussed. The chapter concludes with an overview of observational domains of X-ray astronomy, namely imaging, timing, spectroscopy, and polarimetry.

Chapter 2 discusses the observational facilities and analysis techniques employed throughout the thesis. This chapter begins with an introduction to the space-based X-ray missions, highlighting their capabilities, which are relevant to the present study. A detailed description of the data reduction procedures specific to each instrument is then provided. This is followed by a discussion of the methods adopted for imaging, timing, spectral, and polarimetric analyses. In addition, we briefly discuss the spectral models that are used to interpret the emission properties explored in subsequent chapters.

In Chapter 3, rapid temporal variability occurring over a range of timescales in galactic black hole XRBs (BH-XRBs) is investigated. This includes the detection of an evolving Low-frequency Quasi-periodic Oscillation (LFQPO) feature in hard X-rays (~ 100 keV) for the exceptionally bright black hole X-ray transient Swift J1727.8–1613. Next, a detailed spectro-temporal study is conducted to investigate the High-frequency QPO (HFQPO) properties at ~ 70 Hz for the enigmatic BH-XRB source GRS 1915 + 105, across several variability classes including a newly identified class. Analysis of the wideband spectral distribution reveals that thermal Comptonization contribution dominates in the emission spectra when QPO features are present. These findings suggest an accretion dynamics involving a disc-corona system, where a corona of varying size is located close to the black hole and drives rapid temporal variability in BH-XRBs on different timescales. In particular, the LFQPOs are inferred to arise from the modulation of a large scale coronal region, whereas the HFQPOs are likely to be associated with a small scale compact corona.

Chapter 4 focuses on unveiling the accretion-ejection geometry of BH-XRBs by integrating timing and spectro-polarimetric insights obtained from multi-mission observational data. For this study, we consider eleven BH-XRB sources, namely Cyg X–1,

4U 1630 – 47, Cyg X–3, LMC X–1, 4U 1957 + 115, LMC X–3, Swift J1727.8 – 1613, GX 339 – 4, Swift J151857.0 – 572147, IGR J17091 – 3624, and MAXI J1744 – 294. A detailed broadband spectro-temporal study of these sources confirms the presence of canonical spectral states: LHS, HIMS, SIMS, HSS and SPL, typically observed in BH-XRBs. Among these, significant temporal variability, including the appearance of LFQPO features, is found in the LHS, HIMS and SIMS, whereas the HSS exhibits negligible variability across different sources. Further, the wideband spectra of the sources are found to be well described by a combination of a standard accretion disc, coroneae with different geometries, and reflection based models, highlighting the inherent degeneracies in modeling the disc-corona configuration. Next, the polarization properties of the sources and their energy dependence are obtained using both model-independent and model-dependent techniques. We find that, except LMC X–1, Swift J151857.0 – 572147 and MAXI J1744 – 294, all the sources exhibit a significant polarization degree in the range of 1.2 – 21.4% across various spectral states. Based on the findings of the spectro-polarimetric correlation study for all the sources, and using the available radio jet position angles, we attempt to constrain the disc-corona dynamics and geometry. Our study favors a disc-corona configuration in which the corona is radially extended in the equatorial plane at the inner region of the accretion disc for most of the sources.

Chapter 5 explores the complex accretion dynamics of extragalactic black hole ultraluminous X-ray sources (BH-ULXs): NGC 1313 X–1, NGC 5408 X–1, NGC 6946 X–1, IC 342 X–1, M82 X–1, NGC 55 ULX1, NGC 4395 ULX1, NGC 5204 X–1 and NGC 4190 ULX1, through a comprehensive study using archival *XMM-Newton* observations. We investigate their temporal variability properties across diverse timescales, and detect short-term variability and QPO features of frequency 8 – 667 mHz. Subsequently, our spectral analysis using both phenomenological and physical models reveals distinct ultra-luminous spectral states over much longer timescales of variability for the sources. This, in turn, results in an accretion scenario comprising a geometrically thin accretion disc along with a ‘cool’ (~ 2 keV) Comptonizing corona in the vicinity of the black hole. Further, we examine the correlation properties among the spectro-temporal parameters and find various correlations in $L_{\text{disc}} - T_{\text{col}}$ plane of both positive and negative types. The negative correlation between disc luminosity and temperature suggests the possibility of obscuration of the primary emission from the disc-corona system by radiation pressure driven disc winds. Collectively, these findings support accretion scenarios in which powerful winds, in conjunction with the disc-corona system, regulate the accretion dynamics of BH-ULXs across various spectral states observed at different inclinations. Finally, by modeling key observables of BH-ULXs, such as bolometric luminosity and QPO frequency using a relativistic, steady, viscous, optically thin, advective accretion flow model around BH-ULXs, we constrain the mass, spin, and accretion rates of a set of BH-ULXs.

In Chapter 6, we summarize the findings from our study and discuss the future prospects in Chapter 7.

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Chapter 1

Introduction

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1.1 Astrophysical Compact Objects

Stars, the basic building blocks of the universe, follow a remarkable yet predictable journey through various evolutionary stages governed by the fundamental laws of physics. While every star is born from the collapse of a dense molecular cloud, the way it evolves and ultimately reaches its end phase is profoundly influenced by its initial mass. This mass dictates the duration of its life, the processes it undergoes, and the nature of the remnants it leaves behind. Throughout the majority of its existence, a star remains in a stable state known as the main sequence. During this phase, nuclear fusion in the core converts hydrogen into helium, producing the energy that balances the inward pull of gravity. However, as the hydrogen fuel in the core is exhausted, the fate of the star begins to diverge based on its mass. The core contracts under gravity with the increase in temperature and pressure, while the outer layers expand and cool, thereby transforming the star into a red giant. For the stars beyond a certain mass

threshold, the fusion process in the core extends to heavier elements. This continues until the core reaches a point where further fusion becomes energetically unfavorable, leading to the eventual collapse of the core. The outer layers of the star are expelled in a dramatic event called a supernova ([Fryer, 1999](#)), while the core transforms into a dense remnant. These remnants, commonly referred to as compact objects, represent the final stages of stellar evolution. Interestingly, compact objects are defined by their extreme densities and unique physical properties and are generally classified into three types: white dwarf, neutron star, and black hole, depending on the mass of the progenitor star. In the following sections, we briefly discuss the nature of these remnants and their significance in the broader context of astrophysics.

1.1.1 White Dwarf

A white dwarf is the remnant of a star as massive as the sun after it has exhausted its nuclear fuel. At the end of its nuclear burning phase, the star sheds most of its outer layers, leaving behind a dense and hot core. This core gradually cools over billions of years, eventually becoming a white dwarf. In general, the compactness of the massive core in a white dwarf results in the electron degeneracy pressure following Pauli's exclusion principle and prevents gravitational collapse. Therefore, one of the key defining factors of white dwarfs is their mass limit of $1.44 M_{\odot}$ (where $M_{\odot}$ is the mass of the sun), known as the Chandrasekhar limit ([Chandrasekhar, 1931](#)), beyond which it cannot support against the inward gravity and will collapse into a different type of compact object. It is worth noting that main-sequence stars exhibit non-zero magnetic fields. For these stars, while transforming into a white dwarf, its magnetic flux remains conserved. Given that magnetic flux is inversely proportional to the square of the stellar radius, this collapse can lead to a significant amplification of the magnetic field strength (typically in excess of $\sim 10^6$ Gauss) ([Wickramasinghe and Ferrario, 2005](#)). Thus, white dwarfs are expected to exhibit non-zero magnetic field strengths. Often, due to additional support from strong magnetic fields, white dwarfs can exceed the classical Chandrasekhar mass limit ($1.44 M_{\odot}$), reaching the so-called super-Chandrasekhar mass limit. Such massive white dwarfs are believed to be progenitors of over-luminous Type Ia supernovae, thereby challenging the standard paradigm ([Howell et al., 2006](#), [Das and Mukhopadhyay, 2013](#)). Interestingly, white dwarfs in binary systems with main-sequence stars form the cataclysmic variables (CVs), which are believed to be the ideal objects to study the physics of such compact objects. Typically, the white dwarf in CV accretes matter from its companion star and emits mostly in X-rays ([Warner, 1995](#)). Depending on the magnetic field strength of the white dwarf, the accretion can happen through the formation of a disc or direct channeling of matter along the magnetic field lines ([Giovannelli, 2008](#)).

1.1.2 Neutron Star

Neutron stars represent one of the most extraordinary and exotic outcomes of stellar evolution. For the stars of mass exceeding the Chandrasekhar limit, electron degeneracy pressure remains insufficient to counteract gravity, leading to the fusion of protons and electrons into neutrons and forming more dense stellar remnants known as the neutron stars ([Shapiro and Teukolsky, 1983](#)). Therefore, the gravitational collapse in such objects is balanced by the neutron degeneracy pressure. In general, neutron stars

can have outer layer densities of $\lesssim 10^4 \text{ g cm}^{-3}$ and core densities often exceeding the nuclear matter density $\rho_0 \approx 2.8 \times 10^{14} \text{ g cm}^{-3}$. Such extreme conditions generally give rise to exotic states of matter, including hyperons, quark-hadron mixed phases, and Bose-Einstein condensates of kaons (Ambartsumyan and Saakyan, 1960). These objects are also characterized by immense magnetic fields reaching up to $\sim 10^{12}$ Gauss and rapid rotation with spin periods ranging from milliseconds to seconds. The spin-down rate of neutron stars is remarkably small ($\dot{P} \approx 10^{-15} \text{ s s}^{-1}$) indicating their stability. These properties of neutron stars serve as a natural laboratory for studying fundamental physics under such extreme conditions.

In binary systems, neutron stars are found to accrete material from a companion star forming an accretion disc and emitting X-rays. A subclass of neutron stars, namely the pulsars (Hewish et al., 1968, Ruderman and Sutherland, 1975), emits beams of electromagnetic radiation from their magnetic poles due to the misalignment between the spin axis of the neutron star and the magnetic axis. These radiations act like cosmic lighthouses and produce periodic pulses as the beams sweep across our line of sight (Gold, 1968). Another subclass, the magnetars (Mazets et al., 1979) generally possess a very high magnetic field strength of $\sim 10^{15}$ Gauss and manifest rather complex emission properties in X-rays and gamma-rays. It may be noted that because of the presence of a very high magnetic field accretion onto these objects is often halted at the magnetospheric radius at which the magnetic pressure counteracts the ram pressure of the inflowing material. At this point, the accreting matter is forced to follow the magnetic field lines to reach the magnetic poles of the neutron star.

1.1.3 Black Hole

Similar to the Chandrasekhar limit for white dwarfs, there exists a maximum mass limit of $\sim 3M_\odot$ for the neutron stars, known as the Tolman-Oppenheimer-Volkoff (TOV) limit (Tolman, 1939, Oppenheimer and Volkoff, 1939), beyond which the neutron degeneracy pressure is unable to hold the inward pull of gravity, and the neutron stars collapse into the most densest objects, the black holes. Undoubtedly, black holes are the most enigmatic objects in our universe and, at the same time, the simplest ones to be characterized only by three parameters: mass, spin and electric charge, according to the ‘no-hair’ theorem (Misner et al., 1973). In general, black holes can be found across several ranges of masses with distinct characteristics. The most common one lies in the mass range from 3 to a few tens of $M_\odot$, known as the stellar-mass black holes (StMBHs), which are mostly populated within our Galaxy and a few in the extragalactic environments as well. More massive black holes of mass $10^5 - 10^9 M_\odot$, termed as the supermassive black holes (SMBHs) (Reid and Brunthaler, 2004), are often found to be present at the center of active galactic nuclei (AGN). The existence of intermediate-mass black holes (IMBHs) of mass $10^2 - 10^3 M_\odot$ in the ‘mass gap’ between the StMBHs and SMBHs is also suggested (Miller and Hamilton, 2002). Interestingly, the formation of StMBHs is well understood from the gravitational collapse of massive stars, whereas the formation and evolution of IMBHs and SMBHs are still not well settled problems and give rise to several ambiguities that are currently the topics of active research. Recently, the LIGO collaboration confirmed the observational evidence of an IMBH with a mass of $142 M_\odot$ through the detection of gravitational waves originating from the merger of two massive StMBHs (Abbott et al., 2020). This striking discovery by LIGO has prompted significant interest in studying

the physics of IMBHs in recent years.

As the name suggests, astrophysical black holes are indeed black, meaning even light cannot escape from their immense gravity beyond a mathematical region known as the event horizon. For a non-rotating black hole, this region is defined by the Schwarzschild radius (Schwarzschild, 1916) given as,

$$r_g = \frac{2GM_{\text{BH}}}{c^2}, \quad (1.1)$$

where G is the gravitational constant, M_{BH} is the mass of the black hole and c denotes the speed of light. Thus, the region within the event horizon remains completely forbidden and hidden from the outside world. Further, due to the presence of non-zero angular momentum in progenitor stars, astrophysical black holes are generally expected to possess a non-zero spin parameter indicating their rotational nature. Consequently, the solution of Einstein's field equations for a rotating black hole is described by the Kerr metric, which differs from the non-rotating Schwarzschild solution, where the location of the event horizon depends on the spin of the black hole. Furthermore, Kerr black holes are also surrounded by a spheroidal boundary outside the event horizon, known as the ergosphere (Shapiro and Teukolsky, 1983).

So far, we have discussed the properties of various compact objects as isolated systems. However, most of the astrophysical compact objects are found in binary systems, where they are gravitationally bound to a companion star (Frank et al., 2002). In such binary systems, mass transfer from the companion star onto the compact object becomes possible which gives rise to the accretion process. The accreting matter around the compact object heats up and emits across the electromagnetic spectrum mostly in X-rays. These high energy emissions make accretion powered compact objects prominent targets for observational studies, enabling us to probe their physical properties and underlying astrophysical processes.

1.2 Accretion Process: Source of Astrophysical Power

Accretion is the process through which a compact object accumulates matter from the surrounding environment. The release of the gravitational potential energy of accreting matter into the radiation is considered to be the fundamental mechanism driving the energy output of astrophysical sources across the universe. As matter accretes onto a compact object from a distant location under free-fall conditions, its gravitational potential energy is converted into kinetic energy, and ultimately into radiation. Below, we estimate the order-of-magnitude energy efficiency expected from the accretion process for different types of compact objects. For simplicity, we consider a proton of mass m_p that falls with a free-fall velocity v_{ff} from a distance r onto a compact object of mass M and radius R . Accordingly, we can write the energy balance equation as,

$$\frac{1}{2}m_p v_{\text{ff}}^2 = \frac{GMm_p}{r}. \quad (1.2)$$

As the matter reaches the surface of the compact object (at $r = R$), it releases all its kinetic energy into the thermal energy. Assuming the rate of accretion to be $\dot{m}$, the rate of dissipation of energy equivalent to the luminosity of the source can be written as

$$L_{\text{acc}} = \frac{1}{2}\dot{m}v_{\text{ff}}^2 = \frac{GM\dot{m}}{R}. \quad (1.3)$$

Again, considering the accretion efficiency to be η , the luminosity can be written in terms of the rest mass energy ($\dot{m}c^2$) of accreting matter as $L_{\text{acc}} = \eta \dot{m}c^2$ (Frank et al., 2002). Thus, the accretion efficiency of energy extraction from a compact object remains directly proportional to its compactness ratio M/R . For a white dwarf, assuming a typical mass of $\approx M_\odot$ and $R \approx 5 \times 10^6$ m, we obtain $\eta \sim 3 \times 10^{-4}$. On the other hand, for a neutron star of mass $\approx M_\odot$ and $R \approx 15$ km, the efficiency appears to be $\eta \sim 0.1$. Since a black hole does not have any hard surface and the inner boundary region strictly depends on the spin parameter, the energy efficiency remains largely spin dependent with $\eta = 0.06$ for a non-rotating case, and $\eta = 0.4$ holds for a rapidly rotating hole (Bardeen et al., 1972, Frank et al., 2002, Longair, 2011). With this, in the following, we discuss two fundamental processes through which accretion takes place in compact objects.

1.2.1 Roche Lobe Overflow

The Roche lobe overflow is the process through which the mass transfer happens from the secondary star to the primary in a binary system, first studied by Edouard Roche back in the nineteenth century. The central idea of this process relies on the fact that, during the evolution of a binary system, the size of the secondary star expands, or the orbital separation between the two can decrease. Due to this, the massive

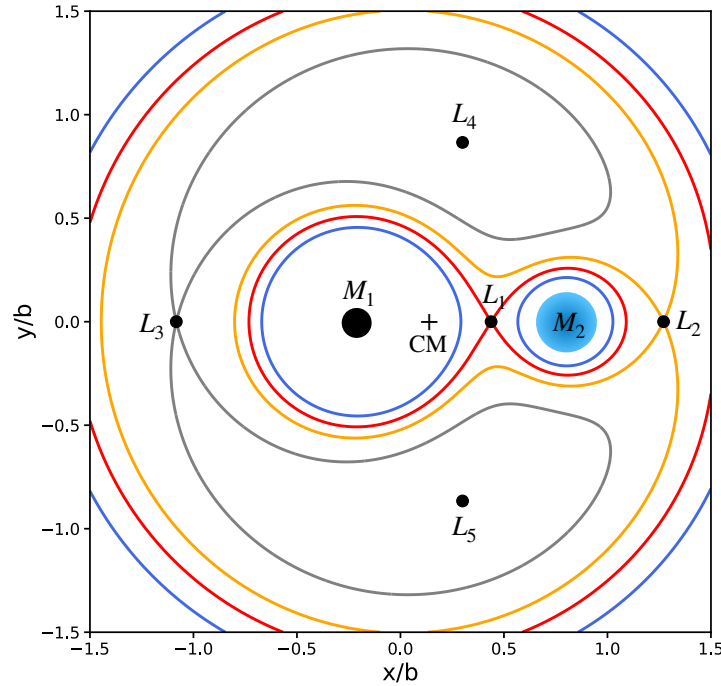


Figure 1.1: Pictorial representation of the equipotential surfaces of $\Phi_R(\mathbf{r})$ for a binary system having secondary to primary star mass ratio $q_0 = 0.25$. L_1 is the inner Lagrange point where the Roche lobes of the two stars are connected and through which mass transfer occurs.

gravitational attraction of the primary compact object can strip away the outer layers of the secondary star. For a mathematical framework of the process, we consider the mass of the primary and secondary stars to be $M_1 = m_1 M_\odot$ and $M_2 = m_2 M_\odot$, respectively, and they are approximately in circular orbits in the binary. If b is the binary separation and P_0 is the binary period, then according to Kepler's law, we can

write

$$4\pi^2 b^3 = GM_3 P_0^2, \quad (1.4)$$

where $M_3 = M_1 + M_2 = mM_\odot$. Now, the potential experienced by a test particle at a distance $\mathbf{r}$ can be expressed as the Roche potential (Frank et al., 2002) given by,

$$\Phi_R(\mathbf{r}) = -\frac{GM_1}{|\mathbf{r} - \mathbf{r}_1|} - \frac{GM_2}{|\mathbf{r} - \mathbf{r}_2|} - \frac{1}{2}(\boldsymbol{\Omega} \times \mathbf{r})^2, \quad (1.5)$$

where $\Omega = \sqrt{GM_3/b^3}$ is the angular speed of the binary system. $\mathbf{r}_1$ and $\mathbf{r}_2$ are the position vectors of two stars. In Fig. 1.1, we show the equipotential surfaces corresponding to $\Phi_R(\mathbf{r})$, which depends on the mass ratio $q_0 = M_2/M_1 = 0.25$ of the binary system. We note that, at large distance ($r \gg b$), the system behaves as a single point mass concentrated at the center of mass (CM). However, the equipotential surfaces become circular near each star, and the test particle experiences a strong gravitational attraction. Thus, $\Phi_R(\mathbf{r})$ has two potential wells centered at $\mathbf{r}_1$ and $\mathbf{r}_2$. Notably, the inner equipotential surfaces represented by the red curve in Fig. 1.1 indicate how these two potential wells of the stars are connected. Moreover, this surface resembles a dumbbell shape in three dimensions, and the part of the surface close to each star is known as the Roche lobe of the respective stars. It is worth mentioning that there exist five Lagrange points in the system ($L_1 - L_5$), where a test mass would experience no net force and the Roche lobes of the individual stars connect at L_1 (see Fig. 1.1). In a binary system, when the companion star fills its Roche lobe, matter enters into the Roche lobe of the primary star through L_1 . As a consequence, the accreting matter essentially forms a disc-like structure around the primary compact object instead of directly falling onto it due to the presence of non-zero angular momentum in the matter. This process, known as Roche lobe overflow accretion, remains the fundamental mechanism of mass transfer in low-mass X-ray binaries (LMXBs), such as GX 339 – 4.

1.2.2 Stellar Winds

Accretion of matter onto a compact object can also occur through the direct interception of stellar wind released from the companion star. This mode of accretion is particularly relevant in many high-mass X-ray binaries (HMXBs), such as Cyg X–1, where observational evidence suggests that the compact object primarily acquires material via wind capture. In systems where the donor star is a massive and luminous O/B-type star, strong radiation pressure drives substantial mass outflows in the form of stellar winds, which feed the primary compact object (Puls et al., 2008). In this scenario, at a radial distance r from the donor's center, the wind speed can be approximated by the escape velocity from the stellar surface (Frank et al., 2002) as,

$$v_w(r) \sim v_{\text{es}}(R_d) = \sqrt{\frac{2GM_2}{R_d}}, \quad (1.6)$$

where M_2 and R_d represent the mass and radius of the donor star, respectively, and v_{es} is the escape velocity at the surface. We consider that the compact object moves in the binary orbit with a velocity of v_{co} , then the relative velocity of the stellar wind sweeps past the compact object can be written as (Frank et al., 2002),

$$v_{\text{rel}} = \sqrt{v_{\text{co}}^2 + v_w^2}. \quad (1.7)$$

If the wind passes sufficiently close to the compact object at a velocity v_{rel} , so that their kinetic energy is less than the gravitational potential energy, it will be captured. Moreover, this results in the formation of a cylindrical accretion region aligned with the relative wind direction (v_{rel}), with a characteristic radius (see Fig. 1.4),

$$r_{\text{acc}}^{\text{w}} \sim \frac{2GM}{v_{\text{rel}}^2}, \quad (1.8)$$

where M denotes the mass of the compact object. Thus, material located within the so called wind accretion radius, $r_{\text{acc}}^{\text{w}}$, measured from the compact object, will eventually be captured and accreted to the primary.

1.2.3 Eddington Luminosity and Accretion Rate

So far, we have discussed the fundamental processes involved in accretion onto compact objects. In this section, we focus on some of the key aspects related to the accretion rate and luminosity, which are crucial for understanding the energetics of these systems. In general, the radiation that emerges from the accretion onto compact objects retards the ongoing infalling of accreting materials by exerting radiation pressure. Therefore, at some point, the inward gravitational force acting on matter must be balanced by the outward radiation force. We consider a spherically symmetric steady accretion scenario in which the accreting material is fully ionized hydrogen. The net gravitational force acting on each electron-proton pair at a distance r can be approximated as,

$$f_g = \frac{GM(m_p + m_e)}{r^2} \approx \frac{GMm_p}{r^2}, \quad (1.9)$$

where m_e ($\ll m_p$) is the mass of electron. It is noteworthy that the outward radiation force acts mainly on the free electrons via Thomson scattering since the scattering cross section for protons is much smaller ($(m_e/m_p)^2 \sim 2.5 \times 10^{-7}$) (Frank et al., 2002) as compared to the electrons. However, due to the Coulomb attraction between electrons and protons, the outward motion of electrons results in the protons being carried along with them. Considering the photon flux of the source measured at a distance r as $F = \frac{L_{\text{acc}}}{4\pi r^2}$, the radiation force exerted on each electron-proton pair can be approximated as $f_{\text{rad}} = \sigma_T F/c$. This represents the momentum transferred per scattering event. Here, σ_T denotes the Thomson scattering cross section for electrons. The luminosity at which this radiation force balances the gravitational pull on the protons is known as the Eddington luminosity (L_{Edd}), which is given by,

$$L_{\text{Edd}} = \frac{4\pi GMm_p c}{\sigma_T} \approx 1.3 \times 10^{38} \left(\frac{M}{M_{\odot}} \right) \text{ erg s}^{-1}. \quad (1.10)$$

Thus, L_{Edd} remains the maximum luminosity obtained from a spherically symmetric accretion flow in the steady state. Although the above estimation is carried out considering spherical symmetry, this limit remains applicable as an order-of-magnitude estimate for more generic accretion scenarios. Further, following $L_{\text{acc}} = \eta \dot{m} c^2$, the Eddington accretion rate ($\dot{m}_{\text{Edd}}$) can be estimated corresponding to the Eddington luminosity (L_{Edd}) as $\dot{m}_{\text{Edd}} = L_{\text{Edd}}/\eta c^2$.

1.3 Accretion-Powered X-ray Binaries

X-ray binaries (XRBs) are binary systems in which a compact object, either a black hole or a neutron star, accretes matter from a companion star. The companion star can be a main-sequence star, a subgiant, or an evolved star such as a red giant. Based on the nature of the accreting compact object, these systems are further classified as black hole X-ray binaries (BH-XRBs) or neutron star X-ray binaries (NS-XRBs). To date, 72 confirmed galactic BH-XRB transients¹ (see Fig. 1.2 and Corral-Santana et al. 2016) and 10 persistent (Tetarenko et al., 2016) sources have been detected with various X-ray observatories. In general, the mass transfer in XRBs primarily occurs through Roche lobe overflow or stellar wind capture. In Roche lobe overflow, the donor

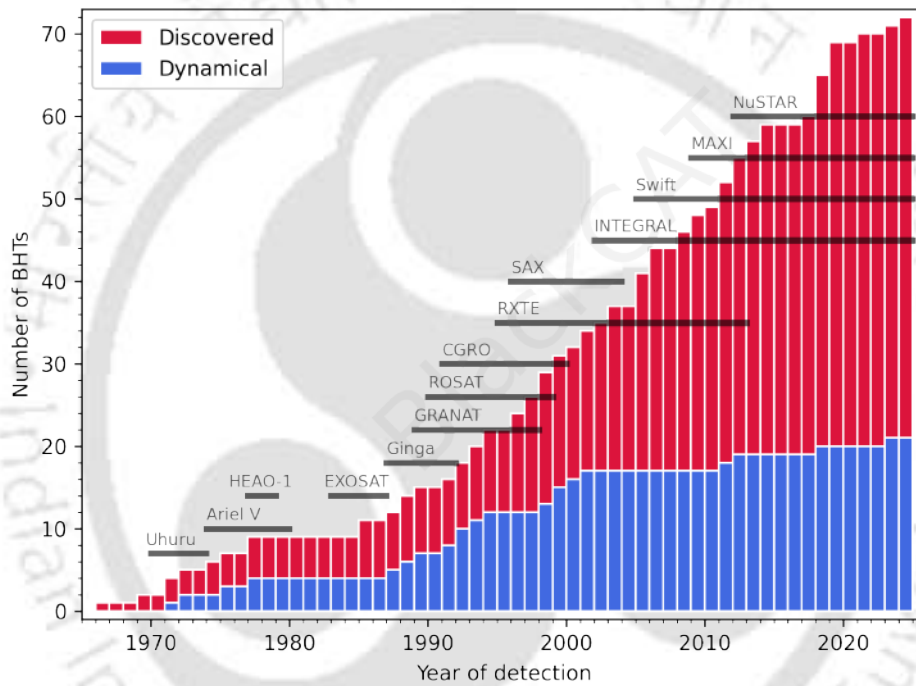


Figure 1.2: Histogram representing the number of transient black hole candidates discovered so far through various X-ray astronomy missions. Blue bars indicate the dynamically confirmed black holes, whereas the red bars denote the detections through other indirect methods. Credit: BlackCAT catalogue (<https://www.astro.puc.cl/BlackCAT/>).

star fills its Roche lobe, allowing matter to flow through the inner Lagrange point (L1) (see Fig. 1.1) toward the compact object (see §1.2.1). In contrast, wind-fed accretion occurs when the compact object captures a portion of the stellar wind ejected by a high-mass companion (see §1.2.2). As the accreting material spirals inward, it forms the accretion disc around the compact object due to the presence of angular momentum in the material. Subsequently, the viscous torque generated between different radii of the disc transports angular momentum outward and matter gets accreted, converting its gravitational potential energy into thermal energy. This process results in the emission mostly in X-rays and such systems are therefore termed as ‘X-ray binaries’. In the following, we discuss different types of XRBs in a more generic context.

¹<https://www.astro.puc.cl/BlackCAT/>

1.3.1 Low-Mass X-ray Binaries

The low-mass X-ray binaries (LMXBs) are a subclass of X-ray binary systems in which a main-sequence companion star of mass typically $\lesssim 1 M_{\odot}$ feeds the primary compact object, either a neutron star or a black hole, through accretion. In most of the LMXBs, the donor star expands to fill its Roche lobe (Frank et al., 2002). As a result, mass transfer in these systems predominantly occurs via Roche lobe overflow (see Fig. 1.3 for the pictorial representation and §1.2.1 for details). Interestingly, LMXBs represent some of the most luminous point sources in the X-ray sky when undergoing episodes of enhanced accretion. The detection and classification of LMXBs are predominantly based on their X-ray emission, which is closely connected with the accretion of matter onto the primary compact object. However, a majority of LMXBs do not sustain persistent accretion and continuous X-ray activity; instead, they are identified as transients. Typically, these transients exhibit episodic outbursts that persist over timescales rang-

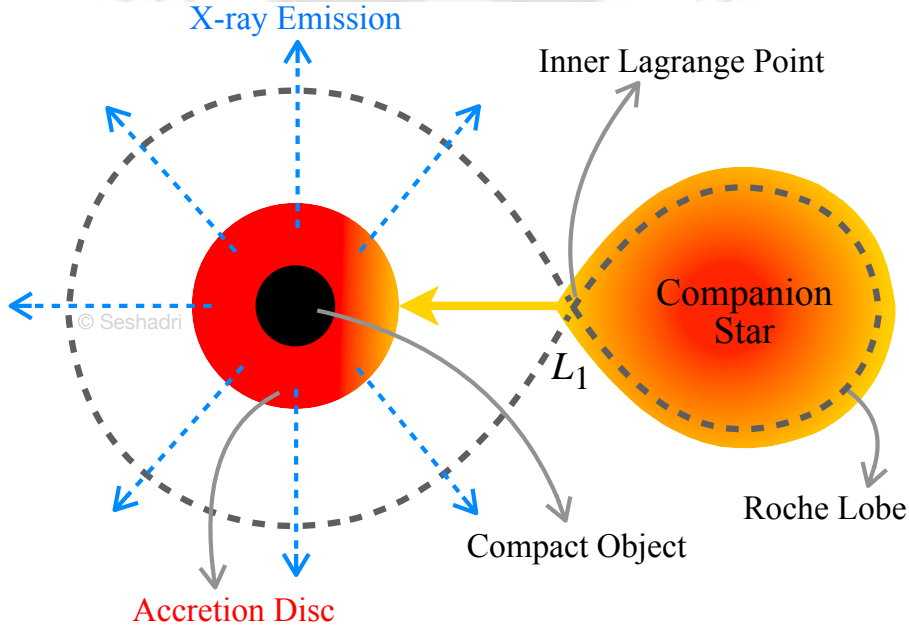


Figure 1.3: Schematic depiction of the mass accretion process in LMXBs, where the donor star fills its Roche lobe and transfers matter to the compact object through the inner Lagrange point (L_1). The illustration assumes a mass ratio of $q_0 = 0.25$ (donor to compact object), which determines the size of the Roche lobe.

ing from weeks to several months and occasionally decades for a few instances, during which the mass accretion rate onto the compact object increases significantly, resulting in a sharp rise in the X-ray luminosity (Frank et al., 2002). Following these periods of enhanced brightness, transient LMXBs again enter into the prolonged states of quiescence in which the accretion rate drops redundantly and X-ray activity remains below the detection limit. In general, these quiescent intervals can extend over months to decades, depending on the properties of the LMXBs, before they reappear again into the outbursting phase. Notably, the most widely accepted explanation of the transient nature of LMXBs is the thermal-viscous instability model of an accretion disc (Smak, 1983, Menou et al., 2000, Dubus et al., 2001). According to this model, the viscous instability developed into the accretion disc triggers the outburst in LMXBs, resulting in the release of copious amounts of X-rays. In Fig. 1.5(a-b), we present the *MAXI/GSC* light curves showing the typical recurrent outburst profiles of the BH-LMXB transients GX 339–4 and 4U 1630–47, lasting for several months timescale

(Kuulkers et al., 1997, Zdziarski and Gierliński, 2004). In contrast, panel (c) illustrates the X-ray outburst activity of the ‘quasi-persistent’ BH-LMXB GRS 1915+105, which generally continues for several years (Fender et al., 2004).

To date, more than ~ 200 galactic LMXB candidates have been identified based on their X-ray activity (Tetarenko et al., 2016, Corral-Santana et al., 2016, Bambi and Sanganelo, 2022). However, the precise nature of the compact object remains uncertain for a significant fraction of these systems. While in several dozen cases, the primary accretor has been confirmed to be either a black hole or a neutron star, the classification of many LMXBs remains inconclusive. Although spectral and timing characteristics of LMXBs provide a phenomenological basis for distinguishing between black hole and neutron star accretors, these diagnostics often lack definitive confirmation. In addition to the accretion-driven spectral and timing characteristics, several other methods can be employed to determine the nature of the compact object in LMXBs. One such method involves the detection of X-ray bursts and pulsations, which serve as strong indicators of a highly magnetized neutron star. In general, the presence of a hard surface in the neutron star is essential for generating a thermonuclear burst, which results from the rapid runaway fusion of accreted material (Lewin et al., 1993). Conversely, one of the most reliable techniques for confirming the presence of a BH in LMXBs is the radial velocity measurements obtained through optical or near-infrared spectroscopy. This method relies on the Doppler shifts of spectral features associated with the companion star, allowing for the determination of the mass of the compact object. For a more comprehensive discussion on the various techniques used to identify the compact objects in LMXBs, readers are referred to Bambi and Sanganelo (2022). Further, it has been observed that the number of identified NS-LMXBs is approximately twice that of BH-LMXBs (Bahramian and Degenaar, 2023), which agrees well with the theoretical predictions on the formation of black holes and neutron stars (Kalogera and Webbink, 1998).

1.3.2 High-Mass X-ray Binaries

High-mass X-ray binaries (HMXBs) comprise a neutron star or black hole that accretes matter from a stellar companion of mass $\gtrsim 10 M_{\odot}$ (Frank et al., 2002). In most HMXBs, the donor star is either a supergiant O/B star or a Be star, both of which exhibit higher mass loss rates than main sequence O/B type stars. Unlike LMXBs, the primary compact objects in HMXBs are predominantly fed through wind accretion (see Fig. 1.4 for schematic representation and §1.2.2 for wind-fed accretion process). Typically, high-mass companion stars generate strong stellar winds with mass loss rates of $10^{-6} M_{\odot} \text{ yr}^{-1}$, enabling direct wind accretion to sustain relatively high accretion rates and produce X-ray luminosities in the range of $10^{35-40} \text{ erg s}^{-1}$ (Davidson and Ostriker, 1973, Walter et al., 2015, Bambi and Sanganelo, 2022). Consequently, the wind-fed persistent HMXBs are generally explained through the simple spherically symmetric accretion models (see §1.4.1). However, observational evidence also suggests the presence of accretion discs in some HMXBs, as indicated by (i) exceptionally high luminosities and accretion rates exceeding the limits expected from direct wind accretion, (ii) modeling of optical light curve that requires an accretion disc component (Tjemkes et al., 1986), and (iii) optical spectral lines, which require higher temperatures than those of supergiant star surfaces and exhibit radial velocity curves in anti-phase with donor star lines (Hutchings et al., 1977). Additionally, it has been

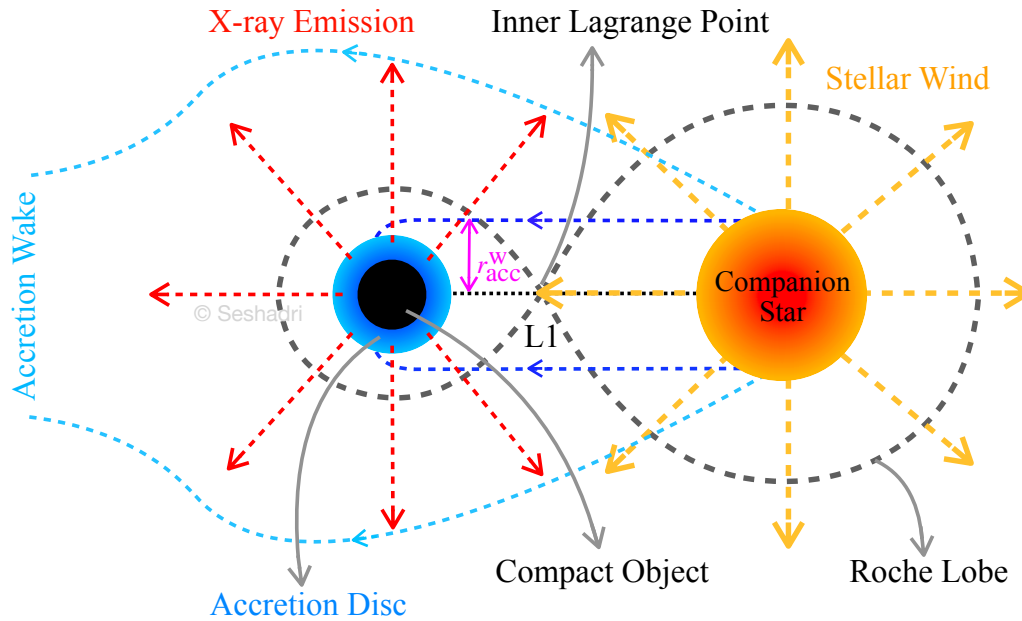


Figure 1.4: Schematic illustration of the wind-fed accretion process in HMXBs, where the compact object accretes matter from the radiatively driven stellar wind of the massive companion star. The system shown assumes a mass ratio of $q_0 = 4$ (companion to compact object), which defines the size of the Roche lobe.

proposed that in HMXBs with close binary separations, where supergiant donors have slower stellar winds, accretion discs can form temporarily even in the absence of Roche lobe overflow (Kretschmar et al., 2019). This mechanism has been successfully applied to explain accretion disc formation in HMXBs such as Cyg X–1 and Cen X–3. So far, around 152 HMXBs have been detected in our galaxy (Fortin et al., 2023) and about 200 such systems have been found to be present in the near Large and Small Magellanic Clouds. In Fig. 1.5(d-f), we depict the long-term light curves of the persistent HMXBs (Cyg X–1, LMC X–3, and Cen X–3), which indicate that these objects always remain above the detection limit, unlike the case of LMXBs.

1.3.3 Intermediate-Mass X-ray Binaries

In addition to LMXBs and HMXBs, a third class of binary systems has been propounded as intermediate-mass X-ray binaries (IMXBs), where the companion star possesses a mass typically in the range of $2 - 10 M_{\odot}$. It has been suggested that a substantial fraction of LMXBs may have evolved from IMXBs (Podsiadlowski et al., 2002). In this context, the LMXB Cyg X-2 serves as a compelling case study. More specifically, the donor star in Cyg X-2 of high intrinsic luminosity suggests that the initial mass of the star could be around $3.5 M_{\odot}$, which evolved to $0.6 M_{\odot}$ due to substantial mass loss (King and Ritter, 1999, Podsiadlowski and Rappaport, 2000, Podsiadlowski et al., 2002). This scenario possibly implies that Cyg X-2 is most likely originated as an IMXB. Moreover, Cyg X-2 provides observational evidence that even when the mass transfer rate from the donor to the primary star exceeds the Eddington limit, such IMXB systems remain stable by expelling most of their transferred mass (Podsiadlowski et al., 2002). Furthermore, Davies and Hansen (1998) proposed that IMXBs could be the progenitors of millisecond pulsars found in globular clusters. These theoretical and observational studies have increased scientific interest in IMXBs. However, very few IMXBs have been observed so far (Tauris and van den Heuvel, 2006). As a

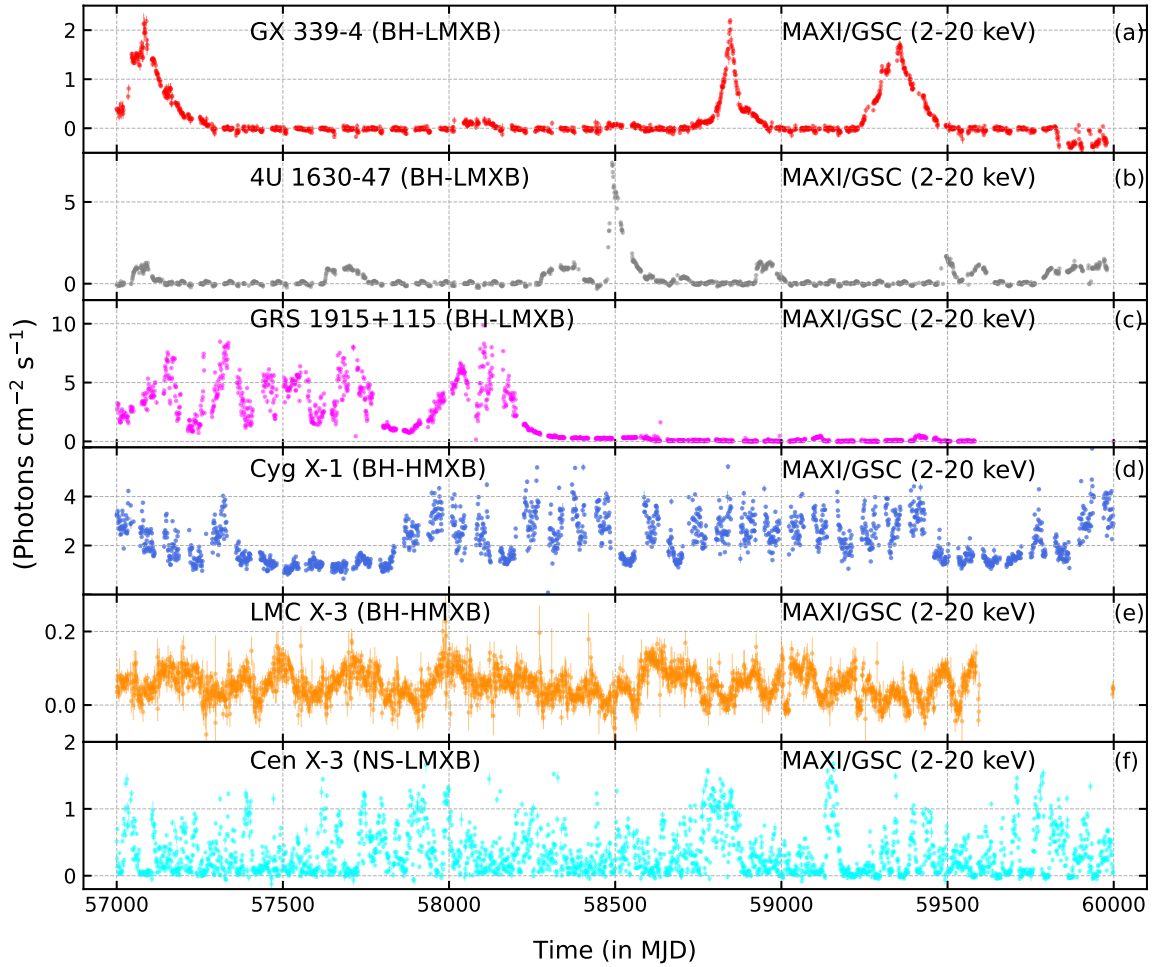


Figure 1.5: Long-term *MAXI/GSC* light curves in 2–20 keV energy range of the LMXB source GX 339–4, 4U 1630–47, GRS 1915+105, Cyg X–1, LMC X–3 and Cen X–3 are depicted from top to bottom panels, respectively. Some of the data points for the persistent sources LMC X–3 and Cen X–3 appear to be $\lesssim 0$, which could be due to their relatively faint nature and the background domination in the *MAXI/GSC* observations. The figure is generated using the on-demand *MAXI/GSC* data available at <http://maxi.riken.jp/mxondem/>.

result, their detailed characteristics are poorly understood to date.

1.3.4 Ultra-luminous X-ray Sources

Ultra-luminous X-ray sources (ULXs) are mostly extra-galactic off-nuclear point-like distinct type of XRBs with bolometric luminosity above $\sim 10^{39}$ erg s $^{-1}$ (see [Feng and Soria 2011](#), [Kaaret et al. 2017](#), [Fabrika et al. 2021](#) for reviews). Because of their position away from the center of the host galaxy, the possibility of having supermassive black holes at the core of these objects gets automatically ruled out. The existence of such peculiar objects was first confirmed back in the 1980s with the Einstein Observatory ([Long et al., 1981](#), [Fabbiano, 1989](#)), and thereafter, several hundred ULXs have been detected to date in different galaxies. In general, the ULXs are found in galaxies of low metallicity and young stellar populations ([Kaaret et al., 2017](#)). Although ULXs are mostly extra-galactic objects, Swift J0243.6+6124 and Cyg X–3 remain two promising galactic ULX candidates ([Tsygankov et al., 2018](#), [Veledina et al., 2024a](#)). Despite being discovered more than 30 years ago, the true nature of these objects remains elusive and is under active research so far. Meanwhile, several models have been proposed over the

years to explain these high luminosities of ULXs. In particular, two of them turned out to be the most widely discussed explanations of these objects. One proposes that the ULXs possibly harbor the stellar-mass black holes that accrete at a super-Eddington rate (see [Fabrika and Mescheryakov 2001](#), [Watarai et al. 2001](#), [Ebisawa et al. 2003](#), [Poutanen et al. 2007](#), [Ghosh and Rana 2023](#) and references therein). In contrast, the other explanation relies on the fact that sub-Eddington accretion into the IMBHs of mass $10^3 - 10^5 M_\odot$ can power the ULXs ([Colbert and Mushotzky, 1999](#), [Makishima et al., 2000](#), [Miller et al., 2003](#), [Strohmayer and Mushotzky, 2009](#), [Brightman et al., 2016a](#), [Das et al., 2021](#)).



Figure 1.6: Composite image of the Whirlpool Galaxy M51, with X-ray emission observed with Chandra X-ray Observatory shown in purple, and optical data from Hubble Space Telescope displayed in red, green, and blue. The ULX source is marked in the image with a circle. Credit: NASA/CXC/Caltech/M.Brightman et al.; Optical: NASA/STScI.

Interestingly, several ULXs exhibit compelling signatures of strong outflows in both X-ray and optical spectra. These outflows are believed to originate from the geometrically thick accretion discs, typically associated with the super-Eddington accretion scenarios ([Kaaret et al., 2017](#)). Such observational characteristics suggest that at least a subset of the ULX population is powered by super-Eddington accretion. Further, large-scale optical bubble nebulae spanning tens to hundreds of parsecs are detected in the surroundings of several ULXs. Often, the spectroscopic analysis of these nebulae indicates shock interactions, likely driven by fast-moving winds or jets impacting the ambient interstellar medium ([Bambi and Sanganelo, 2022](#)). However, for a substantial fraction of the ULX population, the X-ray spectro-temporal variabilities resemble those of BHs accreting at the sub- or super-Eddington rate, and these ULXs are believed to harbor IMBHs. The prime example of a promising IMBH ULX candidate is HLX-1 in ESO 243-49 galaxy with a very high luminosity often reaching up to $\sim 10^{42}$ erg s $^{-1}$ ([Straub et al., 2014](#)). Meanwhile, one of the most surprising discoveries came in 2014 with the detection of coherent X-ray pulsation in the ULX source M82 X-2 ([Bachetti et al., 2014](#)). These results opened up the possibility of having magnetized neutron stars as the central accretor in ULXs. Later on, several ULXs are also found to exhibit such pulse profiles (see [Fürst et al. 2016](#), [Israel et al. 2017](#), [Carpano et al. 2018](#), [Rodríguez Castillo et al. 2020](#), [Quintín et al. 2021](#) and references therein) and identified as the objects powered by accretion into neutron stars. Subsequently, a sig-

nificant fraction of the ULX population is now believed to harbor strongly magnetized accreting neutron stars as well. The most notable examples of the two best studied pulsating ULXs are NGC 7793 P13 and NGC 5907 ULX–1, showing luminosity up to $\sim 10^{41}$ erg s $^{-1}$. Contemporarily, an alternative scenario based on the sub-Eddington accretion onto stellar-mass black holes producing beamed emission is also propounded (Reynolds et al., 1997, King, 2002), although it encounters the lack of enough observational evidence (Feng and Soria, 2011). It is noteworthy that a subset of ULXs has been identified as black hole ULX (BH-ULX) candidates with their central accretors inferred to be black holes. This is typically inferred from distinct observational characteristics such as the detection of millihertz Quasi-periodic Oscillations (QPOs) in BH-ULXs and the absence of pulsed emission (Das et al., 2021, Majumder et al., 2023, 2025a). Nevertheless, none of the above models can explain all the observational signatures of the ULXs in a fully consistent manner and hence remain under debate.

Furthermore, the study of the stellar environments around these objects predicts that ULXs are the high-luminosity extension of HMXBs. In general, ULXs in the starburst galaxies with active star formation are often seen in the proximity to young star clusters, typically around 6 million years old. However, in galaxies with moderate star formation rates, ULXs are frequently found close to the OB stellar associations of ages of 10–20 million years (Kaaret et al., 2017). These spatial correlations further imply that the companions or donor stars in ULXs are likely to be massive stars, as is the case for a typical HMXB. However, as most of the ULXs are generally found in the crowded region of the host galaxies, the identification of optical counterparts remains largely ambiguous except for a few cases. Although the ULXs are believed to be the higher-luminosity end of HMXBs, their X-ray spectral properties largely differ from a standard HMXB candidate. In Fig. 1.6, we depict the composite image of a ULX source in the M51 galaxy, obtained from the Chandra X-ray Observatory and Hubble Space Telescope data, for representation purposes.

1.4 Theoretical Frameworks of Accretion Models

In this section, we discuss several accretion models proposed over the years to understand the accretion dynamics of compact objects. This, in turn, helps to explain the observational characteristics of XRBs, particularly for BH-XRBs and BH-ULXs.

1.4.1 Bondi-Hoyle Accretion

The study of accretion began more than eighty years ago with the seminal work by Hoyle and Lyttleton (1939), examining how a star moving through a uniform medium can gravitationally attract surrounding pressureless matter. Despite its simplicity, the model provided a crucial starting point for understanding accretion onto compact objects. Later on, a more realistic treatment was proposed by Bondi and Hoyle (1944), including the role of gas pressure in the dynamics. Eventually, Bondi (1952) developed the formal solution for the spherical accretion process, ignoring the angular momentum of the infalling matter.

In the Bondi model, a compact object of mass M radially accretes matter under the influence of its gravity, in a steady state with an accretion rate $\dot{m}$. To derive the physical solutions for such a spherical accretion process, one must solve the coupled equations governing the conservation of mass, radial momentum, and energy. For

simplicity, we consider that the inverse square law describes the gravitational influence of the compact object. Further, we consider the adiabatic equation of state $P = K\rho^\gamma$, being the closure equation of the system, where P denotes the gas pressure, ρ represents the specific density of the accreting matter. Here, K is a constant describing the entropy of the flow, and γ is the adiabatic index, defined as the ratio of specific heats. After simple algebra and using the flow governing equations, we show that there exists a specific radius referred to as the sonic point (see Frank et al. 2002), defined as,

$$r_s = \frac{GM}{2c_s^2(r_s)}, \quad (1.11)$$

which determines the transonic nature of accretion solutions. Here, c_s is the adiabatic sound speed, which can be expressed as $c_s(r_s) = c_s(\infty) \left(\frac{2}{5-3\gamma}\right)^{1/2}$, where $c_s(\infty)$ is the sound speed at spatial infinity. More specifically, the radial speed of the accreting gas crosses the local sound speed and becomes supersonic ($v_r > c_s$) at $r < r_s$, whereas it remains subsonic ($v_r < c_s$) at larger distances ($r > r_s$). Further, a key aspect of this model is the presence of an accretion radius, known as the Bondi radius, which is given by,

$$r_{\text{acc}} = \frac{2GM}{c_s^2(\infty)}. \quad (1.12)$$

Notably, r_{acc} determines the radial extent of the gravitational influence of the compact object on accreting gas. In particular, at $r < r_{\text{acc}}$, the gravitational binding energy per unit mass (GM/r) of the matter dominates over the thermal energy (proportional to $c_s(\infty)$), and thereby accretion proceeds. In Fig. 1.7, we depict the typical

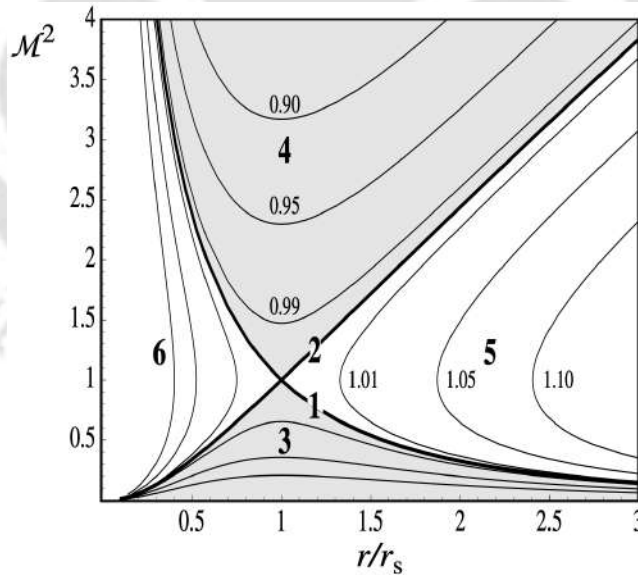


Figure 1.7: Variation of the square of Mach number, $\mathcal{M}^2 = v_r^2(r)/c_s^2(r)$, as a function of the normalized radial distance r/r_s , representing characteristic solutions for a spherically symmetric adiabatic flow under the gravitational influence of a compact object. $v_r < 0$ cases describe accretion flows, whereas $v_r > 0$ corresponds to stellar winds. The figure is adapted from Frank et al. (2002).

Mach number profiles resulting from such spherically symmetric flows, showing both accretion and wind solutions for $\gamma = 4/3$. Notably, the Mach number is defined as $\mathcal{M} = v_r(r)/c_s(r)$ and describes the sonic properties of the accretion flow across different radii. The Mach number profiles corresponding to Cases 1 and 2 (thick curves

in Fig. 1.7) represent the transonic solutions with sonic point (r_s) corresponding to $\mathcal{M} = 1$, while Cases 3 to 6 represent non-transonic solutions without any sonic points.

Furthermore, the accretion rate of the radially infalling gas onto the compact object (Frank et al., 2002) can be obtained as

$$\dot{m} = \pi G^2 M^2 \frac{\rho(\infty)}{c_s^3(\infty)} \left[\frac{2}{5 - 3\gamma} \right]^{(5-3\gamma)/2(\gamma-1)}, \quad (1.13)$$

where $\rho(\infty)$ is the specific density at spatial infinity. We calculate the accretion rate considering the fiducial value of the gravitational constant along with $\gamma = 1.4$. With this, we obtain from Eq. (1.13) as,

$$\dot{m} \cong 1.4 \times 10^{11} \left(\frac{M}{M_\odot} \right)^2 \left(\frac{\rho(\infty)}{10^{-24}} \right) \left(\frac{c_s(\infty)}{10 \text{ km s}^{-1}} \right)^{-3} \text{ g s}^{-1}. \quad (1.14)$$

Using the accretion rate expression in Eq. (1.14) into $L_{\text{acc}} = \eta \dot{m} c^2$ and considering $\rho(\infty) = 10^{24} \text{ g cm}^{-3}$ with $c_s(\infty) = 10 \text{ km s}^{-1}$ (Frank et al., 2002), the order-of-magnitude estimate of the accretion luminosity (L_{acc}) for a neutron star system ($\eta = 0.1$) gives $\sim 2 \times 10^{31} \text{ erg s}^{-1}$. This is at least two orders of magnitude lower than the average observed solar luminosity. However, for most of the X-ray binaries, much higher luminosities are generally observed. Thus, it is evident that the simplest assumption of spherical accretion is far from the realistic accretion scenarios of compact objects in X-ray binaries. This motivates us for further exploration of alternative models of the accretion process.

1.4.2 Standard Accretion Disc

The first successful attempt to model the ‘accretion disc’ phenomenon was carried out by Shakura and Sunyaev (1973) in the early 70s, and is popularly known as the ‘standard disc’ model. Around the same time, the general relativistic framework of this model was developed by Novikov and Thorne (1973). In this formalism, the accretion disc is assumed to be geometrically thin ($H \ll r$, where H is the vertical scale height of the disc and r is the radial extent) and optically thick, with the accreting matter possessing a Keplerian angular momentum profile throughout the disc. The radial inflow velocity of accreting material remains much smaller than the free-fall velocity. Therefore, the accreting matter revolves around the disc with a Keplerian angular velocity of $\Omega_k(r) = (GM/r^3)^{1/2}$. In Fig. 1.8, we present a schematic representation of the standard Keplerian disc configuration.

From Fig. 1.8, it is evident that layers of accreting matter at different radii rotate with different velocities, leading to differential rotation between successive layers. This gives rise to shear viscosity in the disc, which is responsible for transporting angular momentum outward, allowing accretion to proceed. Moreover, the standard disc model assumes the viscous stress ($t_{r\phi}$) to be proportional to the thermal pressure (P) of the accreting gas, which results

$$t_{r\phi} = \alpha_s P, \quad (1.15)$$

where $\alpha_s (< 1)$ is the viscosity parameter. In general, higher values of α_s correspond to more efficient angular momentum transport in the disc. Since the radial infall velocity is much smaller than the azimuthal velocity of the matter, the disc has sufficient

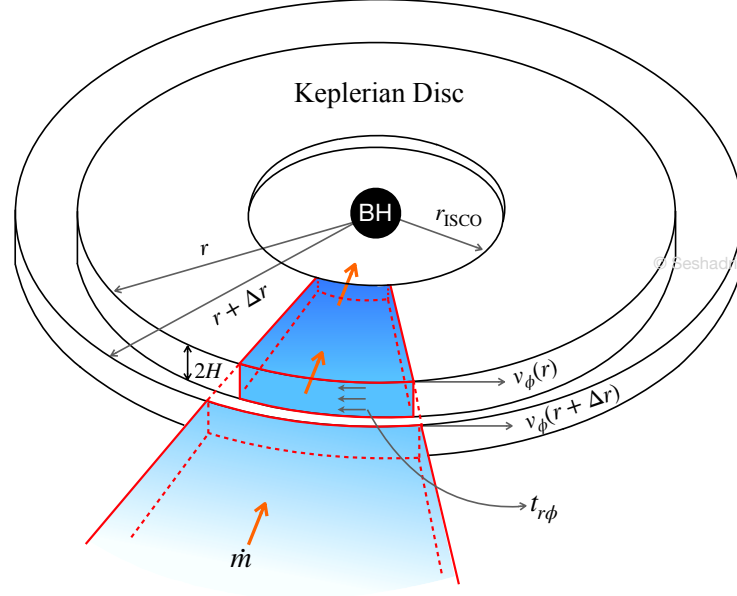


Figure 1.8: Schematic representation of the accretion process in a standard Shakura-Sunyaev Keplerian disc. In the figure, v_ϕ denotes the azimuthal component of the flow velocity, and r_{ISCO} represents the innermost stable circular orbit. The illustration concept has been adapted from [Bisnovatyi-Kogan and Lovelace \(2001\)](#).

time to radiate the viscous heating as thermal energy, making it radiatively efficient. Therefore, each concentric layer of the disc is assumed to radiate locally as an optically thick blackbody with a distinct characteristic temperature. Assuming that the dissipation rate in the disc equals the blackbody flux, the local effective temperature of the disc ([Frank et al., 2002](#)) at a distance r can be obtained as

$$T_{\text{eff}}(r) = \left[\frac{3GM\dot{m}}{8\pi r^3 \sigma_S} \left(1 - \left(\frac{R}{r} \right)^{1/2} \right) \right]^{1/4}, \quad (1.16)$$

where σ_S is the Stefan-Boltzmann constant, and all other quantities are of their usual meanings as previously defined. Empirically, it has been observed that $T_{\text{eff}}(r)$ peaks around ~ 1 keV for most of the BH-XRBs and, therefore, the model has been extremely successful in explaining soft X-ray emissions. However, it has also been pointed out that the standard disc model fails to explain the moderate to hard X-ray emission beyond ~ 10 keV. This limitation has motivated the community to explore alternative accretion disc models that incorporate the effects of advection, which were neglected in the standard disc scenario.

1.4.3 Slim Disc Prescription

The standard disc model assumes the geometrically thin accretion disc to be radiatively efficient, such that all the heat generated through viscosity is immediately radiated away. However, this assumption is valid only at relatively low accretion rates. Most importantly, at higher luminosities ($\approx 0.3L_{\text{Edd}}$), the radial drift velocity of the infalling matter increases significantly, and the corresponding scale height of the accretion disc becomes much larger as compared to the thin disc case. Under these conditions, the heat generated by viscous dissipation does not have sufficient time to be converted into photons and radiated away. Instead, a significant portion of the viscous heat is

advected inward with the accreting gas. Furthermore, as the luminosity increases, the role of advective cooling becomes increasingly significant and eventually comparable to radiative cooling, rendering the standard disc approximation invalid. The physical

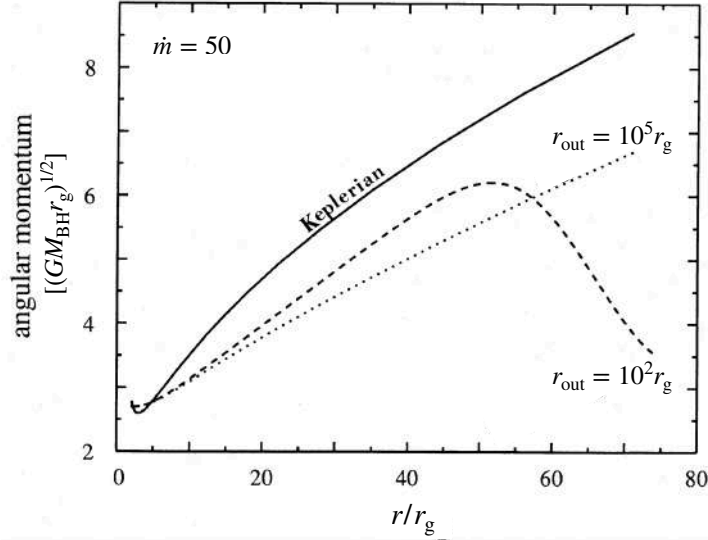


Figure 1.9: Angular momentum profiles of typical slim disc solutions (dashed and dotted curves) are depicted along with the Keplerian angular momentum of the accretion flow. Here, $\dot{m}$ is the accretion rate in units of 16 times the Eddington accretion rate ($\dot{m}_{\text{Edd}}$) and r_{out} is the outer edge of the disc. The figure is adapted from [Abramowicz et al. \(1988\)](#).

solution to such an accretion scenario was first introduced by [Abramowicz et al. \(1988\)](#) and is referred to as the ‘slim-disc’ model. Another important characteristic of this model is the sub-Keplerian angular momentum profile of the flow in contrast to the standard disc, where the accretion flow remains strictly Keplerian. In Fig. 1.9, we depict typical angular momentum profiles for slim discs. Further, it was pointed out that, when advective energy transport dominates over radiative cooling, as in the case of a slim disc, the radial temperature profile becomes flatter ([Watarai et al., 2000](#)) following the relation,

$$T_{\text{eff}}(r) \propto r^{-1/2}, \quad (1.17)$$

which deviates substantially from the standard disc case of $T_{\text{eff}}(r) \propto r^{-3/4}$ (see Eq. 1.16). It is noteworthy that several BH-XRBs and BH-ULXs often exhibit deviations from the standard radial distribution of temperature profile ([Watarai et al., 2000, 2001, Majumder et al., 2025a](#)). This leads to the changes in the expected correlation between disc luminosity and temperature as predicted by standard disc theory. Consequently, the slim disc model has become increasingly appealing over the past few decades to explain these observations. We will study these properties in more detail in later chapters.

1.4.4 Advection Dominated Accretion Flow (ADAF)

The Advection-dominated Accretion Flow (ADAF) model represents an extreme limit of the slim-disc scenario, where nearly all of the heat generated through viscous dissipation is advected into the black hole. This type of accretion process was initially proposed by [Ichimaru \(1977\)](#), and subsequently self-similar solutions for such flows were introduced by [Narayan and Yi \(1994, 1995a,b\)](#). In contrast to the slim-disc

model, which is applicable at very high luminosities, ADAF solutions are generally relevant for comparatively low-luminosity accretion states. As a result, ADAFs are

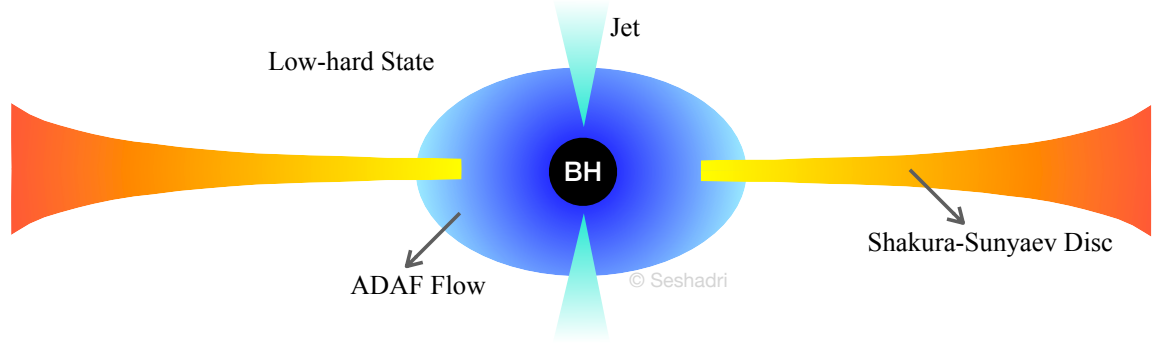


Figure 1.10: Cartoon representation of the cross-section view of ADAF configuration in the low-hard state of BH-XRBs. The concept for this illustration is taken from [Narayan and McClintock \(2008\)](#).

significantly less radiatively efficient than the standard thin discs. Unlike the standard disc model, the angular momentum distribution in ADAFs generally deviates from the Keplerian profile, like the slim discs. Nevertheless, certain solutions within the ADAF framework also exhibit Keplerian flow characteristics ([Abramowicz et al., 1995](#)). Additionally, the emission spectra associated with ADAF discs are non-thermal and are typically characterized by power-law profiles, primarily attributed to inverse Comptonization processes. Due to their low radiative efficiency, ADAFs have been explored to explain the emission spectra of BH-XRBs in the hard state. Note that, beyond a critical accretion rate ($\sim 10\%$ of the Eddington limit), the ADAF region in the accretion flow shrinks significantly, leading the system to make a transition from the hard to the soft spectral state ([Esin et al., 1997](#)). Consequently, the thin standard accretion disc extends towards the black hole, and the Comptonization becomes less efficient. For further details, the readers are referred to the review on ADAF by [Narayan and McClintock \(2008\)](#). In Fig. 1.10, we illustrate the ADAF configuration in the low-hard state (LHS) of BH-XRBs.

1.4.5 Two Component Advective Flow (TCAF)

The two-component advective flow (TCAF) ([Chakrabarti and Titarchuk, 1995](#)) is a widely explored model framework that provides global accretion solutions based on the first principles of the flow governing hydrodynamic equations. Moreover, it successfully explains most of the spectral and timing properties of BH-XRBs (see [Chakrabarti and Manickam 2000](#), [Chakrabarti et al. 2008](#), [Nandi et al. 2012](#), [Iyer et al. 2015](#) and references therein). In the TCAF framework, accretion flow is considered to be the combination of two distinct flow components: a Keplerian flow of high viscosity, which remains sandwiched at the equatorial plane between a low viscosity sub-Keplerian flow (see Fig. 1.11). Unlike the standard Keplerian accretion disc, the radial velocity of the accreting matter in the TCAF framework can attain a very high value near the black hole. In general, the sub-Keplerian accreting matter starts swirling from a large radial distance at a subsonic speed and approaches the black hole with a supersonic radial velocity. Thus, to satisfy the inner boundary condition at the event horizon ($v_r \sim c$), accretion onto black holes is necessarily transonic. Depending on the physical conditions, the accretion flow in the TCAF framework passes through multiple critical

points, where the flow velocity changes from subsonic to supersonic regime. Thus, after passing through the outer critical point, the initial subsonic flow approaches the black hole with a supersonic speed. Given that the accreting matter follows a spiral trajectory, it experiences two competing forces: the inward gravitational pull of the black hole and the outward centrifugal force due to the angular momentum. Therefore, at a certain radius ($r = r_{\text{sh}}$), the centrifugal force may become comparable to the gravitational pull, resulting in the formation of a virtual barrier that temporarily halts the inward flow. As a result, the flow undergoes a ‘shock transition’, where its velocity jumps from the supersonic to the subsonic branch. This barrier is commonly

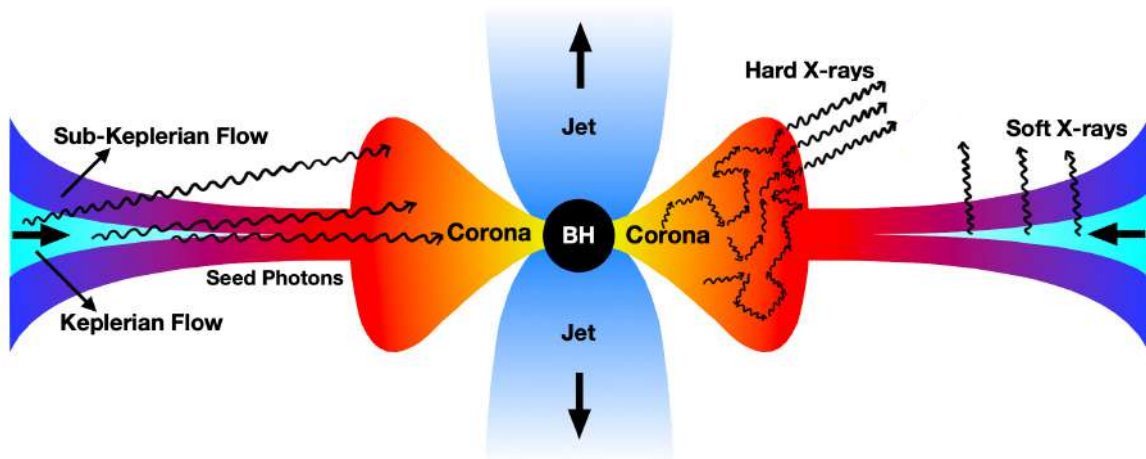


Figure 1.11: Schematic representation of the cross-section view of accretion flow onto black holes under the TCAF model formalism in a typical hard-intermediate state of BH-XRBs. The curved arrows represent the soft and hard X-ray photons that are generated from the accretion disc and Comptonizing corona, respectively. The concept of the schematic is adapted from [Chakrabarti and Titarchuk \(1995\)](#).

known as the CENtrifugal pressure-supported BOundary Layer (CENBOL). Because of this, the density and temperature of the flow increase significantly, and the flow produces a puffed-up region close to the black hole. However, the centrifugal barrier cannot hold back the flow for long. Consequently, the flow velocity increases again and eventually reaches the black hole horizon with a supersonic speed passing through the inner critical point. Interestingly, the region ($< r_{\text{sh}}$), known as the post-shock corona (PSC) or corona (see Fig. 1.11), remains hot and optically thin consisting of high energy electrons. These thermal electrons intercept the soft energy photons originating from the optically thick Keplerian disc and produce the spectral features of BH-XRBs and BH-ULXs at higher energies. Moreover, the canonical spectral state transitions of BH-XRBs are generally explained in the TCAF framework in terms of the emission contributions from the Keplerian and sub-Keplerian flow components, respectively. For instance, the Keplerian disc remains truncated at a larger radius, and the PSC region formed by the sub-Keplerian flow dominates the spectra in the LHS. In contrast, at higher accretion rates in HSS, the Keplerian component extends close to the black hole and becomes the primary source of emission, whereas the PSC region shrinks and becomes compact with negligible contribution. Interestingly, [Molteni et al. \(1996\)](#) first pointed out that the PSC region can also exhibit non-steady oscillations when the infall timescale of matter from this region roughly matches the associated cooling timescale. These oscillations are found to explain the QPO features observed across

various frequencies in several BH-XRBs and BH-ULXs (see [Chakrabarti et al. 2008](#), [Nandi et al. 2012](#), [Das et al. 2021](#), and references therein). Subsequently, several other numerical simulations have also reported the generation of QPOs from the oscillations of the PSC region (see [Lee et al. 2011, 2016](#), [Garain et al. 2014](#), [Das et al. 2014a,b](#), [Debnath et al. 2024](#), [Huang and Singh 2025](#), and references therein).

1.5 Radiative Processes in Astrophysical Environments

The interaction between radiation and matter has long been a subject of significant interest in astrophysics. In particular, the nature of this interaction plays a crucial role in shaping the observed emission characteristics from the region close to compact objects. Consequently, a thorough understanding of the various radiative processes is essential, especially in the context of such extreme environments found near compact objects. In this section, we outline the fundamental aspects of radiative processes that are pertinent to the present study and will be referenced in the subsequent chapters. We mention that the present discussion broadly follows [Rybicki and Lightman \(1986\)](#), [Longair \(2011\)](#) and [Ghisellini \(2013\)](#), to which the readers are referred for a more detailed and comprehensive treatment.

1.5.1 Radiative Transfer: Basic Concepts

We begin by introducing some of the important quantities that serve as foundational concepts for the discussion that follows. To start with, we recap that the concept of luminosity of a source is defined as the energy radiated per unit time and is generally expressed in units of erg s^{-1} . If $L_\nu(\nu)$ represents the luminosity per unit frequency range, then the integrated luminosity over all the frequencies or the bolometric luminosity is obtained as,

$$L_{\text{bol}} = \int_0^\infty L_\nu(\nu) d\nu. \quad (1.18)$$

Similarly, another important and widely used quantity is the energy flux, which is defined as the energy crossing per second per unit area of a surface exposed to the radiation field ($\text{erg cm}^{-2} \text{s}^{-1}$). Thus, for a source emitting isotropic bolometric luminosity L_{bol} , the associated flux at a distance r is given by,

$$F = \frac{L_{\text{bol}}}{4\pi r^2}. \quad (1.19)$$

Further, the monochromatic specific intensity (I_ν) of radiation is defined as the energy perpendicularly passing through unit area per unit frequency range along the unit solid angle per second and is usually measured in $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$. It is important to note that the specific intensity is a Lorentz invariant quantity obeying

$$\frac{I(\nu)}{I(\nu')} = \frac{\nu^3}{\nu'^3} = \text{invariant}, \quad (1.20)$$

where the primed and unprimed quantities correspond to two different reference frames.

In general, when radiation passes through matter, energy can be added or subtracted from the incident beam depending on the emission or absorption properties of that medium. In addition to that, scattering of radiation in the course of interaction

with matter significantly alters the specific intensity of the incident radiation, which we will discuss in the later sections. For simplicity, we consider a beam of radiation of specific intensity I_ν passing through a medium having the effects of absorption and emission only. In this case, the change in the specific intensity of the beam with distance r inside the medium can be written in terms of the well known radiative transfer equation given by,

$$\frac{dI_\nu}{dr} = -\alpha_\nu I_\nu + j_\nu, \quad (1.21)$$

where α_ν and j_ν is the absorption and emission coefficients, respectively. The above transfer equation provides a useful framework for solving the specific intensity in a medium of emitting and absorbing nature. Considering emission only *i.e.*, $\alpha_\nu = 0$, the simplest solution of Eq. (1.21) can be obtained as

$$I_\nu(r) = I_\nu(r_i) + \int_{r_i}^r j_\nu(r') dr', \quad (1.22)$$

which indicates the increase in specific intensity equal to the integrated emission coefficient along the path of the radiation. Similarly, for a purely absorptive medium with $j_\nu = 0$, the specific intensity can be expressed as,

$$I_\nu(r) = I_\nu(r_i) \exp \left[- \int_{r_i}^r \alpha_\nu(r') dr' \right]. \quad (1.23)$$

This results in a decrease in the specific intensity along the line of sight by the exponential of the integrated absorption coefficient. In this context, we define one of the most important quantities in describing radiative processes, which is the optical depth of a medium. It is generally measured along the path of a ray and is defined as,

$$\tau_\nu(r) = \int_{r_i}^r \alpha_\nu(r') dr'. \quad (1.24)$$

Optical depth is the measure of interactions encountered by a photon in a given medium. Conventionally, if the integrated optical depth along a typical path in a medium holds $\tau_\nu > 1$, the medium is said to be optically thick or opaque, whereas for $\tau_\nu < 1$ it becomes transparent or optically thin. Therefore, a photon of frequency ν can traverse an optically thin medium without getting absorbed; however, for an optically thick medium, the photon gets absorbed before it escapes. Another useful concept is the mean free path, which is defined as the average distance that one photon can travel in an absorbing medium without getting absorbed and can be obtained from $\langle \tau_\nu \rangle = \alpha_\nu l_\nu = 1$ as $l_\nu = 1/\alpha_\nu$. Finally, the radiative transfer equation, Eq. (1.21), can be expressed in a more generic form in terms of τ_ν as,

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu, \quad (1.25)$$

where $S_\nu = \frac{j_\nu}{\alpha_\nu}$ is known as the source function. A formal solution of Eq. (1.25) involving both effects of absorption and emission of a medium can be obtained as,

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)} S_\nu(\tau'_\nu) d\tau'_\nu. \quad (1.26)$$

All these aforementioned formalisms will be utilized in a later section when the key radiative processes are discussed in detail.

Generally, X-rays emitted from the XRBs can be of both thermal and non-thermal origin. Typically, the emission from an accretion disc in XRBs remains of thermal origin at equilibrium. However, the non-thermal emissions can be generated from the matter-radiation interactions and are generally associated with distinct physical processes present in the vicinity of these objects. In the following, we discuss some of these key radiative processes, which will be essential in understanding the emission mechanism of XRBs in successive chapters.

1.5.2 Blackbody Radiation and Planck Spectrum

By definition, a blackbody is a ‘perfect’ absorber of all the incident electromagnetic emissions on it and, at the same time, a ‘perfect’ emitter under equilibrium at a fixed temperature across the continuous range of frequencies in the electromagnetic spectrum. In the context of astrophysical systems, many celestial objects generally exhibit emissions from an optically thick atmosphere, which are locally at thermal equilibrium and, therefore, the spectral distribution closely resembles that of a blackbody emission at constant temperature. The intensity associated with a blackbody emission described by Planck’s spectrum at a characteristic temperature T can be obtained as,

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/k_B T) - 1}, \quad (1.27)$$

where ν , h and k_B are the radiation frequency, Planck’s constant, and Boltzmann constant, respectively. Fig. 1.12 shows the blackbody spectral energy distribution, where the peak shifts towards higher energies with increasing temperature, a characteristic feature of blackbody radiation.

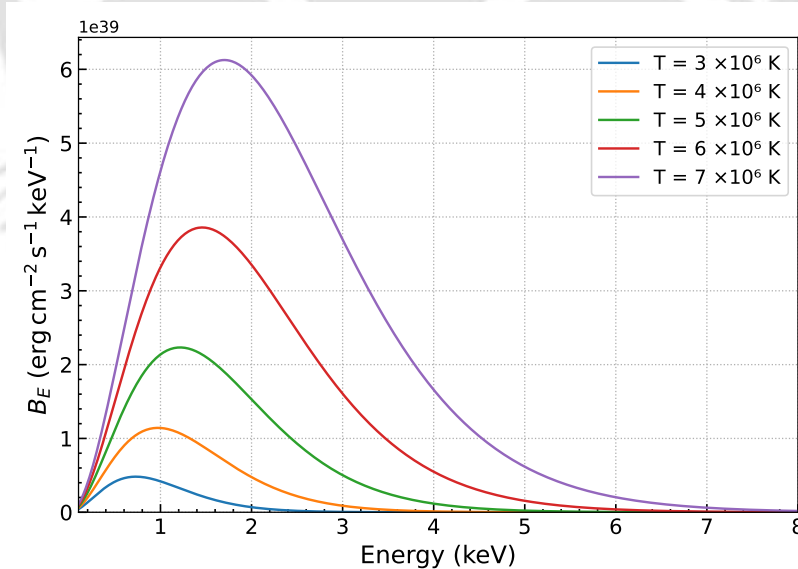


Figure 1.12: Spectral energy distribution of blackbody radiation for different temperatures.

We now look into several important properties of Planck’s law presented in Eq. (1.27). In the limit $h\nu \ll k_B T$, the expansion of the exponential $\exp(h\nu/k_B T)$ gives $1 + h\nu/k_B T$, and we get the so called Raleigh-Jeans law as,

$$I_\nu^{\text{RJ}}(T) = \frac{2\nu^2}{c^2} k_B T, \quad (1.28)$$

applicable at low-frequency limits. In contrast, for $h\nu \gg k_B T$, we get the *Wien's law*, given by,

$$I_\nu^W(T) = \frac{2h\nu^3}{c^2} \exp\left(-\frac{h\nu}{k_B T}\right). \quad (1.29)$$

Further, it can be shown that the wavelength ($\lambda_{\max}$) corresponding to the peak of $B_\lambda(T)$ depends on the temperature as,

$$\lambda_{\max} T = 0.29 \text{ cm deg}, \quad (1.30)$$

which is known as Wien's displacement law.

The definite integral of $B_\nu(T)$ over all frequencies gives the blackbody spectral flux, which can be expressed in terms of the effective temperature (T_{eff}) as,

$$F = \int_0^\infty B_\nu(T) d\nu = \frac{2\pi^4 k_B^4}{15c^2 h^3} T^4 = \sigma_S T^4, \quad (1.31)$$

where σ_S is the Stefan-Boltzmann constant.

We focus on the thermal radiation emitted from an accretion disc around XRBs. In an accretion disc, the temperature varies at different radii of the disc, following a well-defined profile, and thus, the disc locally emits blackbody emission at a constant temperature at each radius. Thus, a typical accretion disc can be considered as a multi-temperature blackbody emitter as a whole. Following the analytical treatment of accretion discs (Shakura and Sunyaev, 1973, Pringle, 1981), one can express the local blackbody temperature $T_{\text{eff}}(r)$ at a distance r inside the disc using Eq. (1.16). Thus, the emitted multi-temperature disc blackbody spectral flux from an accretion disc, integrated over all the radii, is given by,

$$F_{\text{disc}} = \int_{r_{\text{in}}}^{r_{\text{out}}} 2\pi r B_\nu[T_{\text{eff}}(r)] dr, \quad (1.32)$$

where r_{in} and r_{out} are the inner and outer radial extents of the accretion disc, respectively. Accordingly, the bolometric luminosity integrated over all frequencies associated with the isotropic multi-temperature disc blackbody emission from a binary source at a distance D is given by,

$$L_{\text{bol}} = \int_0^\infty 4\pi D^2 F_{\text{disc}} d\nu. \quad (1.33)$$

1.5.3 Bremsstrahlung Emission

Bremsstrahlung, or 'braking radiation', is one of the fundamental radiative processes in the accretion disc atmosphere, where high energy electrons are accelerated by the Coulomb force of ions, leading to the emission of a continuous spectrum. The intensity of Bremsstrahlung emission at energy ϵ is given by,

$$I_B(\epsilon, T_p) = A G_0(\epsilon, T_p) Z^2 n_e n_i (k_B T_p)^{1/2} e^{-\epsilon/k_B T_p}, \quad (1.34)$$

where Z is the ion charge, n_e and n_i are the electron and ion number densities, respectively. T_p is the proton temperature, G_0 is the Gaunt factor corresponding to the quantum corrections and A is the normalization constant. In Fig. 1.13, we depict Bremsstrahlung emission spectra obtained from the physical modeling of the accretion flow dynamics around black holes for illustration purposes.

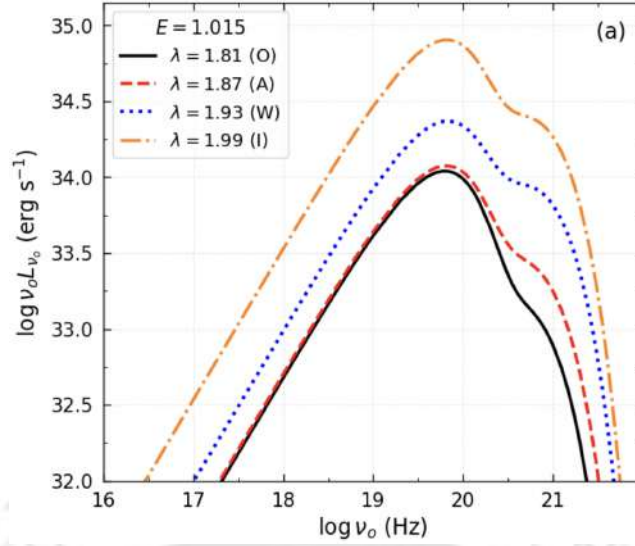


Figure 1.13: Bremsstrahlung emission spectrum computed from the modeling of accretion flow properties around black holes. The curves represent spectra calculated for different values of input parameters, namely specific energy (E) and angular momentum (λ) that govern the accretion flow. The figure is adapted from [Patra et al. \(2024\)](#), to which the readers are referred for further details.

1.5.4 Sychrotron Emission

Charged particles accelerated by a magnetic field B radiate in the electromagnetic spectrum, resulting from the gyration of particles along the magnetic field lines (see Fig. 1.14). When particles move at non-relativistic velocities, the emission is commonly referred to as cyclotron radiation, and the emission frequency corresponds to the gyration frequency in the magnetic field. In contrast, for relativistic particles, the frequency becomes much more complex depending on the strength of the magnetic field, and the emission is termed as synchrotron radiation. For an isotropic distri-

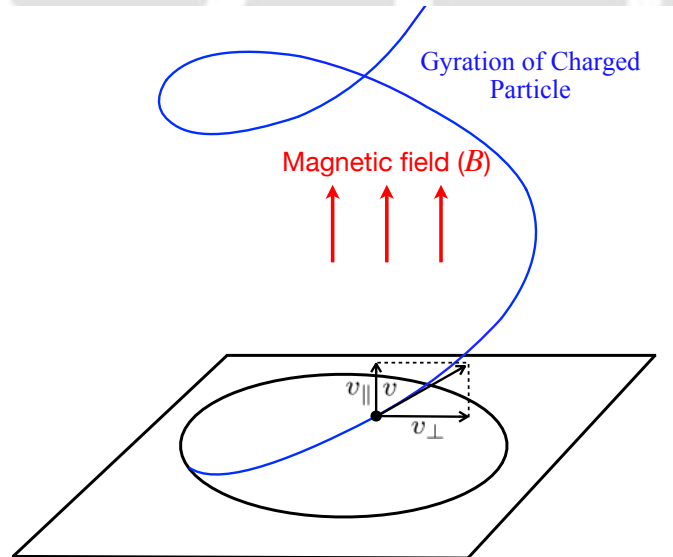


Figure 1.14: Depiction of the gyration of a charged particle around magnetic field lines, responsible for synchrotron emission. v is the velocity of the particle, while $v_{||}$ and $v_{\perp}$ are the velocity components. Concept of the figure is adapted from [Rybicki and Lightman \(1986\)](#).

bution of pitch angles (α_p), defined as the angle between the magnetic field and the velocity of the charged particles, the average power emitted via synchrotron radiation

at a given speed $\beta(=v/c)$ can be written as,

$$P'_{\text{syn}} = \frac{4}{3} \sigma_T c \beta^2 \gamma_0^2 U_B, \quad (1.35)$$

where $\sigma_T = 8\pi r_0^2/3$ with r_0 being the classical radius of the charged particle, $U_B = B^2/8\pi$ denotes the magnetic energy density and $\gamma_0 = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor considering a particle velocity v . The characteristic spectrum of synchrotron radiation is closely tied to the way the electric field varies as seen by an observer. Due to relativistic beaming effects, the emitted radiation is concentrated within a narrow range of directions aligned with the velocity of the particle. As a result, an observer perceives a pulse of radiation occurring within a time frame significantly shorter than the particle's gyration period. Thus, the power emitted by a single electron per unit frequency can be written as,

$$P'(\omega) = \frac{\sqrt{3}}{2\pi} \frac{q^3 B \sin \alpha_p}{m_q c^2} f\left(\frac{\omega}{\omega_c}\right), \quad (1.36)$$

where q and m_q are the electric charge and mass of the charged particle in gyration. Here, ω is the frequency and

$$f(\omega/\omega_c) \equiv \frac{\omega}{\omega_c} \int_{\omega/\omega_c}^{\infty} K_{5/3}(y) dy, \quad (1.37)$$

with $K_{5/3}(y)$ being the modified Bessel function of order 5/3 (Ghisellini, 2013). $\omega_c = \frac{3\gamma_0^2 q B \sin \alpha_p}{2m_q c}$ is known as the critical frequency. Furthermore, assuming the number density of particles with energies between ϵ and $\epsilon + d\epsilon$ to be $N(\epsilon)d\epsilon = C\epsilon^{-p}d\epsilon$, the power-law dependency of the synchrotron spectrum can be obtained as,

$$P'_{\text{tot}}(\omega) \propto \omega^{-(p-1)/2}. \quad (1.38)$$

Here, $P'_{\text{tot}}(\omega)$ is the total integrated power per unit frequency per unit volume of the aforementioned distribution of particles and C depends on the pitch angle of the particles.

Interestingly, the synchrotron process is capable of producing luminosity of the order of $\sim 10^{33}$ erg s⁻¹ for a system consisting of spherically accreting 10 $M_\odot$ black hole (Ipser and Price, 1982). Moreover, spectral modeling of BH-XRBs in a radio-loud low-hard state often requires a synchrotron emission component in addition to the disc and thermal Comptonization component (Markoff et al., 2001, Vadawale et al., 2001).

1.5.5 Compton and Inverse Compton Scattering

The most basic form of interaction between photons and free electrons is scattering, which plays a central role in the radiative transfer problem in astrophysical contexts. When the energy of the incident photons, measured in the electron's comoving frame, is much lower than the electron's rest mass energy *i.e.*, $h\nu \ll m_e c^2$ (where m_e is the mass of the electron), the scattering process is known as Thomson scattering. This type of scattering can be effectively described using classical electrodynamics. Assuming the incident photons are unpolarized electromagnetic waves, the differential cross-section for Thomson scattering can be approximated as,

$$\frac{d\sigma_T}{d\Omega_s} = \frac{r_0^2}{2} (1 + \cos^2 \theta), \quad (1.39)$$

at $\epsilon = \epsilon_1$. Here, ϵ and ϵ_1 denote the energies of the incident and scattered photons, θ is the angle between the direction of the incident and scattered photons, r_0 is the classical electron radius and Ω_s represents the solid angle into which the radiation is scattered. Thus, it is evident that Thomson scattering is the elastic scattering process. However, when the incident photon energy increases and becomes comparable to $m_e c^2$, the scattering becomes inelastic and is referred to as Compton scattering. For this, the energies of the incident and scattered photons, resulting from the interaction with an electron at rest, are related as,

$$\epsilon_1 = \frac{\epsilon}{1 + \frac{\epsilon}{m_e c^2} (1 - \cos \theta)}, \quad (1.40)$$

which reads in wavelength as,

$$\lambda_1 - \lambda = \lambda_c (1 - \cos \theta), \quad (1.41)$$

where $\lambda_c = \frac{h}{m_e c} = 0.02426 \text{ \AA}$ is the Compton wavelength of electrons. Further, at the limit of incident photon energy comparable to $m_e c^2$, a quantum mechanical correction becomes necessary, leading to the Klein-Nishina regime. Accordingly, incorporating the quantum effects, the differential cross section of unpolarized photons can be expressed by the Klein-Nishina formula as,

$$\frac{d\sigma_{\text{KN}}}{d\Omega_s} = \frac{r_0^2}{2} \frac{\epsilon_1^2}{\epsilon^2} \left(\frac{\epsilon}{\epsilon_1} + \frac{\epsilon_1}{\epsilon} - \sin^2 \theta \right), \quad (1.42)$$

and the total Klein-Nishina cross section is given by,

$$\sigma_{\text{KN}} = \frac{3\sigma_T}{4} \left[\frac{1+x}{x^3} \left\{ \frac{2x(1+x)}{1+2x} - \ln(1+2x) \right\} + \frac{1}{2x} \ln(1+2x) - \frac{1+3x}{(1+2x)^2} \right], \quad (1.43)$$

where $x \equiv h\nu/m_e c^2$. It may be noted that the primary effect of quantum correction appears in the reduction of differential cross section (see Eq. 1.42) than its classical value (see Eq. 1.39), at higher incident photon energies. Therefore, at higher energies, the Compton scattering remains less efficient.

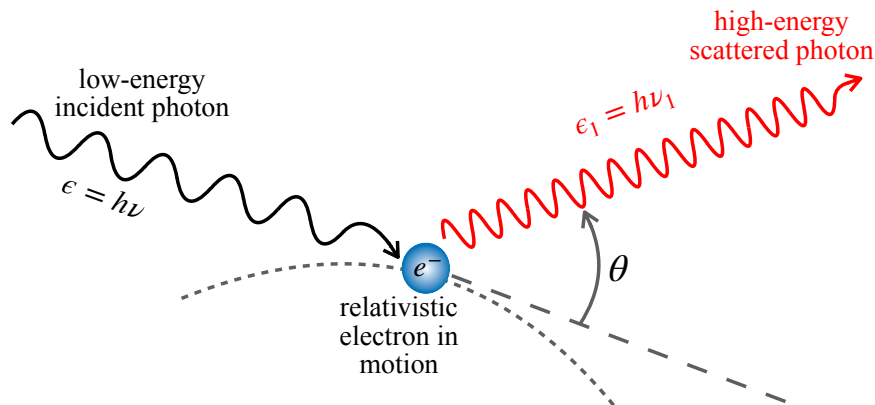


Figure 1.15: Schematic of the inverse Comptonization process, in which a low-energy photon interacts with a relativistic electron in motion, resulting in a scattered photon that gains energy from the electron.

On the other hand, when relativistic electrons with sufficient kinetic energy interact with comparatively lower energy photons, energy can be transferred from the

electrons to the photons. This process is known as inverse Comptonization, in which the electrons upscatter the photons (see Fig. 1.15), contributing to the spectrum at higher energies. Further, for single inverse Compton scattering, the net power lost by the electron and, therefore, transferred to a photon is estimated as,

$$P'_{\text{compt}} = \frac{4}{3} \sigma_T c \gamma_0^2 \beta^2 U_{\text{ph}}, \quad (1.44)$$

where U_{ph} is the initial photon energy density.

We consider the effects of repeated inverse Compton upscatterings in the thermal distribution of electrons on the spectrum and energy of incident photons. Accordingly, the quantity known as the Compton y -parameter (y_{par}), which is the measure of the effects of inverse Comptonization can be defined in a finite medium as

$$y_{\text{par}} \equiv [\text{average fractional energy change per scattering}] \times (\text{mean number of scatterings}). \quad (1.45)$$

Conventionally, for $y_{\text{par}} \gtrsim 1$ case, the emitted photon energy spectrum is significantly altered by the inverse Comptonization process, whereas $y_{\text{par}} \ll 1$ indicates marginal effects of inverse Compton scattering on the emerged spectrum. For the non-relativistic thermal distribution of electrons, the Compton y_{par} parameter takes the form

$$y_{\text{par}} = \frac{4k_B T_e}{m_e c^2} \text{Max}(\tau, \tau^2), \quad (1.46)$$

where τ ($\sim \rho \kappa_{es} R_{cs}$) is the electron scattering optical depth inside a finite medium of size R_{cs} , density ρ , temperature T_e and electron scattering opacity κ_{es} . Here, the function $\text{Max}(\tau, \tau^2)$ denotes the maximum value between τ and τ^2 . Thus, for an optically thin medium ($\tau < 1$), $\text{Max}(\tau, \tau^2) \sim \tau$, and for an optically thick medium ($\tau > 1$), $\text{Max}(\tau, \tau^2) \sim \tau^2$. In this context, considering the repeated inverse Compton scattering of photons by the non-relativistic thermal electrons, one can write the evolution of the density of photon distribution using the well-known Kompaneets equation (Kompaneets, 1957) given by,

$$\frac{\partial n}{\partial t_c} = \left(\frac{k_B T_e}{m_e c^2} \right) \frac{1}{z^2} \frac{\partial}{\partial z} \left[z^4 (n' + n + n^2) \right], \quad (1.47)$$

where n is the photon phase space number density and $n' \equiv \partial n / \partial z$. Here, $z \equiv \frac{\hbar \omega}{k_B T_e}$ is the dimensionless photon energy of frequency ω and t_c is the measured time in units of the mean time between scatterings. In general, to obtain the inverse Comptonized spectrum resulting from the multiple scatterings inside a finite region of thermal electrons, one needs to solve Eq. (1.47) using numerical integration with a source photon distribution. In the context of accretion disc-corona systems, it is physically motivated and convenient to consider blackbody radiation or multi-temperature accretion disc blackbody distribution as a source photon term while solving the Kompaneets equation. The readers are referred to Rybicki and Lightman (1986), Titarchuk (1994), Zdziarski et al. (1996) for further details on the thermal Comptonization process and its implications in high energy astrophysical contexts.

1.5.6 Line Emission and Profile

In addition to the primary thermal and non-thermal emissions discussed above, several line emissions associated with the accretion disc atmosphere are also observed in the high-resolution energy spectrum of XRBs. These spectral lines may originate from the interaction of incident X-rays and the accretion disc material and/or outflowing plasma winds, leading to photoionization processes (see [Neilsen and Degenaar 2023](#) for a review). In particular, high energy X-ray photons can ionize neutral atoms present in such environments by ejecting electrons from their inner shells, leaving the atom in an excited state. Thereafter, the de-excitation of the ion happens via the transition of an electron from the outer shell to the vacant inner shell, leading to the fluorescent emission lines. Typical energy of such emission lines can be in the X-ray range and remains distinct for a given atomic element. Therefore, the appearance of such emission lines indicates the abundance of the respective elements in the astrophysical contexts. For example, one of the most commonly observed emission lines is the Fe $K\alpha$ feature at rest energy of ~ 6.4 keV ([García and Kallman, 2010](#)). Apart from this, several other emission lines associated with different atomic species are also observed in the accretion disc environments. Interestingly, this Fe line complex, abundantly seen in BH-XRB spectra, appears as a prominent feature of the reflection spectrum, which we discuss next.

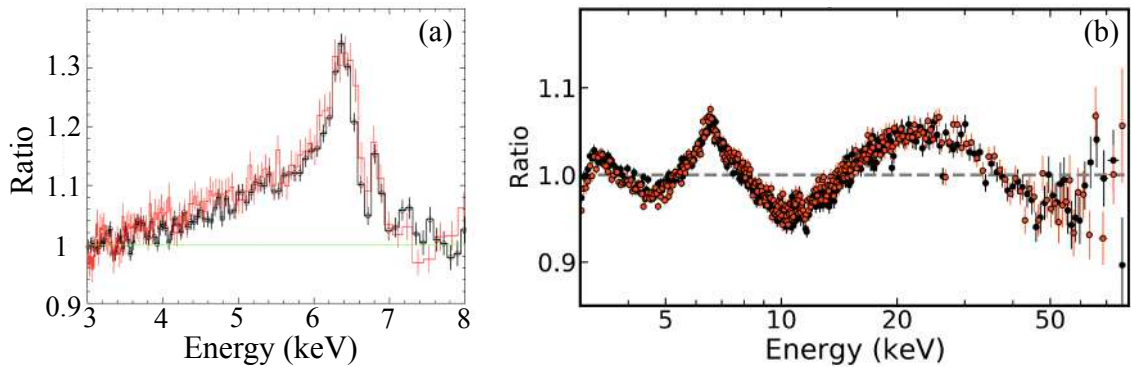


Figure 1.16: Panel (a): The Fe $K\alpha$ line emission profile in the residuals of the continuum-fitted X-ray spectrum of the Seyfert 1 galaxy MCG-6-30-15, showing asymmetric broadening due to relativistic effects near the black hole. The figure is adapted from [Miniutti et al. \(2007\)](#). Panel (b): Model-fitted residuals of the spectrum of the BH-XRB MAXI J1535-571, illustrating the presence of the Fe $K\alpha$ line at ~ 6.4 keV and the Compton hump in 20-30 keV energy range. The figure is adapted from [Liu et al. \(2023\)](#).

1.5.7 Reflected X-ray Emission

X-ray reflection spectroscopy involves studying the reprocessing of high energy coronal emission from the ‘cold’ and optically thick accretion disc in BH-XRBs. In general, the reflection spectrum in the rest frame of the accreting material typically exhibits narrow fluorescent emission lines below 10 keV with the most notable feature as the iron $K\alpha$ line at 6.4 keV (see Fig. 1.16a) for neutral or mildly ionized iron and shifts up to 6.97 keV for fully ionized iron. Additionally, a broad Compton hump is usually observed as the prominent reflection feature, which peaks in 20-30 keV range (see Fig. 1.16b and [García and Kallman 2010](#)). Typically, photoelectric absorption and Compton scattering are the two dominant radiative processes that shape the reflected spectrum in BH-XRBs. The energies of the observed emission features below 10 keV

are consistent with photoelectric absorption, whereas the high energy bump in 20 – 30 keV energy range likely results from Compton scattering of the incident X-rays by electrons present in the optically thick accretion disc material.

Interestingly, the width of the Fe K α line is generally found to be significantly altered due to the relativistic effects close to the black hole. For example, the observed line profile gets broadened and skewed (see Fig. 1.16a), when observed by a distant observer, primarily because of the Doppler effect and gravitational redshift. Thus, modeling the shape of the Fe K α line reveals valuable information about such relativistic effects along with the accretion dynamics and spacetime curvature in the vicinity of a black hole. In addition, Fe K α line generally serves as a powerful tool to probe the spin of black holes present in BH-XRBs, because the extent of line broadening is directly influenced by the inner edge of the accretion disc, which in turn is determined by the spin (see Reynolds (2014) for details).

1.5.8 Polarization

So far, our discussion on the radiation field has not accounted for its polarization state. However, one should incorporate the polarization properties of radiation for a precise analysis of scattering phenomena in the astrophysical context, as light generally becomes polarized upon scattering. For instance, according to Rayleigh's classical law, an unpolarized beam, scattering at an angle Θ relative to its incident direction, remains linearly polarized (Chandrasekhar, 1960). The intensity of scattered light varies with direction, following a ratio of $1 : \cos^2 \Theta$ for components perpendicular and parallel to the scattering plane, respectively. The scattering plane is defined by the plane containing the incident and scattered light. In this section, we provide a basic overview of polarization and outline relevant theoretical frameworks. Our discussion broadly follows Chandrasekhar (1960), Rybicki and Lightman (1986), to which readers are referred for further details.

We consider the electric and magnetic field vectors of a monochromatic plane electromagnetic wave of frequency ω described by,

$$\mathbf{E} = \hat{\mathbf{a}}_1 E' e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)}, \quad (1.48a)$$

$$\mathbf{B} = \hat{\mathbf{a}}_2 B' e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)}, \quad (1.48b)$$

where $\hat{\mathbf{a}}_1$ and $\hat{\mathbf{a}}_2$ are the unit vectors along the perpendicular direction of wave propagation. E' and B' are constants and $\mathbf{k}$ denotes the wave vector. From Eq. (1.48a), we observe that the electric field vector oscillates along $\hat{\mathbf{a}}_1$ direction, representing the linearly polarized wave. In general, the polarization state of a wave can be described by the superposition of two such plane waves with orthogonal polarization directions. Consider the corresponding electric field vector at any arbitrary point in space (say $\mathbf{r} = 0$). Therefore, the generic polarization state of the wave can be expressed as,

$$\mathbf{E} = \mathbf{E}_0 e^{-i\omega t} = (\hat{\mathbf{x}} E_1 + \hat{\mathbf{y}} E_2) e^{-i\omega t}, \quad (1.49)$$

where the complex components (E_1 and E_2) of $\mathbf{E}_0$ can be written as,

$$E_1 = \mathcal{E}_1 e^{i\phi_1}, \quad E_2 = \mathcal{E}_2 e^{i\phi_2}. \quad (1.50)$$

Now, the components of the electric field vector along $\hat{x}$ and $\hat{y}$ can be obtained by taking the real part of $\mathbf{E}$ from Eq. (1.49) as,

$$E_x = \mathcal{E}_1 \cos(\omega t - \phi_1), \quad E_y = \mathcal{E}_2 \cos(\omega t - \phi_2). \quad (1.51)$$

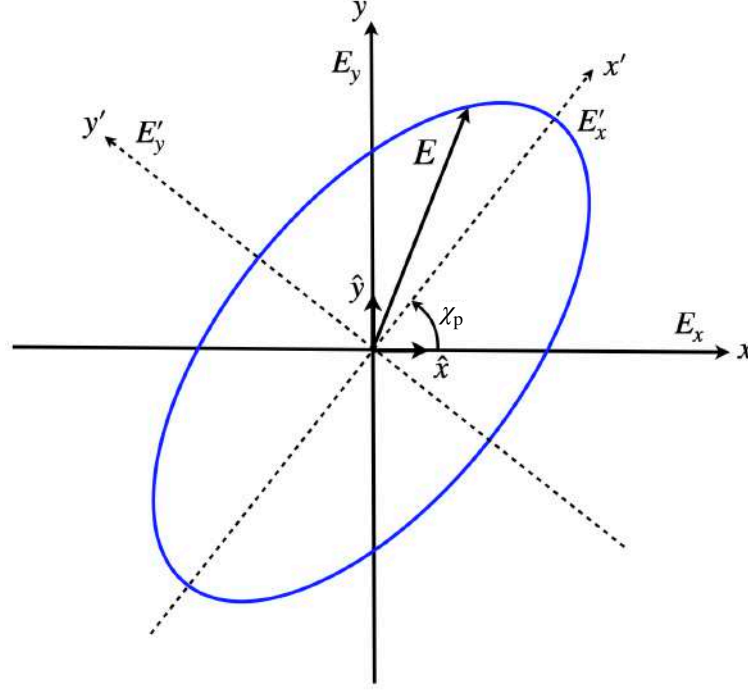


Figure 1.17: Representation of the polarization ellipse with electric field components E_x and E_y rotated at an angle χ_p relative to the principal axes of the ellipse. The figure is adapted from Rybicki and Lightman (1986).

Here, $\mathcal{E}_1$ and $\mathcal{E}_2$ denote the amplitudes of the electric field components along the x and y directions, respectively. ϕ_1 and ϕ_2 represent the phases of the oscillating electric field in the x and y directions, respectively. Generally, Eq. (1.51) represents the electric field vector in the $x - y$ plane, which traces out an ellipse. Thus, we note that the most generic polarization of a wave is the elliptically polarized state. It is noteworthy that the equation of a general ellipse with its principal axes being x' and y' (see Fig. 1.17) can be written as

$$E'_x = \mathcal{E}_0 \cos \psi \cos \omega t, \quad E'_y = -\mathcal{E}_0 \sin \psi \sin \omega t, \quad (1.52)$$

where $-\pi/2 \leq \psi \leq \pi/2$. From Eq. (1.52), it is evident that the ellipse is traced out in the clockwise direction, resulting in right-handed polarization for $\psi > 0$, whereas it will be traced out in an anti-clockwise sense for $\psi < 0$, leading to the left-handed polarization. Moreover, for $\psi = \pm\pi/4$ ($0, \pm\pi/2$), the ellipse turns out to be a circle (straight line), representing the circularly (linearly) polarized state. From Fig. 1.17, we note that the principal axes of the ellipse are tilted at an angle χ_p relative to the x - and y -axis. Therefore, to connect the field components in Eq. (1.50) with that of the principal axes of the ellipse, we take the transformation of E'_x and E'_y along the x - and y -axis, considering a rotation by angle χ_p and obtain

$$E_x = \mathcal{E}_0 (\cos \psi \cos \chi_p \cos \omega t + \sin \psi \sin \chi_p \sin \omega t), \quad (1.53a)$$

$$E_y = \mathcal{E}_0 (\cos \psi \sin \chi_p \cos \omega t - \sin \psi \cos \chi_p \sin \omega t). \quad (1.53b)$$

The above equations take an identical form to that of Eq. (1.51) if we consider

$$\mathcal{E}_1 \cos \phi_1 = \mathcal{E}_0 \cos \psi \cos \chi_p, \quad (1.54a)$$

$$\mathcal{E}_1 \sin \phi_1 = \mathcal{E}_0 \sin \psi \sin \chi_p, \quad (1.54b)$$

$$\mathcal{E}_2 \cos \phi_2 = \mathcal{E}_0 \cos \psi \sin \chi_p, \quad (1.54c)$$

$$\mathcal{E}_2 \sin \phi_2 = -\mathcal{E}_0 \sin \psi \cos \chi_p. \quad (1.54d)$$

For a given choice of $\mathcal{E}_1$, $\mathcal{E}_2$, ψ_1 and ψ_2 , these set of equations can be solved for $\mathcal{E}_0$, ψ and χ_p by introducing the set of Stokes parameters as,

$$I = \mathcal{E}_1^2 + \mathcal{E}_2^2 = \mathcal{E}_0^2, \quad (1.55a)$$

$$Q = \mathcal{E}_1^2 - \mathcal{E}_2^2 = \mathcal{E}_0^2 \cos 2\psi \cos 2\chi_p, \quad (1.55b)$$

$$U = 2\mathcal{E}_1\mathcal{E}_2 \cos(\phi_1 - \phi_2) = \mathcal{E}_0^2 \cos 2\psi \sin 2\chi_p, \quad (1.55c)$$

$$V = 2\mathcal{E}_1\mathcal{E}_2 \sin(\phi_1 - \phi_2) = \mathcal{E}_0^2 \sin 2\psi. \quad (1.55d)$$

Rearranging Eq. (1.55), we can get the following important relations as:

$$\mathcal{E}_0 = \sqrt{I}, \quad (1.56)$$

$$\sin 2\psi = \frac{V}{I}, \quad (1.57)$$

$$\tan 2\chi_p = \frac{U}{Q}, \quad (1.58)$$

$$I^2 = Q^2 + U^2 + V^2. \quad (1.59)$$

We now focus on the implications of the Stokes parameters. Here, I represents the total intensity or energy flux of the radiation. Most importantly, Q , U , and V define the state of polarization of the radiation. In general, V represents the circularity of the polarization, and therefore, $V = 0$ for linearly polarized radiation. Thus, the linear polarization degree (PD) and polarization angle (PA) of a radiation of intensity I can be defined as,

$$\text{PD} = \frac{\sqrt{Q^2 + U^2}}{I}, \quad (1.60)$$

$$\text{PA} = \frac{1}{2} \tan^{-1} \left(\frac{U}{Q} \right). \quad (1.61)$$

In the astrophysical context, PD and PA demand prime interest as they are potentially capable of revealing a wealth of scientific information by unveiling the polarimetric properties of the emission generated from the region very close to the compact objects under extreme physical conditions. We study these polarization properties in detail in the later chapters.

1.6 Interpreting X-ray Observables

In this section, we discuss some of the commonly used X-ray observational techniques, namely imaging, timing, spectroscopy, and polarimetry, that are employed to interpret the X-ray emission from BH-XRBs. All of these techniques will be utilized in the analysis of observational data from various X-ray missions in the subsequent chapters.

1.6.1 Imaging Studies

Image analysis is an essential component of observational studies in X-ray astronomy, offering a direct method to explore the morphology and spatial characteristics of high energy astrophysical sources. Unlike optical astronomy, where direct imaging techniques capture visible light from celestial objects, X-ray images are constructed using space-based detectors such as charge-coupled devices (CCDs), which register the arrival time, energy, and position of individual X-ray photons. These instruments are capable of generating two-dimensional maps of the sky in X-rays, where each pixel represents the intensity of detected photons within a given spatial resolution. Although

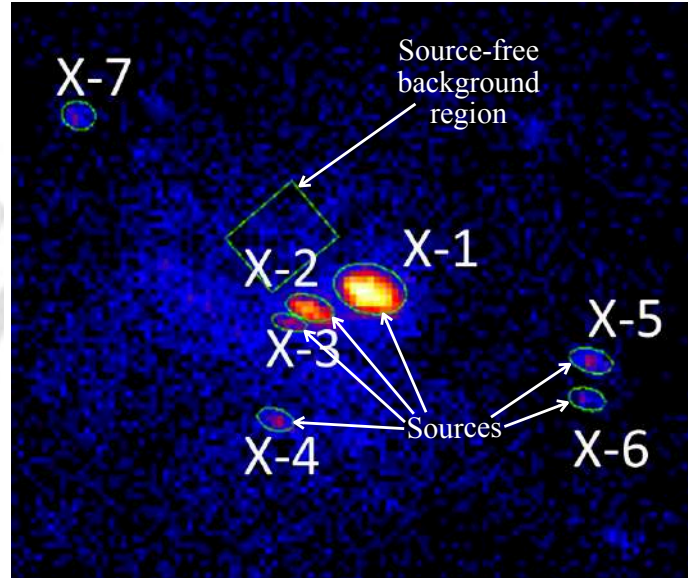


Figure 1.18: Image of a part of the M82 galaxy observed with the *Chandra* X-ray observatory. The elliptical regions indicate the positions of various astronomical X-ray sources, while the square region marks an example of a source free background region. The figure is adapted from [Brightman et al. \(2020\)](#) and edited for representation purposes.

these images do not represent visual impressions in the traditional sense, they provide a rich dataset that encodes valuable information about the source. In particular, analyzing the spatial distribution of X-ray photons helps in accurately locating the point source of interest, distinguishing it from any surrounding extended emission associated with the host galaxy (see Fig. 1.18). Image analysis also plays a critical role in understanding the diffuse background radiation in X-rays and the identification of artifacts or systematic effects. It is important to emphasize that an accurate estimation of the background emission is important, as it can substantially affect the measured flux and the apparent morphology of the source under study. The methods for selecting suitable background and source regions, and consequently extracting the source emission, are discussed in detail in the next chapter. In Fig. 1.18, we depict *Chandra* X-ray observatory sample image of the M82 galaxy, marking the bright astrophysical sources.

1.6.2 Timing Studies

In the study of accreting BH-XRBs, timing analysis of the emitted X-ray emissions plays a crucial role in understanding the underlying physical processes governing their variability. A fundamental technique in this analysis is the study of X-ray light curve, which represents the variation in photon counts over time (see Fig. 1.5). In particular,

a light curve provides a graphical depiction of the number of detected X-ray photons within a given time interval, offering insights into the temporal behavior of the source. In general, the photons are accumulated in predefined time bins according to the requirements of scientific interests. The primary objective of analyzing light curves is to investigate changes in source intensity over time, which can indicate variations in the accretion process or other intrinsic properties of the system. The timescales over which these variations occur span a broad range, from milliseconds to months or years in some cases.

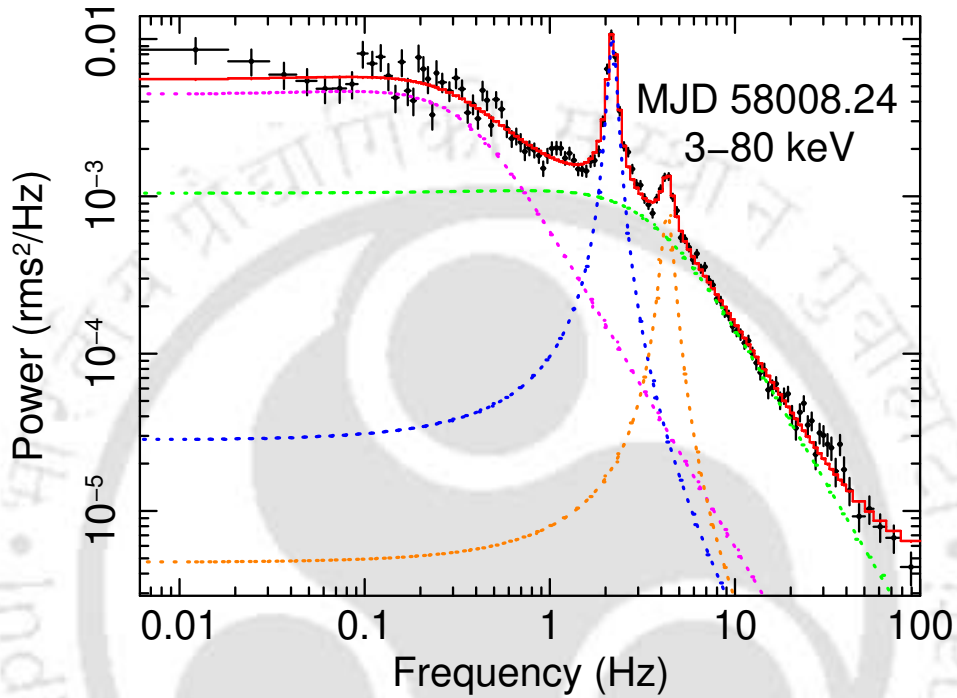


Figure 1.19: Power density spectrum (PDS) of the BH-XRB MAXI J1535–571 showing the presence of a strong QPO feature along with its harmonic. The PDS is modeled using a combination of Lorentzian profiles representing distinct features at various frequencies. Credit: [Sreehari et al. \(2019a\)](#).

Needless to mention that beyond the overall intensity variations, X-ray timing studies frequently reveal distinct periodic or quasi-periodic signals embedded within the light curve, which require a more detailed study to interpret. These signals correspond to much shorter timescales and are generally connected with the rapid variability, often associated with the nature of the BH-XRB system of interest. One of the most significant features among these variability characteristics is the QPOs, which are the transient oscillatory features that appear as narrow peaks at distinct frequencies in the Fourier space of the associated time series, commonly known as the ‘power density spectrum’ (PDS). The PDS provides a quantitative representation of how the signal power is distributed across different frequency components, allowing for a systematic investigation of the underlying variability mechanisms. In Fig. 1.19, we depict the typical PDS of the BH-XRB MAXI J1535–571 showing different power components modeled by various Lorentzian profiles at distinct frequencies, including the presence of a strong QPO feature around ~ 2 Hz.

Moreover, QPOs are particularly important in probing the accretion dynamics of BH-XRBs, as their frequency, amplitude, and coherence properties can offer direct constraints on the geometry and dynamics of the emitting region within the accretion disc (see [Ingram and Motta 2019](#) for a review). Depending on their frequency, QPOs

are classified into two broad categories: low-frequency QPOs (LFQPOs) with frequencies below 30 Hz, and high-frequency QPOs (HFQPOs) which exceed 30 Hz (Casella et al., 2005, Remillard and McClintock, 2006). LFQPOs display distinct characteristics and are further categorized into type-A, type-B, and type-C (Casella et al., 2005). In general, type-A LFQPOs are weak, broad features that are rarely observed in BH-XRBs. However, type-C LFQPOs are characterized by strong *rms* amplitude, high quality factor, and variable frequency (0.1 – 15 Hz), which are commonly observed in the hard and hard-intermediate states (HIMS) of BH-XRBs (Casella et al., 2005, Motta et al., 2011). In contrast, type-B LFQPOs are of lower amplitude, weak features and are typically seen during soft-intermediate states (SIMS), often associated with transient jet ejections (Casella et al., 2005, Fender et al., 2009). On the other hand, HFQPOs appear to be a rare phenomenon, exhibited by only a handful of BH-XRBs, including the enigmatic BH-XRB GRS 1915+105. We discuss the characteristics of HFQPOs in detail in the later chapters. Further, it may be noted that the evolution of QPO characteristics over time in different spectral states provides crucial insights into the physical mechanisms driving the variability, which are again closely connected to the geometry of the BH-XRBs. Therefore, by systematically analyzing the QPO features, it is possible to infer properties such as the inner disc structure, the presence of relativistic effects, and the role of magnetohydrodynamic instabilities in shaping the observed variability (see Kato and Fukue 1980, Molteni et al. 1996, Ingram et al. 2009, Musoke et al. 2023 and references therein).

1.6.3 Spectral Studies

X-ray spectra provide a detailed representation of the energy distribution of observed emission, providing insights into the physical processes governing astrophysical sources. By fitting these spectra with physical or phenomenological models, one can infer the plasma temperature, ionization state, optical depth, and geometry of the emitting regions. These analyses are fundamental in understanding the interaction between matter and radiation in the extreme environments close to the compact object.

A spectrum, in its simplest form, is a record of photons detected across a continuous range of energies. In general, these photons are measured by the X-ray detectors within discrete energy channels, typically spanning from ~ 0.1 keV to hundreds of keV. In BH-XRBs, the observed spectrum is a composite of multiple emission components arising from different regions of the system. In Fig. 1.20, we depict the spectral components generally observed in BH-XRBs along with their origin in a disc-corona configuration. The soft X-ray excess is dominated by the thermal radiation from the optically thick, geometrically thin accretion disc, well described by a multi-temperature blackbody model. At higher energies, Comptonization in the corona produces a power-law-like emission with a high energy cutoff that encodes information about the electron temperature and optical depth of the corona. Additionally, reflection features, such as the broad Fe K α line at ~ 6.4 keV and Compton hump around 20 – 30 keV, result from X-ray photons reprocessing off the accretion disc. Interestingly, constraints on the inner disc structure, ionization state, and the black hole spin are generally obtained through the modeling of relativistic broadening effects on the reflection features.

Most astonishingly, the spectral characteristics of BH-XRBs are also seen to evolve while transitioning between several spectral states, primarily driven by the accretion rate onto the black hole. It may be noted that such spectral variabilities, often ob-

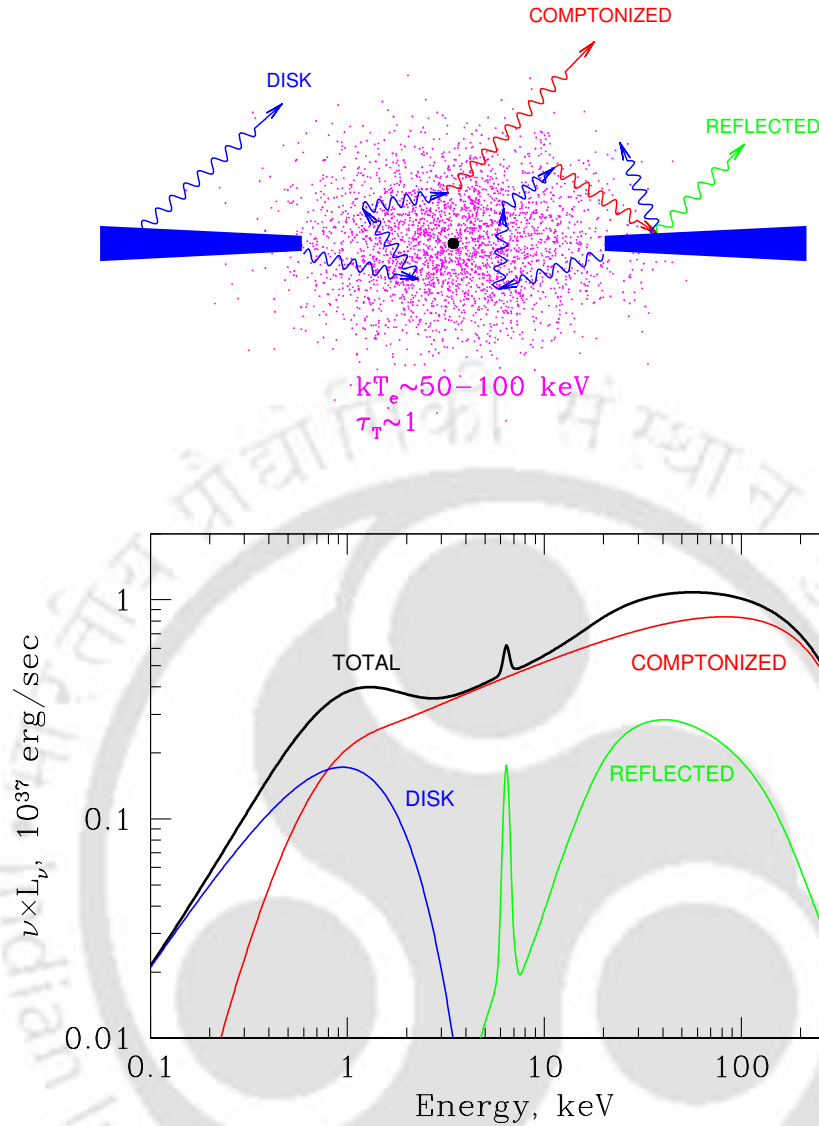


Figure 1.20: *Top*: The origin of different emissions in an accretion disc-corona configuration. *Bottom*: Different spectral components, typically observed in the wide-band spectra of BH-XRBs. Credit: Gilfanov (2010).

served in conjunction with X-ray timing properties termed as ‘spectro-temporal’ features, serve as a crucial diagnostic tool for probing the complex accretion dynamics in BH-XRBs. In general, during the outburst of a transient BH-XRB, the system traces a ‘q-shaped’ hysteresis pattern in the hardness-intensity diagram (HID), a pictorial representation of the X-ray luminosity/flux of the source plotted against the hardness ratio, computed from the emitted X-ray radiation. In Fig. 1.21, a typical HID of BH-XRB systems showing different spectral states along with key spectro-temporal characteristics are shown. Depending on the contribution of several physical spectral components in the emitted spectrum along with other prime spectro-temporal characteristics, the spectral states in BH-XRBs can be classified into distinct types as discussed below.

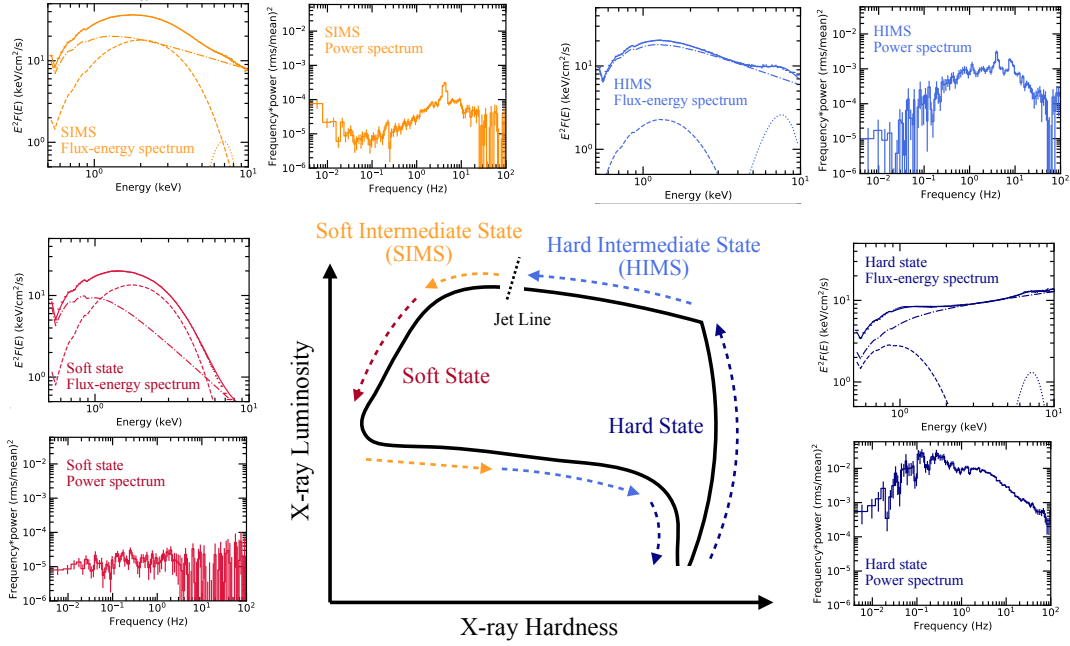


Figure 1.21: The hardness intensity diagram (HID), generally traced by the BH-XRBs during the outburst phase is shown in the middle panel. All the other panels depict the key timing and spectral characteristics exhibited by the BH-XRBs in distinct spectral states during the evolution of the outburst. See text for details. The figure is adapted from Wang et al. (2022).

Low-Hard State (LHS)

At the onset of an outburst, BH-XRBs typically enter into the bright hard spectral state of low accretion rate, where the emission is primarily dominated ($\gtrsim 80\%$ flux contribution) by the high energy X-ray photons produced via thermal Comptonization of low energy photon distribution (Done et al., 2007). The X-ray spectrum at higher energies in the LHS remains flat and is generally well described by a power-law distribution (see Fig. 1.21) of photon index $\Gamma_{\text{PL}} \lesssim 1.7$ (Remillard and McClintock, 2006). Although the canonical hard state is primarily characterized by this non-thermal emission, occasionally a faint contribution from the weak thermal accretion disc can be noticed (see Fig. 1.21). In general, when detectable, the disc remains truncated at a larger radius from the black hole, typically exceeding several tens of gravitational radii (McClintock et al., 2001). Apart from this, distinct timing features including low-frequency band-limited noise, power spectral breaks, and occasional appearance of type-C QPO features are also noticed in the PDS during LHS (see Fig. 1.21). Notably, high temporal variability resulting in root mean square (rms) amplitude of $\gtrsim 30\%$ is generally observed in the entire PDS of a wide frequency range. In addition, this state is frequently associated with the presence of steady radio jets in many BH-XRB systems.

Intermediate States

As the outburst progresses, the mass accretion rate increases, leading to a stronger contribution from the accretion disc in the X-ray spectrum. During this phase, the system undergoes a transition from the canonical hard state to the soft state, typically passing through two intermediate states (IS). These transition states exhibit properties

that lie between typical soft and hard states. In general, BH-XRBs first enter into the hard intermediate state (HIMS) followed by the soft intermediate state (SIMS). Throughout this evolution, the spectrum gradually starts to soften, primarily due to the increased dominance of the disc emission at lower energies (see Fig. 1.21). The power-law component usually becomes steeper than in the LHS, with Γ_{PL} ranging within 2–3. In terms of timing properties, PDS in the HIMS is generally characterized by prominent type-C QPOs along with harmonics, superimposed on a flat-topped broad-band noise (see Fig. 1.21). As the source evolves into the SIMS, the QPO features become weak, resulting in type-B or occasionally type-A QPOs. Subsequently, the overall variability in the PDS decreases ($\text{rms} \sim 10 - 20\%$) during the HIMS and diminishes even further in the SIMS. Most importantly, the transition from HIMS to SIMS is often associated with the launch of powerful relativistic jet ejections (see the jet line in Fig. 1.21 and also Fender et al. 2004, Radhika et al. 2016, Choudhury et al. 2025).

High-Soft State (HSS)

During the peak of an outburst, BH-XRBs typically enter into the high soft state (HSS), where the observed spectral flux is mostly of thermal origin. In the HID, the HSS is located at the extreme left, characterized by the lowest X-ray hardness ratio and high luminosity. During this phase, the coronal region undergoes significant contraction, and the accretion disc extends inward, reaching close to the innermost stable circular orbit (r_{ISCO}). As a result, the contribution from the coronal (non-thermal) emission becomes negligible in the overall spectral distribution. As illustrated in Fig. 1.21, the spectral profile in the HSS is distinctly dominated by a strong thermal component peaking around ~ 1 keV, well modeled by a multi-temperature accretion disc blackbody. In addition, a steep power-law component with photon index $\Gamma_{\text{PL}} \gtrsim 2.8$ is often observed at higher energies (Remillard and McClintock, 2006). Further, spectral modeling in this state enables the estimates of the inner disc radius, which is typically found to lie within a few gravitational radii, reinforcing the notion that the disc extends close to the black hole in the HSS. Interestingly, while the disc luminosity often exhibits significant variability, the inner disc radius remains largely unchanged, suggesting that the observed luminosity changes are primarily driven by variations in the disc temperature. Studies have shown that the disc luminosity (L_{disc}) and inner disc temperature (T_{in}) follow the relation $L_{\text{disc}} \propto T_{\text{in}}^4$, again indicating a blackbody like origin for the disc emission. However, several XRBs are also observed to deviate from the standard $L_{\text{disc}} \propto T_{\text{in}}^4$ relation, suggesting a more complex accretion physics, which remains the topic of active research and will be discussed in detail in the subsequent chapters. Due to the proximity of the disc close to the black hole in HSS, the spin of the black hole and various general relativistic effects, including gravitational lensing and returning radiation, can have a substantial influence on the observed spectral features. Thus, the HSS data of BH-XRBs are generally used to probe these effects. Further, from a timing perspective, the HSS is characterized by minimal variability, with the fractional rms amplitude typically limited to a few percent, and a notable absence of QPOs (see Fig. 1.21).

It is worth noting that BH-XRBs generally follow a similar track during the decay phase of the outburst, transitioning from the HSS back to the LHS via the intermediate states (see the lower branch of the HID in Fig. 1.21). In this phase, the spectro-

temporal characteristics across different spectral states remain largely consistent with those observed during the rising phase, except for a significant decrease in the overall luminosity. Moreover, it is important to note that persistent BH-XRBs generally do not exhibit spectral state transitions with the same characteristics as the transients. Instead, they typically remain in long duration spectral states, often in the HSS.

Steep Power-law State (SPL)

Apart from the canonical spectral states discussed above, several transient and persistent BH-XRBs are observed to evolve through an additional spectral state known as the steep power-law state (SPL) or very high state (VHS). These states are generally characterized by a notably steep power-law photon index, typically exceeding $\Gamma_{\text{PL}} > 2.4$ (Remillard and McClintock, 2006). SPL states generally occur at comparatively higher luminosities, in the range of $0.2 - 0.3 L_{\text{Edd}}$ (Zdziarski and Gierliński, 2004). Although the steep spectral index may resemble that of the canonical soft state, the SPL state is distinct due to the presence of significant thermal and/or non-thermal Comptonization effects in the spectral distribution (Gierliński and Done, 2003). Additionally, models incorporating bulk motion Comptonization have been proposed to account for the spectral and timing properties observed during this state (Titarchuk and Shrader, 2002). A particularly intriguing feature of the SPL state is the simultaneous presence of both low- and high-frequency QPOs, which adds further complexity to understanding the underlying accretion dynamics associated with this state (Dexter and Blaes, 2014).

1.6.4 Polarimetry

In addition to X-ray timing and spectral studies, polarimetry has recently emerged as a powerful diagnostic tool for probing the accretion-ejection dynamics and geometry of BH-XRBs (see Dovčiak et al. 2024 for a review). Specifically, the orientation of the electric field vector of detected photons carries imprints of the physical processes near the black holes through which they originated. The polarimetric information of the emitted radiation is typically characterized by two key parameters: the polarization degree (PD) and the polarization angle (PA). Usually, PD is expressed in percentage and represents the fraction of linearly polarized photons of the detected emission, while PA specifies the orientation of the electric field vector projected onto the plane of the sky. In general, the polarimetric study can be performed across different energy bands and orbital phases of the binary system. Notably, the distinct spectral states of BH-XRBs, traditionally classified through spectro-temporal analyses, also show correlations with their corresponding polarimetric properties. Consequently, combining spectral and polarimetric information gives rise to the emerging and increasingly successful field of X-ray ‘spectro-polarimetry’. In Fig. 1.22, we present the typical polarimetric measurement results for the BH-XRB source Cyg X–1, illustrating the inferred disc-corona geometry. We discuss the measurement and analysis techniques of X-ray polarimetry in detail in Chapter 2.

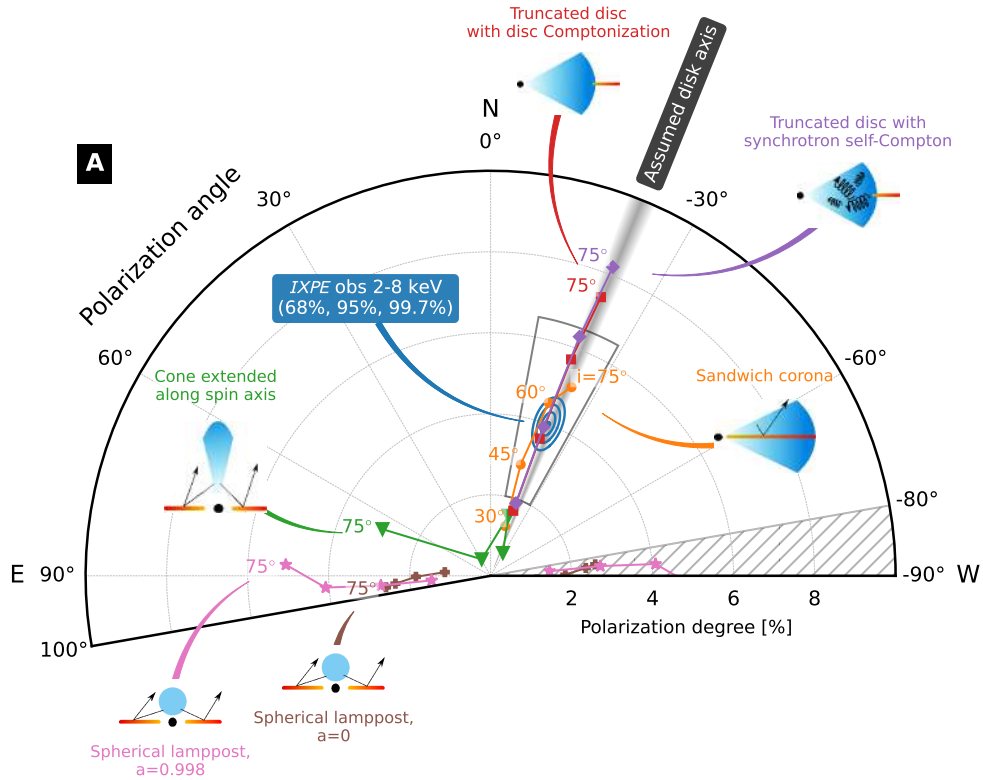


Figure 1.22: Representation of the predictions of X-ray polarimetry for different disc-corona configurations of BH-XRB Cyg X-1. Credit: [Krawczynski et al. \(2022\)](#).

1.7 Motivation and Plan of the Thesis

Following the detailed review of the fundamentals of accretion physics and the radiative properties of plasma in the context presented above, it turns out that several key aspects of BH-XRBs and BH-ULXs are still not fully understood. These unresolved issues are broadly due to the complex interplay between the physical processes governing the accretion flow in the presence of strong gravity near black holes. Motivated by these challenges, the primary objective of this thesis is to investigate the observational characteristics of various accretion-powered BH-XRB and BH-ULX systems using data from multiple space-based observatories. Through detailed analysis of timing, spectral, and polarimetric properties, this thesis aims to provide deeper insights into these systems that can refine existing theoretical models for accretion physics and offer a more enriched understanding of the physical mechanisms active in such extreme environments. While doing so, in **Chapter 2**, we present a comprehensive overview of the data reduction techniques and analysis methodologies adopted for processing observational data from various X-ray missions, used in this thesis. This thesis comprises three main working chapters, each addressing specific aspects of different accretion-powered BH-XRB and BH-ULX systems. A brief overview and motivation for each of these chapters, along with the overall flow of the thesis content, are presented below.

- **Chapter 3:** We recall that fast timing variability features such as QPOs are typically observed in galactic BH-XRBs (see §1.6.2) and are believed to be key diagnostic tools of the accretion dynamics around black holes. Moreover, these features, often originating from regions very close to the black hole, carry the

imprint of strong gravity effects. Despite rigorous studies of QPOs across distinct frequency ranges in various BH-XRBs, several open questions persist. The fundamental issue concerns the origin of these features. To address this, several models based on contemporary theoretical frameworks have been proposed over the years. For example, most competing explanations for QPOs rely either on geometrical effects under strong gravity or on physical mechanisms related to the accretion dynamics (see [Ingram and Motta 2019](#) for a review). Nevertheless, a significant lack remains in explaining the properties of these features and their inherent connection with the emission mechanisms near black holes. In pursuit of a deeper understanding, in this chapter, we perform a comprehensive study of the broadband spectro-temporal variabilities in two BH-XRBs, namely Swift J1727.8 – 1613 and GRS 1915 + 105, using the unique observational capabilities of the *AstroSat* mission.

- **Chapter 4:** In line with the previous chapter, X-ray spectro-temporal studies over the past few decades have provided glimpses into the accretion-ejection dynamics and geometry of BH-XRBs. However, there are certain limitations to this approach, mostly because of the degeneracy between different models of alternative disc-corona geometries in explaining the observations. In this context, X-ray polarimetry, being a comparatively unexplored domain of X-ray astronomy, promises to provide completely new insights (see §1.6.4 and [Dovčiak et al. 2024](#) for a recent review). Motivated by this, in this chapter, we carry out in-depth spectro-polarimetric and timing studies of a sample of Galactic and extragalactic BH-XRBs using multimission observational data. While doing so, our primary goal is to extract insights from the timing and spectro-polarimetric studies of individual sources. With this, we aim to establish a comprehensive picture of the accretion-ejection dynamics and geometry in BH-XRBs by integrating the findings of our study.
- **Chapter 5:** As outlined in §1.3.4, BH-ULXs offer several challenges in understanding their accretion dynamics, mostly driven by various observational shortcomings. Fortunately, BH-ULXs exhibit distinct spectro-temporal features such as mHz QPOs and spectral curvature, which can serve as powerful diagnostic tools to probe the physics of these objects in a manner analogous to that of galactic BH-XRBs. Indeed, the observed mHz QPOs in BH-ULXs are believed to be a scaled-down version of the typical type-C QPOs commonly seen in BH-XRBs ([Kaaret et al., 2017](#)). Under such circumstances, it becomes essential to test whether the theoretical models of accretion dynamics that successfully explain spectro-temporal features in BH-XRBs can also be applied to BH-ULX systems. Motivated by all these research prospects, in this chapter, we carry out a comprehensive investigation focusing on the long-term evolution of the spectro-temporal variabilities of several BH-ULXs. Furthermore, we employ a novel model formalism based on relativistic, viscous, advective accretion flows around black holes, to interpret the spectro-temporal observables of BH-ULXs. This allows us to place possible constraints on the black hole mass, spin, and accretion rate of BH-ULXs. Moreover, we aim to unveil plausible disc-corona-wind driven accretion scenarios and predict system inclinations in BH-ULXs.

Finally, in **Chapter 6**, we provide a summary of the key findings of this thesis and

outline the main conclusions drawn from the work. Additionally, in **Chapter 7**, potential directions for future research endeavours arising from this study are discussed.



Observation, Data Reduction and Analysis Techniques

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2.1 Overview of X-ray Observatories

The Earth’s atmosphere is opaque to X-rays, and hence, astronomical observations of high energy radiation were limited in the early days. With the deployment of space-based instruments in the mid-twentieth century, the detection of cosmic X-ray sources became feasible. In the early phase of X-ray astronomy, rockets were employed to carry instruments above the Earth’s atmosphere to detect X-ray radiation from cosmic sources. However, their brief flight durations imposed major constraints on the observations, particularly after the discovery that many X-ray sources exhibit temporal variability. After that, the introduction of high altitude balloons allowed for extended observation periods, lasting several hours. A major turning point occurred in 1970 with the launch of *Uhuru*, the first satellite specifically designed for X-ray astronomy. Unlike previous short duration rocket or balloon experiments, *Uhuru* enabled sustained observations over multiple years, significantly extending the temporal baseline for X-ray studies (Giacconi et al., 1971). *Uhuru* identified 339 X-ray sources spanning various astrophysical classes, including X-ray binaries, supernova remnants, Seyfert galaxies, and galaxy clusters. The next technological advancement came in 1979 with the launch of the *Einstein Observatory*, the first to utilize Wolter-type grazing-incidence focusing

optics in X-ray astronomy (Giacconi et al., 1979). With progressive advancements in X-ray detection capabilities over the past five to six decades, numerous pioneering X-ray observatories have emerged, greatly enhancing our understanding of the high energy universe. At present, several state-of-the-art X-ray missions remain operational, offering exceptional spectral and timing resolution that continues to facilitate detailed investigations of various astrophysical phenomena. In this study, we analyze data from a range of active X-ray missions, including *XMM-Newton*, *NuSTAR*, *NICER*, *AstroSat*, *IXPE*, *MAXI* and *Swift*, to explore the physics of BH-XRBs. In this Chapter, we provide a brief overview of each of these missions, followed by a discussion of the techniques used for data acquisition, reduction, and analysis.

2.1.1 X-ray Multi-Mirror Mission (XMM-Newton)

The *X-ray Multi-Mirror Mission Newton* (*XMM-Newton*) observatory (Jansen et al., 2001), launched on December 10, 1999, is equipped with three advanced X-ray telescopes designed to perform observations across the low energy X-ray band. Two of these telescopes are coupled with *Reflection Grating Spectrometers* (*RGS*) (den Herder et al., 2001), which deflect approximately half of the incoming X-ray photons for high-resolution spectroscopy. The remaining photons from these two telescopes are directed to *Metal Oxide Semiconductor* (*MOS*) cameras (Turner et al., 2001). The third telescope channels all its collected photons directly to the *PN* camera (Strüder et al., 2001). The *MOS* and *PN* cameras together form the *European Photon Imaging Camera* (*EPIC*), which serves as the primary X-ray imaging system in 0.15 – 15 keV energy range. In addition to the X-ray instruments, a co-aligned UV/optical telescope, the *Optical Monitor* (*OM*), is also present as a complementary payload. In general, simultaneous observations with all six instruments can be performed depending on the scientific objectives. Each X-ray telescope incorporates 58 Wolter type I mirrors, nested in concentric shells that are coaxial and share a common focal point. This configuration is designed to achieve a reasonably good effective area across the entire energy range, with enhanced performance near 7 keV.

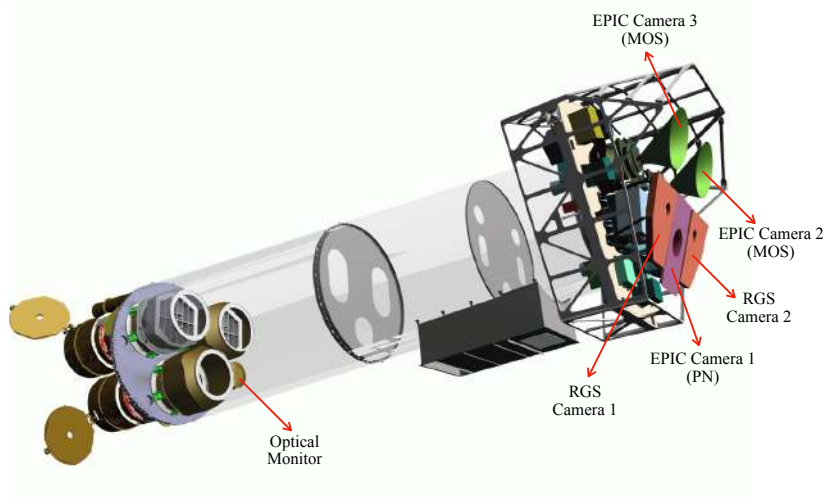


Figure 2.1: Schematic overview of *EPIC-PN*, *EPIC-MOS1*, *EPIC-MOS2*, *RGS* and *OM* instruments onboard *XMM-Newton*. Credit: <https://www.cosmos.esa.int/web/xmm-newton/xmm-payl>.

In particular, the *EPIC* detectors provide a substantial effective area across 0.15–12 keV band, reaching up to $\sim 2500 \text{ cm}^2$ at 1.5 keV and $\sim 1800 \text{ cm}^2$ at 5 keV. The *RGS*

operates within 0.4 – 2.2 keV range, delivering a combined effective area of $\sim 120 \text{ cm}^2$ at 0.8 keV. In general, *EPIC* offers high-resolution imaging over a $30'$ circular field of view, with moderate spectral resolution of $E/\Delta E \sim 20 - 50$ and spatial resolution characterized by a point spread function of $6''$ FWHM. The *EPIC* cameras support various observational modes such as full frame, extended full frame, large window, small window, timing, and burst, allowing time resolution up to $7\mu\text{s}$. Therefore, *EPIC* onboard *XMM-Newton* remains a powerful instrument for X-ray timing and spectral studies. In this work, we use *EPIC* data taken in different observation modes depending on availability. In Fig. 2.1, we present the schematic representation of the payloads onboard *XMM-Newton*.

2.1.2 The Nuclear Spectroscopic Telescope Array (NuSTAR)

The *Nuclear Spectroscopic Telescope Array (NuSTAR)* (Harrison et al., 2013), launched by NASA on 13 June 2012, marked a major milestone in high energy astrophysics as the first space based telescope capable of focusing hard X-rays in 3 – 79 keV energy range. Before *NuSTAR*, instruments operating in this band used non-focusing techniques with limited sensitivity and spatial resolution. *NuSTAR* overcomes these limitations by employing multilayer coated grazing incidence optics configured in a nested Wolter-I geometry. The optics with low grazing angles, combined with the multilayer coatings

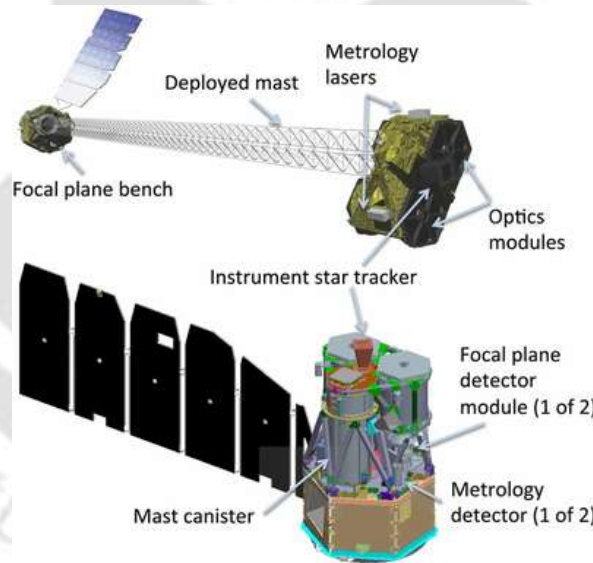


Figure 2.2: Illustration of the *NuSTAR* observatory, showing its advanced X-ray focal plane module and other key scientific instruments. Credit: Harrison et al. (2013).

and a total effective area of 847 cm^2 at 9 keV and 60 cm^2 at 78 keV, enable detection of hard X-rays up to $\sim 79 \text{ keV}$. The observatory consists of two co-aligned telescopes, each comprising a set of focusing optics and a corresponding focal plane module, named FPMA and FPMB. The focal planes use Cadmium Zinc Telluride (CdZnTe) crystal detectors, arranged in 2×2 pixel arrays per module. These detectors provide a spectral resolution of 0.4 keV at 10 keV and 0.9 keV at 68 keV. Additionally, *NuSTAR* offers complementary timing capabilities with a temporal resolution of $2 \mu\text{s}$, making it suitable for studying rapid temporal variability in astrophysical sources. The design of *NuSTAR* also effectively reduces pile-up effects, enabling high quality observations for bright sources.

2.1.3 Neutron star Interior Composition Explorer (NICER)

The *Neutron Star Interior Composition Explorer (NICER)* (Gendreau et al., 2016) is a NASA-led mission, which was launched aboard the International Space Station (ISS) in June 2017. Designed primarily for investigating neutron star systems, *NICER* operates in the soft X-ray band, covering the energy range of 0.2 – 12 keV. At the core of *NICER*'s scientific instrumentation remains the *X-ray Timing Instrument (XTI)*, which is optimized for high quality timing and spectroscopic studies. The *XTI* comprises 56 co-aligned X-ray concentrator optics, each coupled with a corresponding focal plane module (FPM) consisting of silicon drift detectors. This configuration enables *NICER* to achieve excellent temporal and spectral resolutions, making it especially suitable for probing the emission mechanism of various compact objects. The detector system is supported by seven measurement power units (MPUs), each capable of processing signals from up to eight FPMs. These MPUs are responsible for recording the energy of incoming photons and utilize a GPS-based time reference to assign precise time stamps to each detected event.

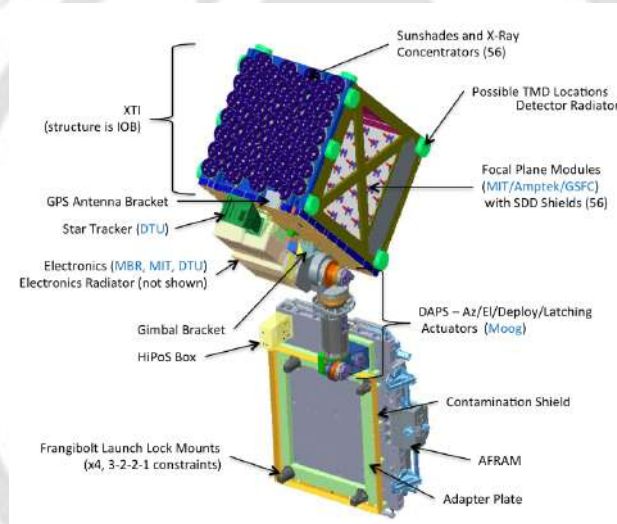


Figure 2.3: Schematic representation of the *NICER* mission placed at the ISS, showing all major components. Credit: Gendreau et al. (2016).

The *XTI* captures incoming X-ray photons through grazing incidence optics, effectively focusing the soft X-rays onto the detectors. Typically, it provides an effective collecting area of over 2000 cm² at 1.5 keV and about 600 cm² at 6 keV. A spectral resolution of approximately 85 eV at 1 keV and 137 eV at 6 keV, along with an exceptional timing resolution of around 300 nanoseconds, is achievable with *NICER/XTI*. Thus, it enables detailed investigations of rapid spectro-temporal variability in astrophysical sources. In our study, we utilize the *NICER* data for both spectral and timing studies.

2.1.4 AstroSat

AstroSat (Agrawal, 2006), India's pioneering multi-wavelength space observatory, was launched on 28 September 2015 and placed into a low Earth orbit at an altitude of 650 km and an inclination of 6°. With the aim of broadband study of astrophysical objects, AstroSat contains five primary scientific instruments along with one auxiliary payload. Four of the scientific instruments are co-aligned and mounted on a common platform,

enabling simultaneous observations in the UV and X-ray band (0.3 – 80 keV). The fifth instrument is mounted orthogonally on a rotating platform, specifically designed to perform all-sky scans. The onboard instruments include a *Soft X-ray Telescope* (*SXT*) (Singh et al., 2017) optimized for low energy X-ray imaging and spectroscopy, three *Large Area X-ray Proportional Counters* (*LAXPC*) (Yadav et al., 2016, Antia et al., 2017, Agrawal et al., 2017) for spectro-temporal studies in the low to hard X-ray regime, two *Ultraviolet Imaging Telescopes* (*UVIT*) (Tandon et al., 2017) for UV imaging, and a *Cadmium-Zinc-Telluride Imager* (*CZTI*) (Vadawale et al., 2016) used for imaging and polarization measurements in the hard X-ray band. The *Scanning Sky Monitor* (*SSM*) (Ramadevi et al., 2017) provides continuous monitoring of variable and transient X-ray sources for the possible detection of transient X-ray sources, while the auxiliary payload *Charged Particle Monitor* (*CPM*) (Rao et al., 2017) tracks the local radiation environment to ensure the safety of the primary detectors. Since the aim of our work focuses primarily on the study of XRBs, we use the *SXT* and *LAXPC* data in our analysis. Below, we provide some of the basic characteristics of these two payloads.

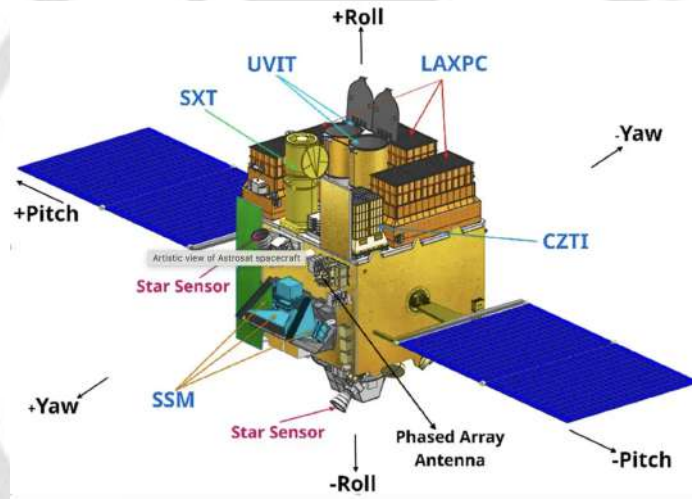


Figure 2.4: Artist's illustration of the *AstroSat* mission, highlighting its major scientific instruments and overall spacecraft design. Credit: https://www.isro.gov.in/Astrosat_Spacecraft.html.

SXT

SXT onboard *AstroSat* employs a grazing incidence mirror assembly to focus incoming X-rays onto a focal plane camera equipped with a charge-coupled device (CCD). *SXT* has a field of view of 40° and utilizes a CCD comprising 600×600 pixels. It delivers a spectral resolution of around 90 eV at 1.5 keV and 136 eV at 5.9 keV, enabling the detection of key spectral features such as iron emission lines in XRBs. The effective area of *SXT* is $\sim 90 \text{ cm}^2$ at 1.5 keV. The CCD supports multiple readout modes tailored for different observational needs. These include the Photon Counting (PC) mode, Fast Window (FW) mode, Bias Map (BM) mode, calibration mode (CM), and housekeeping (HK) mode. Among these, the PC and FW modes are the most widely utilized, operating over CCD windows of 600×600 and 150×150 pixels, respectively. Notably, the CCD readout time is 2.378 s in PC mode, while the FW mode achieves a faster readout time of 0.278 s. The BM and CM modes are primarily utilized for

background calibration and detector tuning, while the HK mode is used to monitor the operational health of the instrument.

LAXPC

LAXPC instrument onboard *AstroSat* consists of three identical and co-aligned proportional counter units, namely *LAXPC10*, *LAXPC20*, and *LAXPC30*. These multi-layered proportional counter detectors are sensitive to X-rays in the broadband energy range of 3 – 80 keV. Each detector contains seven main anodes: two each in the top and middle layers, and one in each of the bottom three layers. Additionally, three veto anodes are placed on the left, right, and bottom sides. The outputs from the seven main anodes and the three veto layers are processed by ten charge sensitive preamplifiers. A high voltage supply in the range of 2000 – 2500 V is applied to all main anodes at a single point to ensure uniform voltage, which can be regulated from the ground. *LAXPC10* and *LAXPC20* are filled with a mixture of 90% xenon and 10% methane at a pressure of approximately 2 atm. *LAXPC30*, on the other hand, contains a gas mixture of 84.4% xenon, 9.4% methane, and 6.2% argon at a similar pressure. Each unit is equipped with a commandable onboard gas purification system, which helps to maintain optimal energy gain and resolution by recirculating purified gas as needed. It is noteworthy that both *LAXPC10* and *LAXPC30* experiences gain instability due to gas leaks after launch. Although *LAXPC10* continued to function effectively until March 2018, after which its gain began to exhibit noticeable drift (Antia et al., 2021). *LAXPC* provides a substantial effective area $\sim 6000 \text{ cm}^2$ at 15 keV and around $\sim 5000 \text{ cm}^2$ at 50 keV (Antia et al., 2017). The collimator enables a field of view of $1^\circ \times 1^\circ$ for incoming X-rays. Each of the three *LAXPC* units offers a high temporal resolution of 10 μs , enabling detailed timing studies for XRBs. It is worth mentioning that each detector experiences a dead time of 42 μs .

2.1.5 Imaging X-ray Polarimetry Explorer (IXPE)

The *Imaging X-ray Polarimetry Explorer (IXPE)* (Weisskopf et al., 2022), a pioneering NASA mission, was launched on December 9, 2021. *IXPE* is specifically designed to explore the largely unexplored domain of X-ray polarimetry, thereby providing a new diagnostic tool for studying astrophysical sources in the low energy X-ray range of 2 – 8 keV. The mission consists of three identical telescope systems, each comprising a mirror module assembly (MMA) and a polarization sensitive X-ray imaging gas pixel detector positioned at the focal point. The payload configuration includes these three telescope assemblies along with their shielding components and a pair of star trackers for accurate orientation in space. Collectively, the three mirror modules focus incident X-rays onto three separate detector units (DUs) having polarization sensitivity. Each *IXPE* mirror module has an angular resolution of $28''$ and an effective area of 166 cm^2 at 2.3 keV and 175 cm^2 in the 3 – 6 keV energy range. The polarimetric information of the incident X-ray photons is extracted using photoelectron tracking techniques (Bellazzini et al., 2003).

2.1.6 Monitor of All-sky X-ray Image (MAXI)

The *Monitor of All-sky X-ray Image (MAXI)* (Matsuoka et al., 2009) is a Japanese mission designed to survey the X-ray sky continuously in the 0.5–30 keV energy range,

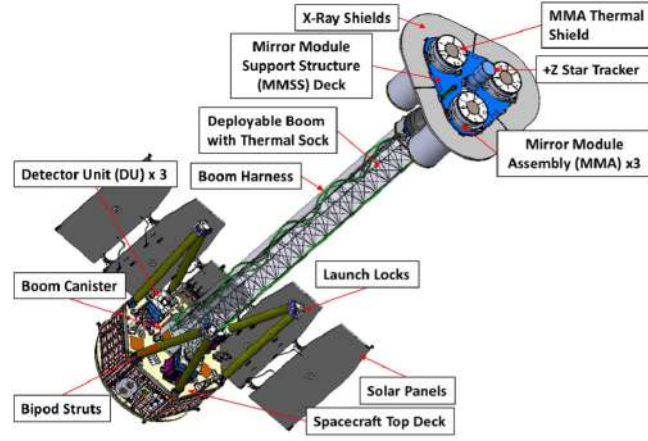


Figure 2.5: Artist's impression of the IXPE mission, detailing its key scientific payloads and spacecraft architecture. Credit: Weisskopf et al. (2022).

deployed on the ISS since August 2009. *MAXI* features two primary instruments: the *Gas Slit Camera (GSC)* (Mihara et al., 2011) and the *Solid-state Slit Camera (SSC)* (Tsunemi et al., 2010). *GSC* being the main instrument onboard *MAXI*, operates in 2 – 20 keV energy range using slit camera configurations and relies on large area proportional counters filled with xenon gas to detect X-rays with high sensitivity. A

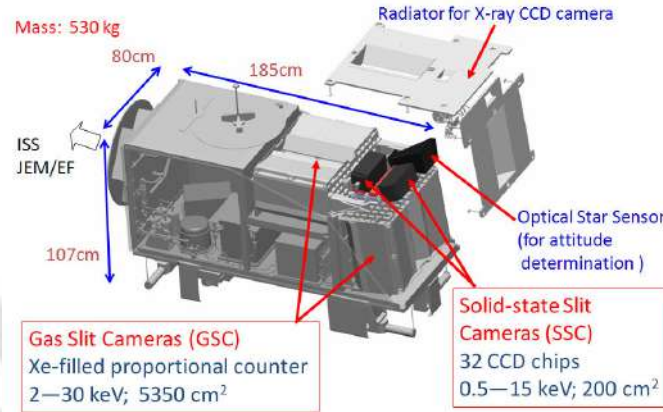


Figure 2.6: Visual representation of the *MAXI* observatory, showcasing its key X-ray instruments. Credit: Mihara et al. (2022).

total of 12 such detectors, collectively covering 5350 cm² effective area, provide high quality detection capabilities. With a field of view of 160° × 1.5°, the system is capable of surveying nearly the entire sky during its 92-minute orbital period. Thus, X-ray activity from transient XRBs in the 2 – 20 keV energy range is promptly detected by *MAXI/GSC*.

2.1.7 Neil Gehrels Swift Observatory (Swift)

The Neil Gehrels *Swift* Observatory (*Swift*) (Gehrels et al., 2004), launched in 2004, is a NASA Explorer mission specifically developed to study gamma-ray bursts (GRBs) and their afterglows in 0.2 – 150 keV energy range. *Swift* is equipped with three scientific instruments, namely the *Burst Alert Telescope (BAT)* (Barthelmy, 2004), which monitors the sky in hard X-rays (15 – 150 keV) over a wide field of view; the

X-ray Telescope (XRT) (Burrows et al., 2005), designed for focused observations in the soft X-ray (0.2 – 10 keV) regime and the *UV/Optical Telescope (UVOT)* covering energy band corresponding to 170 – 650 nm wavelength range. *XRT* utilizes flight-spare mirrors and a CCD detector similar to those used in the *EPIC-MOS* instrument onboard *XMM-Newton* for detecting soft X-rays with a field of view of $23.6' \times 23.6'$. It

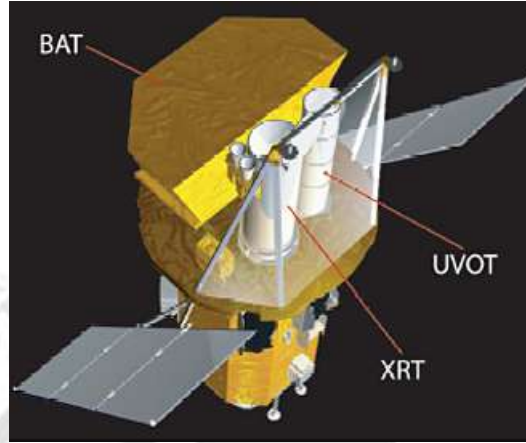


Figure 2.7: Overview of the *Swift* mission, featuring the scientific payloads. Credit: Gehrels et al. (2004).

employs grazing incidence Wolter-I optics to achieve a collecting area of $\sim 110 \text{ cm}^2$ at 1.5 keV. On the other hand, *BAT* is a highly sensitive instrument designed with a large field of view (1.4 steradian), enabling it to monitor a significant portion of the sky for transient high energy phenomena. It consists of a detector array comprising 32,768 Cadmium Zinc Telluride (CdZnTe) elements, each of $4 \text{ mm} \times 4 \text{ mm}$ area and 2 mm thickness. To facilitate efficient electronic control and data handling, these detector elements are organized in a two layer structure. In our study, we make use of the calibrated and processed *Swift/BAT* data in 15 – 50 keV energy band, as provided by the instrument team¹, to investigate the long term variability of a given source in hard X-rays.

2.2 Data Reduction: Techniques and Tools

The data collected by the aforementioned X-ray detectors requires processing to generate standardized files suitable for scientific analysis. This is crucial because the raw data from telescopes is often influenced by various instrumental and environmental factors that must be carefully corrected. For instance, when a spacecraft passes through the South Atlantic Anomaly (SAA) region in space, the X-ray detectors often experience increased background noise from high energy charged particles, in addition to the signal from the source itself. During the data reduction process, these effects are corrected, and the raw data are cleaned to produce calibrated events corresponding to the source of interest. The data reduction process typically involves a series of computational techniques. Each instrument has its dedicated data reduction pipeline, which is based on the HEASOFT software framework. For this study, version 6.26.1 and later of HEASOFT were utilized. The first step in the data reduction process is to retrieve the observational data from the relevant data archives. In the following, we outline

¹<https://swift.gsfc.nasa.gov/results/transients/>

the procedures for acquiring the data and describe the reduction steps employed for each instrument.

2.2.1 MAXI/GSC

For our analysis, we utilize the on-demand² processed daily monitoring data provided by the *MAXI/GSC* instrument team. The user interface allows the selection of the source coordinates, followed by the choice of energy bands and time resolution based on the specific scientific goals. This enables the extraction of source light curves across various energy bands, along with the corresponding spectra. For the present study, we employ *MAXI/GSC* light curves with 1-day time bins to investigate the long term evolution of the source properties.

2.2.2 XMM-Newton/EPIC

XMM-Newton/EPIC data analysis is carried out using the latest **Science Analysis System (SAS)** software³, following the standard data reduction procedures recommended by the instrument team⁴. To begin with, the **SAS** environment is set up by configuring the required environment variables and providing the latest **calibration index files (CIF)** along with the observation data file (**ODF**). The **ODFs** of the *EPIC-PN* and *EPIC-MOS* instruments, available at the **HEASARC** archive⁵, are processed using the **epproc** and **emproc** tasks of the software routine, respectively. These tasks generate calibrated event files for each instrument. Following [Agrawal and Nandi \(2015a\)](#), we adopt the event selection criteria: $\text{PATTERN} \leq 4$ and $\text{PATTERN} \leq 12$ with $\text{FLAG} = 0$, while generating the scientific products from the *EPIC-PN* and *EPIC-MOS* data, respectively. To remove the data intervals affected by high energy particle background flares, a light curve is first extracted in the higher energy range of 10 – 15 keV. Subsequently, the Good Time Intervals (GTIs) are generated using the task **tabgtigen** with the threshold set just above the steady mean count rate of the light curve⁶. This procedure filters out background flares and produces cleaned event files. Furthermore, a barycentric correction is applied to the cleaned event file using the **barycen** task to account for the motion of the satellite with respect to the solar system barycenter. Next, this cleaned and calibrated event file is used to generate the observation image using the **ds9** software to visualize the source of interest. From this image, a circular region of a specific radius centered at the source coordinate is selected to extract the source events for scientific analysis. Similarly, a nearby source free circular region of the same radius is chosen to extract the background events. Thereafter, the source and background light curves and spectra are extracted using the **evselect** task. The light curves are further corrected for instrumental effects such as vignetting and bad pixels, as well as for background contributions, using the **epiclccorr** tool. For spectral analysis, response files and ancillary files are generated using the tasks **rmfgen** and **arfgen**, respectively. Finally, the spectra are grouped using the **specgroup** task to ensure a minimum of 25 counts per energy bin. We mention that both *EPIC-PN* and

²<http://maxi.riken.jp/mxondem/>

³<https://www.cosmos.esa.int/web/xmm-newton/sas>

⁴<https://www.cosmos.esa.int/web/xmm-newton/sas-threads>

⁵<https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl>

⁶<https://www.cosmos.esa.int/web/xmm-newton/sas-thread-epic-filterbackground>

EPIC-MOS data are used in the spectral analysis. In contrast, timing analyses are performed using only *EPIC-PN* data due to its better temporal resolution of ~ 73.4 milliseconds as compared to *EPIC-MOS*.

2.2.3 NuSTAR/FPM

We analyze the *NuSTAR* (Harrison et al., 2013) data obtained from the HEASARC archive using the dedicated NUSTARDAS pipeline⁷, integrated in the HEASOFT software environment. The `nupipeline` task is used to perform standard data screening, including filtering out the intervals affected by passages through the South Atlantic Anomaly (SAA), ensuring good time intervals. This step produces cleaned event files and sky images separately for both focal plane modules, *FPMA* and *FPMB*. Next, the science products are extracted using the `nuproducts` task. For this, a circular source and background regions of $60''$ radii are defined using the `ds9` visualization tool, centered on the source and a nearby source-free region, respectively. Subsequently, the `nuproducts` module generates source and background spectra, light curves, as well as instrument response and ancillary response files for both detectors. Further, the extracted spectra are grouped using the `grppha` tool of HEASOFT to ensure a minimum of 25 counts per energy bin for the spectral fitting. This binning approach enhances the statistical quality of the spectral analysis.

2.2.4 NICER/XTI

The *NICER/XTI* data, available at HEASARC data archive, are processed using the standard data reduction pipeline provided by the NICERDAS⁸ software, integrated within the HEASOFT environment. This software package includes all necessary calibration files and tools to ensure accurate data reduction. To generate the clean event file for each observation, we use the `nicer12` task, which applies updated screening and filtering algorithms to produce cleaned event data suitable for scientific analysis. For spectral extraction, we use the `nicer13-spect` task to produce high quality spectral products by extracting photon counts from the clean event files within the desired energy range. The background model `3c50` (Remillard et al., 2022) is used to extract the corresponding background spectrum files. Additionally, for time domain analysis, we generate light curves with the desired time resolution using the `nicer13-lc` task. This tool allows us to select appropriate time bins suited for both long- and short-timescale temporal studies, depending on the specific scientific objectives.

2.2.5 AstroSat/SXT

SXT data are analyzed following the guidelines provided by the *SXT* instrument team⁹. We obtain level-2 *SXT* data from the Indian Space Science Data Center (ISSDC)¹⁰ archive. The *SXT* data are available in two modes: Photon Counting (PC) mode and Fast Window (FW) mode. These data are stored on an orbit wise basis, meaning event files corresponding to each orbit of an observation are available

⁷<https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/>

⁸https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_analysis.html

⁹https://www.tifr.res.in/~astrosat_xt/index.html

¹⁰https://webapps.issdc.gov.in/astro_archive/archive/Home.jsp

individually. To create a single event file for the entire observation, the orbit wise files are merged using the `event_merger` Python routine¹¹, which is based on the Julia programming language (version 1.1 and above)¹². The source images, light curves, and spectra are generated from the level-2 cleaned event file or the merged event file using `XSELECT` tool available in the `HEASOFT` software package. To examine potential pile-up effects in the data, we check whether the source count rate remains below the thresholds of 0.5 cts/pixel/frame and 40 cts/s within the central 1' circular region of the image. According to the *AstroSat Handbook*¹³ (see also Baby et al. (2020), Katoch et al. (2021) for details), if the source count rate is below these thresholds, the observation is considered to be pile-up free. We find no evidence of pile-up effects in any of the *SXT* data considered in our analysis. Therefore, we do not apply pile-up correction in our study. In general, a region filter file with a specified source region must be considered within `XSELECT` for the extraction of source events. To choose the correct source region, we perform the following exercise. For the PC mode data, we first consider two circular source extraction regions with radii of 12' and 14', concentric with the source coordinates. By comparing the extracted photon counts, we find that the 12' region contains up to 90% of the total photon counts. Therefore, we adopt the 12' circular region as the source region for all PC mode data and extract the corresponding images, light curves, and spectra from this region. For the FW mode observations, we find that the source was offset in the CCD frame for a few observations (Sreehari et al., 2020). As a result, we select a smaller 5' circular region for these two observations. Given the limited timing resolution (~ 2.38 s) of *SXT* compared to *LAXPC*, we use *SXT* data solely for spectral analysis. Further, we use the *SXT* instrument response file, background spectrum file, and ancillary response file (ARF) for both PC and FW mode data, as provided by the *SXT* instrument team¹⁴.

2.2.6 AstroSat/LAXPC

We utilize level-1 data of the *LAXPC* detectors in event analysis mode, available at the *AstroSat* public archive ISSDC¹⁵, to perform both timing and spectral analyses. The data are processed using the latest version of the analysis software `LaxpcSoft`,¹⁶ (Antia et al., 2017), available at the time of data reduction. The software generates level-2 data products from the level-1 data. For our analysis, we extract data from the top layer of the detectors and consider only single event data to ensure optimal signal quality. The background models corresponding to the dates nearest to the observations are used in the data extraction. Further, the instrument response files for the *LAXPC* detectors are generated following the procedures outlined in Antia et al. (2017). The software also generates the Good Time Intervals (GTIs), which exclude time intervals affected by Earth occultation and passages of the satellite through the South Atlantic Anomaly (SAA) region. For each orbit of observation, we consider the longest continuous exposure segment in our analysis. In general, we generate background subtracted light curves from the combined *LAXPC10* and *LAXPC20* data, with a time resolution selected based on the specific scientific objectives. Also, the

¹¹https://www.tifr.res.in/~astrosat_sxt/dataanalysis.html#level2merge

¹²<https://julialang.org/>

¹³http://www.iucaa.in/~astrosat/AstroSat_handbook.pdf.

¹⁴https://www.tifr.res.in/~astrosat_sxt/dataanalysis.html.

¹⁵https://astrobrowse.issdc.gov.in/astro_archive/archive/Home.jsp

¹⁶http://www.tifr.res.in/~astrosat_laxpc/LaxpcSoft.html

light curves are extracted across various energy bands using the appropriate *LAXPC* channel-to-energy conversion relation provided in the corresponding response files. It is important to note that the source spectra are extracted only from the *LAXPC20* detector, as its gain remains stable as compared to the other two detector units (Antia et al., 2021).

2.2.7 IXPE

For polarimetric study, we use the cleaned and calibrated level-2 event data obtained from all three detector units (DUs) of *IXPE* in 2 – 8 keV energy range. The data processing is carried out using the most recent version of the *IXPEOBSSIM* software package (v31.0.3; see Baldini et al. 2022), following the recommended procedures outlined in Kislat et al. 2015, Strohmayer 2017. The source photons are extracted from a circular region of 60'' radius centered on the source position, while background events are selected from an annular region with inner and outer radii of 180'' and 240'', respectively. The extraction of source and background events is performed using the *XPSELECT* tool of *IXPEOBSSIM*. Subsequently, we generate the required data products for model-independent polarization study and spectro-polarimetric analyses using the *XPBIN* tool with appropriate algorithms, including the *PCUBE*, *PHA1*, *PHA1Q*, and *PHA1U*. The latest instrument response files are incorporated in the modeling of Stokes spectra following the guidelines of the *IXPE* instrument team¹⁷. Additionally, light curves with a time binning of 2000 s are extracted from the event file of each DU using the *XSELECT* tool.

2.3 Analyzing the Data: Unveiling Key Insights

Following the reduction of raw observational data from various X-ray missions, the next critical step is to derive physical interpretations through systematic analysis and modeling of the data. In this context, imaging, timing, spectroscopy, and polarimetry are the most important and commonly used analysis techniques in X-ray astronomy. Each technique provides unique insights into different aspects of high energy astrophysical sources, such as their spatial features, temporal behavior, spectral properties and polarization characteristics. All these techniques will be frequently used in the subsequent chapters to interpret the X-ray data collected by different observatories. In this section, we discuss the fundamental concepts, statistical frameworks, and analysis methods associated with each technique.

2.3.1 Image Analysis

The analysis of X-ray images is essential for determining the source position on the detector plane and assessing the brightness of the target source. Typically, the cleaned and calibrated event file from a given observation is visualized using the *SAOImageDS9*¹⁸ software. Once the image is loaded, appropriate source and background regions must be defined to extract the corresponding science products, such as light curves and spectra. After selecting the regions, the event file is filtered accordingly, and the light

¹⁷<https://ixpeobssim.readthedocs.io/en/latest/>

¹⁸<https://sites.google.com/cfa.harvard.edu/saoimageds9>

curves and spectra are extracted for both source and background. In certain cases, especially when the source is exceptionally bright, the extracted image may suffer from *pile-up*, an instrumental effect that occurs when multiple photons are detected at the same or adjacent pixels within a single detector readout frame. This causes the detec-

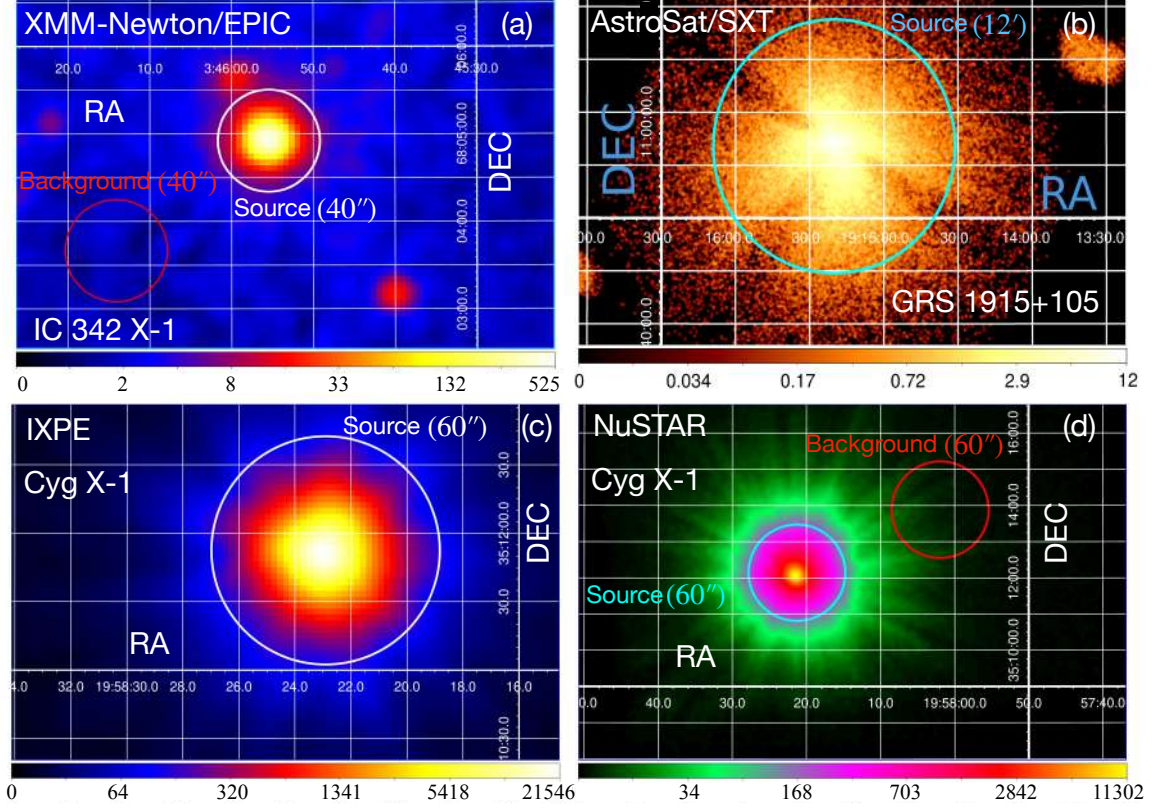


Figure 2.8: Panel (a): Image of the ULX source IC 342 X-1 obtained from the observations of *EPIC* camera onboard *XMM-Newton* mission in 0.3 – 10 keV energy band. Panel (b): Image of the BH-XRB source GRS 1915 + 105 as seen by *AstroSat/SXT* in 0.7 – 8 keV energy range. Panel (c) and (d): Images of the source Cyg X-1 from the *IXPE* and *NuSTAR* observations in the 2 – 8 keV and 3 – 79 keV energy ranges, respectively. In all panels, the circular regions indicate the selected source and/or background extraction regions of specified arcsec ($''$) or arcmin ($'$) radii as mentioned in the figure. Images for different cases are zoomed to different scales for clarity of representation. Images are generated for this thesis except panel (b), which is adopted from Majumder et al. (2022).

tor to misinterpret the combined charge as a single event, leading to erroneous energy and flux measurements. In general, pile-up significantly distorts the spectral properties of the source and must be corrected during the data extraction stage. It is important to note that the threshold for pile-up varies between instruments, depending on their design and readout configurations. For example, in the case of *AstroSat/SXT*, an image is considered to be affected by pile-up if the source count rate exceeds 40 counts s^{-1} within the central region¹⁹. To address this effect, events from the innermost region are generally excluded, and source products are extracted from an annular region surrounding the center. In our analysis, we extract light curves and spectra from the images of *XMM-Newton/EPIC*, *IXPE*, *AstroSat/SXT*, and *NuSTAR* observations for different sources as per the objectives of respective studies. The specific source and background region selections vary across different sources and are mentioned in the later chapters wherever applicable. Notably, none of the observations from various

¹⁹https://web.iucaa.in/~astrosat/AstroSat_handbook.pdf

instruments used in our analysis exhibit pile-up issues. In Fig. 2.8, we present representative X-ray images of different sources, including the ULX IC 342 X-1 observed with *XMM-Newton/EPIC* in 0.3 – 10 keV range, the BH-XRB GRS 1915 + 105 observed with *AstroSat/SXT* in 0.7 – 8 keV range, and Cyg X-1 observed with both *IXPE* (2 – 8 keV) and *NuSTAR* (3 – 79 keV), along with the selected source and background extraction regions.

2.3.2 Temporal Analysis

Lightcurve

Typically, BH-XRBs exhibit variability in photon counts observed in their X-ray light curves across a wide range of timescales, spanning from seconds to months or even years. These variability characteristics are broadly categorized as short-term and long term variabilities. Notably, such variations are intrinsically linked to the underlying accretion dynamics of the system. Empirically, X-ray variability is often quantified using the *fractional variability amplitude* (Vaughan et al., 2003), defined as,

$$F_{\text{var}} = \sqrt{\frac{S^2 - \sigma_{\text{err}}^2}{\bar{x}^2}}, \quad (2.1)$$

where $S^2 = \frac{\sum (x_k - \bar{x})^2}{N-1}$ represents the variance of the light curve, with x_k denoting the photon count in the k^{th} time bin and $\bar{x}$ the mean count rate. N is the number of time bins. Here, σ_{err}^2 is the mean squared error associated with the photon count measurements. In general, F_{var} , when computed for light curves with finer or coarser time binning, characterizes the short-term and long term variability properties of the source, respectively. In our study, F_{var} (expressed in percentage) is employed to systematically compare the variability characteristics of BH-XRBs in a given energy range across multiple observations.

Hardness Ratio

Another simple yet effective quantity frequently employed in X-ray timing studies is the hardness ratio (HR), which provides insights into the nature of the detected emission across distinct energy ranges. We define the hardness ratio as,

$$HR = \frac{C_h}{C_s}, \quad (2.2)$$

where C_h and C_s represent the photon counts in the hard and soft energy bands, respectively. It is important to note that there is no universally fixed criterion for selecting the energy ranges corresponding to soft and hard photons. Indeed, the choice usually depends on several factors, including the available energy coverage of the detectors, the effective area of detectors across different energies, and the reliability of the data within those energy bands for scientific analysis.

The X-ray colors, namely the soft color ($HR1$) and the hard color ($HR2$), is defined as,

$$HR1 = \frac{B}{A}, \quad HR2 = \frac{C}{A}, \quad (2.3)$$

where A , B , and C denote the photon counts in the lower, intermediate, and higher energy bands, respectively. As before, the choice of these energy bands solely depends

on the factors mentioned above. These color ratios are commonly used in constructing color-color diagrams and color-intensity diagrams, which associate the evolution of BH-XRBs across different spectral states. All these concepts are extensively used in the analyses presented in the subsequent chapters.

Power Density Spectrum

Despite offering a broad overview of source variability, light curve analysis alone often falls short in revealing the detailed nature of the underlying variability processes. For example, rapid X-ray variations on timescales of milliseconds can be masked by structured variabilities on much longer timescales, generally studied in the light curve. Therefore, to probe these intrinsic variability components more effectively, the study of power density spectrum (PDS) is employed. The PDS is derived from the Fourier transform of the observed time series and generally represents the decomposition of the light curve into sinusoidal components across a range of frequencies. Thus, it becomes possible to identify fast periodic and aperiodic variability features that are otherwise not evident in the time series. In the following, we present an overview of the techniques of PDS analysis, including the fundamental concepts on the representation of a light curve in Fourier space.

Let us consider a time series with N evenly spaced measurements x_k , sampled at discrete time instances over the interval $[0, T]$. For this, we write the Discrete Fourier Transform (DFT) of x_k and its inverse as,

$$a_j = \sum_{k=0}^{N-1} x_k e^{-2\pi i j k / N} \quad (j = -N/2, \dots, N/2 - 1) \quad (2.4)$$

$$x_k = \frac{1}{N} \sum_{j=-N/2}^{N/2-1} a_j e^{2\pi i j k / N} \quad (k = 0, \dots, N-1). \quad (2.5)$$

In general, computation of the above DFT requires $\sim N^2$ operations involving both multiplication and addition. While doing that, for each Fourier coefficient a_j , it is necessary to multiply each of the N samples, x_k , by a corresponding phase factor $e^{-2\pi i j k / N}$, and then sum the results. This makes the DFT computationally challenging for many instances. To resolve this issue, the Fast Fourier Transform (FFT) algorithm was developed to optimize the evaluation of DFT, reducing the computational complexity to only $\sim N \log_2 N$ operations. Consequently, FFT remains the most commonly used algorithm for computing the PDS in X-ray timing analyses. Furthermore, it is important to note that the discrete signal and its Fourier transform satisfy Parseval's theorem as,

$$\sum_{k=0}^{N-1} |x_k|^2 = \frac{1}{N} \sum_{j=-N/2}^{N/2-1} |a_j|^2, \quad (2.6)$$

which implies that the variance of the signal is equivalent to $1/N$ times the sum of the squared Fourier coefficients (van der Klis, 1989). Thus, the Fourier transform produces a PDS that is proportional to the squared amplitude of the signal in the frequency domain. Notably, several normalization schemes are commonly employed for the PDS analysis, among which the *Leahy normalization* (Leahy et al., 1983) and *rms normalization* (Belloni and Hasinger, 1990) are the most widely used in the context

of astrophysical applications. According to the *Leahy normalization*, the powers are normalized as,

$$P_j^{\text{Leahy}} = \frac{2}{N_{\text{ph}}} |a_j|^2, \quad (2.7)$$

where N_{ph} is the total number of detected photons. Generally, this normalization results in a well defined statistical behavior of the PDS. In particular, when the signal is primarily influenced by Poisson noise and N_{ph} is sufficiently large, the power at each frequency bin follows a chi-squared distribution with two degrees of freedom, yielding an expected power level of $\langle P \rangle = 2$. On the other hand, in the *rms normalization* scheme, the power values are normalized by the square of the mean source count rate as,

$$P_j^{\text{rms}} = \frac{2\Delta t}{N_{\text{ph}} \bar{x}^2} |a_j|^2, \quad (2.8)$$

and expressed in units of squared fractional rms variability (rms^2/Hz). Here, Δt denotes the time resolution and $\bar{x}$ corresponds to the mean source count rate. Notably, the time resolution of the light curve used for the PDS computation determines the Nyquist frequency, defined as

$$f_{\text{Nyq}} = \frac{1}{2\Delta t}, \quad (2.9)$$

which represents the maximum frequency detectable in the PDS. Following the aforementioned methodologies, we compute the PDS using the `powspec`²⁰ tool available in `HEASOFT`, employing different normalization schemes depending on the scientific objectives.

Further, it is important to note that various instrumental effects can influence the PDS. Among these, the most significant effect comes from the dead time of the detectors. Usually, dead time refers to the finite time interval after the detection of a photon during which the detector remains inactive. This leads to a variation in the Poisson noise power level and suppression of the true rms amplitude in the power spectrum. Therefore, it must be carefully accounted for, especially when examining PDS features such as high frequency QPOs, which typically emerge at higher frequencies superimposed on the underlying Poisson noise. Following Zhang et al. 1995, Yadav et al. 2016, Agrawal et al. 2018, Sreehari et al. 2019a, the corrected Poisson noise power is expressed as,

$$P_{\text{noise}}(f) = \frac{1}{r_{\text{obs}}^2} \left[2 + \frac{4\langle r_b \rangle}{r_t} \cdot \frac{-1 + \cos(2\pi f \tau_d) - 2\pi f \tau_d \sin(2\pi f \tau_d)}{2 + (2\pi f \tau_d)^2 - 2\cos(2\pi f \tau_d) + 2\pi f \tau_d \sin(2\pi f \tau_d)} \right], \quad (2.10)$$

where τ_d is the dead time of the detector, f is the frequency and r_{obs} denotes the count rate recorded in the specified energy band. r_t is the dead time corrected count rate computed as $r_t = r_{\text{to}}(1 - r_{\text{to}}\tau_d)$, where r_{to} is the total observed count rate. $\langle r_b \rangle$ refers to the mean count rate per detector unit after correcting for dead time, and is expressed as $\langle r_b \rangle = r_{\text{obs}}(1 + \tau_d N_{\text{det}})$ and $\tau = 1/r_t$. Here, N_{det} is the number of detector units. Finally, the dead time contributed Poisson noise power level is subtracted to get the PDS in rms space. Similarly, the dead time corrected rms amplitude of the resultant PDS is obtained following Sreehari et al. (2019a, 2020). We use customized codes in `python`, developed based on the above methodologies, for the computation of PDS while studying HFQPO phenomena.

²⁰<https://heasarc.gsfc.nasa.gov/docs/xanadu/xronos/examples/powspec.html>

Once the PDS is generated, it is often rebinned in the frequency domain to suppress statistical fluctuations and highlight prominent features. Two widely used rebinning methods include *constant rebinning*, where frequency bins have equal width, and *geometrical rebinning*, where bin widths increase logarithmically. The power values of the rebinned PDS are then plotted against frequency for visual representation and modeling. A combination of analytical functions is typically employed to describe the continuum of the PDS. These include **constant**, **powerlaw** and **Lorentzian** components, representing noise components along with broad and narrow features. The standard form of a Lorentzian used in this context is given by,

$$L_{\text{lor}}(f) = \frac{N_{\text{lor}}}{2\pi} \cdot \frac{\Delta_F}{(f - f_{\text{cen}})^2 + (\Delta_F/2)^2}, \quad (2.11)$$

where f_{cen} is the centroid frequency of the feature, Δ_F is its full width at half maximum (FWHM), and N_{lor} is the normalization. Depending on the complexity of the variability features, multiple **Lorentzian** profiles at distinct frequencies along with zero-centered **Lorentzian** functions are often required to model the entire broadband PDS. Out of this, sharp and coherent peaks in the PDS, known as QPOs, remain of particular interest. These are also modeled using **Lorentzian** functions and are characterized by the following three quantities:

- *Quality Factor (Q-fac)*: Represents the sharpness or coherence of the detected features and is defined as $Q\text{-fac} = f_{\text{cen}}/\Delta_F$. Typically, $Q\text{-fac} > 3$ signifies a coherent QPO feature (Casella et al., 2005, Sreehari et al., 2019a). For a significant QPO feature, the **Lorentzian** centroid frequency (f_{cen}) denotes the QPO frequency (ν_{QPO}).
- *Significance (σ_{QPO})*: Measures the statistical reliability of the detected feature, calculated as $\sigma_{\text{QPO}} = N_{\text{lor}}/\text{err}_{\text{neg}}$, where err_{neg} is the negative 1σ uncertainty on the normalization. Features with $\sigma_{\text{QPO}} > 3$ are generally considered statistically significant (Belloni and Altamirano, 2013, Sreehari et al., 2019a, 2020, Majumder et al., 2022).
- *Fractional rms amplitude*: Defined as the square root of the integrated power in a specific frequency range. It represents the strength of the variability. More specifically, for narrow QPO-like features, it quantifies the contribution of the oscillation to the overall variability. At the same time, for broader components, it characterizes the total rms variability across the broadband frequency range.

2.3.3 Spectral Analysis

Decoding X-ray Spectrum

The X-ray spectrum illustrates how the detected emission from a source varies with photon energy. In practice, X-ray detectors measure photon flux, denoted as $C(I)$, within discrete energy channels I , which are generally defined by the specific characteristics of the detector. However, this observed spectrum $C(I)$ does not reflect the true emission spectrum of the astrophysical object of interest. Empirically, the observed spectrum $C(I)$ is related to the intrinsic source spectrum $S(\epsilon)$ as,

$$C(I) = \int S(\epsilon) R(I, \epsilon) A(\epsilon) d\epsilon, \quad (2.12)$$

through convolution with the response function $R(I, \epsilon)$ and effective area $A(\epsilon)$ of the detector. Here, ϵ represents the energy of the detected photon. It may be noted that $A(\epsilon)$ characterizes the sensitivity of the instrument across different energies, while $R(I, \epsilon)$ represents the probability that a photon of true energy ϵ is detected in channel I .

The response function of a detector is typically represented as a two-dimensional matrix, where each row corresponds to a detector channel and each column corresponds to a discrete bin of photon energy that defines the source spectrum. This response function, or equivalently, the redistribution matrix of the detectors, generally demands special attention in the context of X-ray spectroscopy as it can introduce systematic uncertainties and distortions in the detected spectrum. More specifically, the diagonal elements of the matrix correspond to the capability of the detector to correctly assign the energy of incoming photons over the channels, reflecting the ideal detection scenario. In contrast, the off-diagonal elements represent energy redistribution effects, where photons are detected at incorrect energies due to several challenges that might be involved in the detection techniques of the instrument. Therefore, for a well-calibrated X-ray detector, a linear channel-energy relation is essential for the correct realization of the detected X-ray spectrum.

Spectral Modeling

In principle, the simplest way to recover the source spectrum $S(\epsilon)$ is by directly inverting Eq. 2.12. However, such inversion results in the source spectrum dominated by statistical noise, as demonstrated in several studies (Blissett and Cruise, 1979, Bouchet, 1995). Alternatively, the widely adopted technique for spectral modeling is considered to be the *forward-folding* approach. For this, a theoretical or empirical model, representing the emission of the source, is assumed. Then the model spectrum is convolved with the response function of the detector. More specifically, this technique yields predicted photon flux as it would have been measured by the detector. Thereafter, this predicted spectrum is statistically compared with the observed data using an appropriate likelihood function or fit statistics. During this, the model parameters are systematically adjusted in an iterative way to minimize the chosen statistics, allowing the fit to converge towards the most probable description of the observed spectrum. It is worth noting that a common approach is to assign a ‘guess value’ corresponding to the respective model parameters before fitting using iterative methods, based on the prior assumptions on the nature of the emission. One of the most commonly used statistics for evaluating the goodness of fit in spectral analysis is the chi-squared (χ^2) statistic, which is defined as

$$\chi^2 = \sum \frac{(C(I) - C_m(I))^2}{\sigma^2(I)}, \quad (2.13)$$

where $C_m(I)$ is the model predicted spectrum and $\sigma(I)$ is the uncertainty in the detected spectrum $C(I)$.

Further, to assess the quality of a spectral fit, a goodness-of-fit test is typically performed. In this approach, the reduced chi-squared value, defined as the model fitted χ^2 per degree of freedom ($\chi^2_{\text{red}} = \chi^2/\text{dof}$), is compared with the well accepted range of χ^2_{red} values that indicate the best fit. In general, a χ^2_{red} value significantly higher than or much smaller than unity indicates a poor fit. Furthermore, the credibility

of the model fitted parameters is evaluated from the associated confidence intervals. These intervals represent the range of parameter values over which the increase in chi-squared ($\Delta\chi^2$) from its best-fitted value remains within a specific limit, determined by the desired confidence level (Lampton et al., 1976). For example, at 68% ($\sim 1\sigma$) confidence level, the confidence interval of a model-fitted parameter value lies within the range for which $\Delta\chi^2 = 1$. Notably, other commonly used intervals in the X-ray spectral analysis include 90% ($\sim 1.7\sigma$) and 99% ($\sim 2.6\sigma$) confidence levels for which the acceptable range of $\Delta\chi^2$ varies accordingly. Needless to mention, if a fit fails to satisfy the acceptable χ^2_{red} , the assumed model is identified to be inadequate to delineate the observed spectrum.

Software for Spectral Modeling

There exists a variety of software tools that have been developed for spectral analysis. These programs typically deal with spectral and instrumental response files and offer diverse types of built-in spectral models along with tools for statistical analysis and data visualization. One of the most widely used tools for spectral analysis is XSPEC²¹ (Arnaud, 1996). Inside the XSPEC user interface, the source and background spectral files, along with appropriate response and ancillary files generated from different instruments, are read and modeled using different model combinations. Based on reliable statistical techniques, such as chi-square minimization (see above), different models are generally tested against a given set of observed spectral data.

In general, XSPEC classifies model components into distinct categories, including additive, multiplicative and convolution models. Among these, additive components typically describe emission processes, such as blackbody radiation, power-law, or line emissions in the spectra. In contrast, multiplicative components modify the continuum emission in an energy dependent manner. This includes the photoelectric absorption, high energy cutoffs, or Gaussian shaped absorption features. Unlike these components, convolution models operate by applying more intricate transformations to the entire model spectrum through the use of convolution operators. All of these models can be implemented either through built-in functions or as external table models. In general, these table models represent precomputed spectral grids generated over a range of model parameter values.

Spectral Models in XSPEC

In the following, we outline the fundamental aspects of several phenomenological and physical models that are employed in the spectral modeling of BH-XRBs in subsequent chapters.

Absorption Models

- **Tbabs:** The interstellar medium (ISM) absorption model is often employed to account for the attenuation of X-rays as they pass through the. This model incorporates contributions from various components of the ISM, including gas, dust grains, and molecular clouds, by computing their respective photoelectric absorption cross-sections. User specified customization of the model is possible

²¹<https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/>

by specifying the elemental abundances present in the ISM. In the absence of user-defined values, the model defaults to the Galactic abundances provided by [Wilms et al. \(2000\)](#). The primary free parameter of this model is the hydrogen column density (n_H) along the line of sight, which is expressed in units of 10^{22} atoms cm^{-2} .

- **pcfabs**: The partial covering absorption model accounts for scenarios where only a fraction of the X-ray source is obscured by intervening material. The relative elemental abundances in this model are controlled via the **abund** command in the **XSPEC** environment. The model can be expressed mathematically as,

$$M(\epsilon) = f_{\text{pcfabs}} e^{-n_H \sigma(\epsilon)} + (1 - f_{\text{pcfabs}}), \quad (2.14)$$

where $\sigma(\epsilon)$ is the photoelectric absorption cross-section excluding Thomson scattering, n_H represents the equivalent hydrogen column density (in units of 10^{22} atoms cm^{-2}), and f_{pcfabs} is the dimensionless covering fraction parameter in the range $0 < f_{\text{pcfabs}} < 1$. This model is utilized to describe the attenuation of radiation from the accretion disc due to the presence of absorbing material along the line of sight. The obscuration can arise from outflowing winds, cooler matter located in the outer parts of the disc, or periodic eclipses caused by the companion star in the binary system.

- **smedge**: The model **smedge** ([Ross et al., 1996](#)) is a multiplicative component used to represent the effects of a smeared absorption edge, typically arising from reflection off an ionized accretion disc. It approximates the photoelectric absorption edge with a broadening, accounting for relativistic smearing and Compton scattering. The functional form $M^{\text{smedge}}(\epsilon)$ of the **smedge** model is defined as,

$$M^{\text{smedge}}(\epsilon) = \begin{cases} 1, & \epsilon < \epsilon_c \\ \exp \left[-f \left(\frac{\epsilon}{\epsilon_c} \right)^\alpha \right] \left[1 - \exp \left(-\frac{\epsilon_c - \epsilon}{W} \right) \right], & \epsilon \geq \epsilon_c \end{cases} \quad (2.15)$$

where ϵ_c is the threshold energy of the absorption edge, f is the maximum absorption factor at threshold, and α is the index for photo-electric cross-section (typically fixed at 2.67). This model is particularly useful in describing broad absorption-like features seen in the 7–9 keV energy range, often associated with iron K-edge absorption in ionized material.

- **edge**: The **edge** model is a multiplicative component used to model a photoelectric absorption edge. It modifies the continuum as follows:

$$M^{\text{edge}}(\epsilon) = \begin{cases} 1, & \epsilon \leq \epsilon_c \\ \exp \left[-D_e \left(\frac{\epsilon}{\epsilon_c} \right)^{-3} \right], & \epsilon \geq \epsilon_c \end{cases} \quad (2.16)$$

where ϵ_c is the edge energy and D_e is the absorption depth at the threshold energy.

Accretion Disc Models

To model the spectral features of the thermal accretion disc around black hole systems, several models have been developed based on either pseudo-relativistic or fully relativistic treatments. These are generally implemented as additive components within the overall spectral models. Below, we discuss some of the key aspects of these models.

- **diskbb**: This model represents the thermal emission from an accretion disc. Since the temperature within the disc is not uniform but varies with radius r , this model approximates the emission as a multicolor blackbody spectrum, with the radial temperature profile following $T(r) \propto r^{-3/4}$ (Mitsuda et al., 1984, Makishima et al., 1986). It is characterized by two key parameters: the temperature at the inner edge of the disc, T_{in} , expressed in keV, and a normalization factor defined as $(R_{\text{in}}/D_{10})^2 \cos \theta_{\text{inc}}$. Here, R_{in} is the apparent inner disc radius in kilometers, D_{10} is the source distance in units of 10 kpc, and θ_{inc} denotes the inclination angle of the disc. It is important to note that the value of R_{in} derived from this model corresponds to an apparent radius, which must be corrected to obtain the physical inner disc radius. According to Kubota et al. (1998), the corrected radius is given by,

$$r_{\text{in}} = \xi f_{\text{h}}^2 R_{\text{in}}, \quad (2.17)$$

where f_{h} is the color correction factor or spectral hardening factor typically in the range of $1.7 - 2$ (Shimura and Takahara, 1995), and $\xi \approx 0.412$ is a geometric correction factor that accounts for the zero torque inner boundary condition of the disc (Kubota et al., 1998).

- **kerrbb**: This is an advanced relativistic model that simulates the thermal emission from geometrically thin, optically thick accretion discs around rotating black holes. The model incorporates key general relativistic effects arising in the strong gravity regime, including gravitational redshift, Doppler boosting, frame-dragging, and light bending, as outlined in the relativistic disc framework developed by Novikov and Thorne (1973). The implementation of these effects is based on the detailed calculations by Li et al. (2005), making the model particularly ideal for studying the continuum emission of BH-XRBs. The model offers constraints on several physical and geometric parameters such as the torque at the inner disc boundary (ζ), dimensionless spin parameter (a_*), disc inclination angle (θ_{inc} in degrees), black hole mass (M_{BH} in $M_{\odot}$), mass accretion rate ($\dot{m}$ in units of 10^{18} g s^{-1}), and the source distance (D in kpc). In addition, it includes the spectral hardening factor (f_{h}) in the computation, which accounts for the deviation between color and effective temperatures due to electron scattering in the disc atmosphere. The model also includes flags to control physical effects: a self-irradiation switch (**rflag**), which determines whether returning radiation is included, and a limb-darkening switch (**lflag**) that toggles limb-darkening effects in the emergent spectrum. A normalization parameter is also present, though it is typically fixed or set to unity when used in combination with known source distances and system parameters.
- **diskpbb**: This is an extension of the standard **diskbb** model, allowing a variable radial temperature profile. In particular, the local effective temperature of the disc is assumed to follow the relation $T(r) \propto r^{-p}$, where the exponent p is

a free parameter rather than being fixed (Mineshige et al., 1994, Kubota and Makishima, 2004). Notably, when $p = 0.75$, the conventional `diskbb` model is recovered, which assumes a geometrically thin, optically thick disc. However, deviations from this, specifically $p < 0.75$, suggest a departure from the standard thin disc approximation, indicating the influence of advection-dominated processes. Typically, these scenarios are expected in the high accretion rate regimes, often approaching or exceeding the Eddington limit, where a significant fraction of the viscously generated heat is advected inward rather than being radiated locally. The model is defined by two parameters: the inner disc temperature and normalization, both expressed in units similar to the case of `diskbb` model.

- **slimbh**: This is a relativistic model describing the emission from an advection-dominated slim accretion disc around a stellar-mass black hole. It is particularly effective in constraining X-ray spectral properties in the high luminosity regime, with the disc luminosity exceeding $\sim 10\%$ of the Eddington limit. The model is constructed based on the solutions of slim discs presented in Sadowski (2011), coupled with vertical structure calculations performed using the TLUSTY code. The model incorporates several physical parameters including black hole mass (M_{BH} in $M_{\odot}$), spin (a_*), inclination angle (θ_{inc} in degrees), disc luminosity (L_{disc} in Eddington units), viscosity parameter (α_s), distance to the source (D in kpc) and the spectral hardening factor (f_h). The model also allows for the inclusion of limb-darkening effects, which can influence the observed spectra.

Phenomenological and Physical Models of Comptonization

In order to describe the high energy spectra of BH-XRBs, several phenomenological and physical models invoking thermal Comptonization have been proposed over the years. Unlike thermal disc models, Comptonization models can be of both additive and convolution types. We discuss some of these models, which we use in the spectral modeling in later chapters.

- **powerlaw**: This is the simplest phenomenological model to describe the spectra at higher energies, where the spectral distribution follows a power-law of the form, $S(\epsilon) = \text{norm} \epsilon^{-\Gamma_{\text{PL}}}$. It is commonly applied in phenomenological modeling to represent the Comptonized continuum. The model is characterized by two parameters: the photon index (Γ_{PL}) and the normalization factor (**norm**), which is given in units of photons/keV/cm²/s at 1 keV.
- **simpl**: **simpl** is an empirical Comptonization model, where a fraction of the photons from an input seed spectrum are scattered into a power-law component (Steiner et al., 2009). More specifically, it uses the soft thermal spectra that have a photon index $\Gamma_{\text{simpl}} > 1$. It offers similar fit results as like the **powerlaw** model with two parameters: **par1**, representing the photon index Γ_{simpl} , and **par2**, which denotes the scattered fraction (f_{scatt}) of seed photons (ranging from 0 to 1). Additionally, **par3** remains as a flag denoting the type of scattering, with positive values specifying up-scattering, and negative values allowing both up- and down-scattering.
- **nthcomp**:

nthcomp is a physically motivated thermal Comptonization model that describes the continuum emission arising from the interaction between soft seed photons and a hot electron cloud (Zdziarski et al., 1996, Życki et al., 1999). Despite its relatively simple set of parameters, the model effectively reproduces key spectral characteristics, particularly those observed in the X-ray spectra at higher energies. The high energy spectral cutoff in **nthcomp** is determined by the electron temperature ($k_B T_e$) of the Comptonizing medium, providing a more accurate representation of the rollover compared to a traditional exponentially cut-off power law. An important feature of **nthcomp**, especially relevant for modeling the spectra of X-ray binaries, is its treatment of the low energy rollover. In the Comptonization process, the seed photons originating from thermal emission are upscattered by hot electrons, leading to a suppression of flux at energies lower than the seed photon temperature. Generally, the thermal emission is characterized by blackbody or multicolor disc blackbody like components. This low energy suppression distinguishes **nthcomp** from simpler power-law models. The model offers flexibility in specifying the nature of the seed photons through an input parameter (**inp_type**) that allows selection between a single-temperature blackbody (commonly associated with emission from a neutron star boundary layer) or a multicolor disc blackbody (suitable for accretion disc in X-ray binaries). The seed photon temperature is described by $k_B T_{bb}$, another parameter of the model. The emergent spectral shape between the low and high energy turnovers is primarily governed by the electron temperature ($k_B T_e$) and the optical depth of the scattering region. Note that, although the resulting spectrum is not strictly a power-law, it can be approximated by an asymptotic power-law photon index (Γ_{nth}).

- **thcomp**: It is an improved thermal Comptonization model, essentially an upgraded version of the **nthcomp** model. Detailed comparative studies with Monte Carlo simulations (Zdziarski et al., 2020) have shown that **thcomp** can reproduce Comptonized spectra with improved accuracy than **nthcomp** in several instances (Niedźwiecki et al., 2019). Based on a spherical geometry for the Comptonizing region with a sinusoidal spatial distribution of seed photons, **thcomp** is implemented as a convolution model. It enables Comptonization of any input spectrum, whether soft or hard, and accurately captures both upscattering and downscattering processes. The model employs a simple set of physical parameters, including the photon index (Γ_{th}), electron temperature ($k_B T_e$), and covering fraction (cov_{frac}). The cov_{frac} parameter is particularly important as it quantifies the fraction of seed photons that are Comptonized. It ranges from 0 (no Comptonization) to 1 (all seed photons are Comptonized). Unlike standard additive models, **thcomp** does not include a free normalization parameter; instead, its normalization is directly connected to the seed photon distribution.

Models for Reflection Features

The primary Comptonized emission from the corona can be reflected off the accretion disc, giving rise to the reflection features commonly observed in BH-XRB spectra. In principle, since this emission originates close to the black hole, it is subject to various general relativistic effects. In the following, we discuss some of the reflection models that incorporate the major general relativistic effects relevant in this context.

Notably, these reflection models are additive in nature and will be employed in our spectral analysis.

- **relxill/relxillCp/relxillp**: The models of the **relxill** family (Dauser et al., 2010, García and Kallman, 2010, Dauser et al., 2013, 2016, 2022, García et al., 2022) are widely used spectral components designed to simulate the relativistically blurred reflection spectrum that arises when primary high energy X-ray emission from the corona irradiates an accretion disc. It integrates two key components: **xillver**, which models the reflection from ionized material, and **relline**, a convolution kernel that accounts for relativistic effects near the black holes. By combining these elements, **relxill** provides a self-consistent description of both reflected emission and the intrinsic primary continuum of the spectrum. It is important to note that different implementations of the **relxill** model are primarily distinguished by their assumptions on the geometry of the corona and the resulting emissivity profile, as well as the spectral shape of the primary emission. A standard geometry independent approach treats the emissivity as a broken power-law function and considers the primary spectrum to be described by a **cutoffpl** profile. Alternatively, a **lamppost** geometry, in which the corona is modeled as a point source located on the rotational axis above the black hole, is considered to calculate the emissivity profile in the **relxillp** component. Notably, **relxillCp** uses the **nthcomp** component (Zdziarski et al., 1996) to represent the primary coronal spectrum. These reflection models typically provide a set of parameters, including intrinsic source properties such as the binary inclination and black hole spin. Therefore, reflection spectroscopy serves as a powerful diagnostic tool for probing the spin of astrophysical black holes. In addition, a key parameter is the reflection fraction (R_f), which quantifies the amount of the total emission that is reprocessed by the accretion disc and reflected, relative to the part that reaches the observer directly as the primary continuum. For a comprehensive description of the model parameters corresponding to various reflection flavors, readers are referred to the **relxill** model documentation²² and the papers mentioned above.

2.3.4 Polarimetric Analysis

In this section, we present an overview of the fundamental methodologies commonly employed in the measurement of X-ray polarization. The detection of polarized X-ray photons primarily relies on two distinct techniques: photoelectron tracking, utilized in polarimeters based on the photoelectric effect, and X-ray scattering, as implemented in scattering based polarimeters. This section places particular emphasis on the methodologies used in photoelectric effect based polarimeters (see Fig. 2.9), which are one of the central relevance to our analysis in subsequent chapters. Photoelectric polarimeters determine the polarization properties of X-ray photons by employing the principles of the photoelectric effect. Upon absorption of an X-ray photon, a photoelectron is ejected from the detector surface, and the direction of this electron is tracked in the detector plane. This directional information, especially the azimuthal angle of the photoelectron, carries the polarization signatures of the incident X-ray.

Note that, according to the convention set by IAU²³ (Contopoulos and Jappel,

²²<https://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/>

²³<https://aas.org/posts/news/2015/12/iau-calls-consistency-use-polarization-angle>

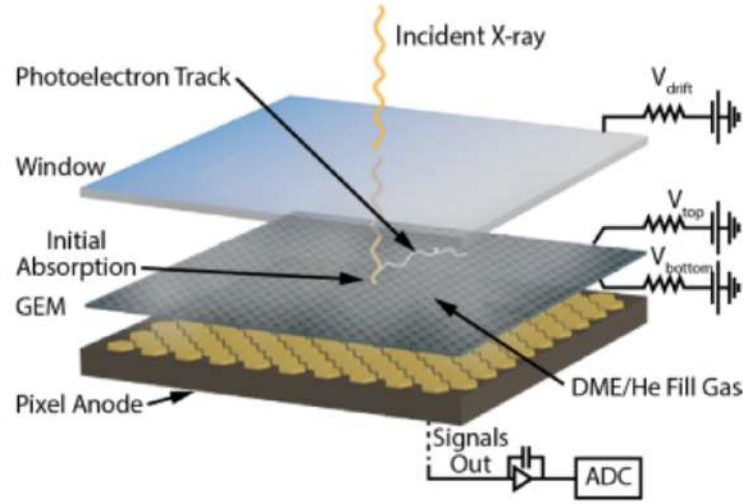


Figure 2.9: Schematic representation of the working principle of a typical photoelectron tracking based X-ray polarimeter. Credit: Di Marco et al. (2022).

1974), a reference frame is established on the plane of the sky, in which the x -axis is aligned towards local north, while the y -axis points to the local east. The polarization angle is then defined as the azimuthal angle measured counter-clockwise from the x -axis when viewed from the observer's line of sight, equivalently the direction of wave propagation. Therefore, completing a right-handed system, the z -axis extends from the astrophysical source towards the observer. By standard convention, the local north direction corresponds to a polarization angle of $\psi = 0$, while the east direction corresponds to $\psi = \pi/2$, where ψ denotes the polarization angle.

In principle, polarimetric analysis can be carried out using either model-independent or model-dependent methodologies, as outlined below.

Model-independent Approach: Polarimetry

In this approach, the analysis is performed without any prior assumptions about the emission mechanism of the source of interest. The following discussion on the model-independent polarimetry is based on Kislat et al. (2015), to which readers are referred for a more detailed treatment. We consider a dataset comprising N_0 measured angles, denoted as ϕ_k for $k = 1, \dots, N_0$. Each angle ϕ_k is associated with the most probable azimuthal orientation ψ_k of the incident electric field vectors. Note that, in the case of photoelectric effect polarimeters, $\psi_k = \phi_k$. Usually, these measured angles follow a sinusoidal modulation with a period of 180° (Weisskopf et al., 2006, Krawczynski et al., 2011), described by,

$$f(\psi) = \frac{1}{2\pi} (1 + p_0 \mu \cos(2(\psi - \psi_0))), \quad (2.18)$$

where p_0 represents the intrinsic polarization fraction and ψ_0 indicates the orientation at which the distribution of ψ reaches its extremum. The parameter μ is the modulation factor, which is determined by the specific characteristics of the polarimeter. Generally, it quantifies the strength of the azimuthal modulation observed for a completely polarized beam (*i.e.*, when $p_0 = 1$), and therefore satisfies the condition $0 \leq \mu \leq 1$.

We recall that the polarization characteristics of an electromagnetic wave can be represented using the set of Stokes parameters. These parameters offer a complete and convenient mathematical framework to describe both intensity and the state of polarization. An important advantage of using Stokes parameters lies in their additive nature. This allows for the straightforward addition of the measurements across multiple events. Additionally, the distribution of Stokes parameters is frequently well-approximated by a normal distribution (Kislat et al., 2015), which simplifies the statistical analysis when working with these parameters.

Thus, while analyzing linear polarization properties, one can construct the following set of Stokes parameters (Chandrasekhar, 1960, Rybicki and Lightman, 1979) for every detected event as,

$$i_k = 1, \quad q_k = \cos 2\psi_k, \quad u_k = \sin 2\psi_k. \quad (2.19)$$

Furthermore, due to their additive nature, the Stokes parameters for each event can be summed to obtain the total contribution for such N_0 events, given by,

$$I = \sum_{k=1}^{N_0} i_k = N_0, \quad Q = \sum_{k=1}^{N_0} q_k, \quad U = \sum_{k=1}^{N_0} u_k. \quad (2.20)$$

For convenience, the above Stokes parameters are usually normalized with the intensity as,

$$\mathcal{Q} = Q/I, \quad \mathcal{U} = U/I. \quad (2.21)$$

Given the sinusoidal modulation of ψ angles (see Eq. 2.18), we can calculate the expectation values of the normalized Stokes parameters as

$$\langle \mathcal{Q} \rangle = \int_0^{2\pi} \cos(2\psi) f(\psi) d\psi = \frac{1}{2} p_0 \mu \cos(2\psi_0), \quad (2.22)$$

$$\langle \mathcal{U} \rangle = \int_0^{2\pi} \sin(2\psi) f(\psi) d\psi = \frac{1}{2} p_0 \mu \sin(2\psi_0). \quad (2.23)$$

From Eq. 2.22 and Eq. 2.23, we obtain

$$\langle \mathcal{Q} \rangle^2 + \langle \mathcal{U} \rangle^2 = \frac{p_0^2 \mu^2}{4}, \quad (2.24)$$

$$\frac{\langle \mathcal{U} \rangle}{\langle \mathcal{Q} \rangle} = \tan 2\psi_0. \quad (2.25)$$

Thus, the reconstructed polarization fraction p_r and polarization angle ψ_r can be determined from the Stokes parameter $\mathcal{Q}$ and $\mathcal{U}$ as

$$p_r = \frac{2}{\mu} \sqrt{\mathcal{Q}^2 + \mathcal{U}^2}, \quad (2.26)$$

$$\psi_r = \frac{1}{2} \arctan \frac{\mathcal{U}}{\mathcal{Q}}. \quad (2.27)$$

We note that Eq. 2.26 and 2.27 serve as the most accurate estimates of the true polarization fraction (p_0) and polarization angle (ψ_0) based on the observed $\mathcal{Q}$ and $\mathcal{U}$. However, several important considerations should be taken into account in this context. The factor $2/\mu$ in Eq. 2.26 arises because the measured Stokes parameters are affected

by the modulation factor of the detectors. Moreover, the sinusoidal modulation of the measured azimuthal angles (see Eq. 2.18), which peaks at ψ_0 , reduces the expected value of the derived Stokes parameters (see Eq. 2.22 and 2.23) by a factor of $1/2$ compared to the intrinsic Stokes parameters.

Another crucial aspect of polarimetric measurements is to assess the significance of the measured polarization fraction in Eq. 2.26. To understand this, we first note that under the null hypothesis of zero polarization, the Stokes parameters $\mathcal{Q}$ and $\mathcal{U}$ remain uncorrelated. Therefore, according to the central limit theorem, for sufficiently large detected events (N_0), both $\mathcal{Q}$ and $\mathcal{U}$ follow normal distributions with zero mean and standard deviation given by $\sigma = 1/\sqrt{2N_0}$. The corresponding probability function of a bivariate normal distribution can be written as,

$$f(\mathcal{Q}, \mathcal{U}) d\mathcal{Q} d\mathcal{U} = \frac{N_0}{\pi} e^{-N_0(\mathcal{Q}^2 + \mathcal{U}^2)} d\mathcal{Q} d\mathcal{U}. \quad (2.28)$$

Now, we recall that N_0 detected events yield a measured polarization fraction p_r . Accordingly, the probability P_c of observing a polarization fraction greater than p_r purely due to statistical fluctuations can be obtained by integrating Eq. 2.28 over the region where $\mathcal{Q}^2 + \mathcal{U}^2$ exceeds to p_r . This leads to

$$P_c = \exp\left(-\frac{N_0}{4}\mu^2 p_r^2\right). \quad (2.29)$$

Using this, we can calculate the minimum detectable polarization (MDP) at 99% confidence level. By fixing the polarization detection threshold at random chance $P_c = 1\%$, and solving for p_r in Eq. 2.29, we obtain

$$\text{MDP}_{99} \approx \frac{4.29}{\mu\sqrt{N_0}}. \quad (2.30)$$

This suggests that an observed polarization fraction (p_r) greater than MDP_{99} indicates a significant detection of non-zero polarization at a 99% confidence level. It is important to note that, for a given detector (with a fixed μ), the MDP_{99} level depends solely on the photon count events, N_0 . Therefore, to achieve a significant polarization detection and reduce the MDP_{99} level, a large number of photons are required, implying the need for long exposure observations.

The methodology of polarization measurements described above is implemented in the software `IXPEOBSSIMv31.0.3`²⁴ through the polarization cube (PCUBE) algorithm, which has been specifically developed for model-independent analysis of data from the *IXPE* mission (Baldini et al., 2022). We utilize `IXPEOBSSIMv31.0.3` in our model-independent polarimetric study presented in Chapter 5. It is worth mentioning that, according to the guidelines for presenting polarization results from the *IXPE* team²⁵, the Stokes parameters, polarization degree, and polarization angle are generally reported with their corresponding 1σ Gaussian uncertainties or standard deviation (σ). Following this, the significance of the polarization degree is generally estimated as p_r/σ . For energy-dependent polarization studies, it is often important to test the significance or variation of polarization parameters across different energy bins. In such cases, the polarization parameter measured over the full energy band (2 – 8 keV) is

²⁴<https://ixpeobssim.readthedocs.io/en/latest/>

²⁵https://ixpe.msfc.nasa.gov/for_scientists/documentation/IXPE_stats-Advice.pdf

typically treated as the null hypothesis. A χ^2 test is then used to estimate the confidence level at which the variation of the polarization parameter across energy bins becomes significant by rejecting the null hypothesis (Krawczynski et al., 2022, Majumder et al., 2024a). These statistical methods for X-ray polarization analysis are employed in Chapter 5.

Model-dependent Approach: Spectro-polarimetry

The methodology of model-dependent polarimetry is fundamentally based on the forward folding technique as described in §2.3.3. In the context of spectro-polarimetry, the observable space is extended by incorporating the position angle (ψ), which defines the orientation of the polarization vector of each detected photon as projected onto the sky. Next, we will explore how the integration of polarimetric information with conventional spectroscopy has led to the development of the widely used technique known as *spectro-polarimetry* in related studies. The following discussion will be based on the seminal work of Strohmayer (2017), to which the readers are referred for a more detailed technical discussion. In the framework of spectro-polarimetry, for any given energy channel I , the distribution of observed sky angles defined above, referred to as the modulation curve, can be expressed in a general form as,

$$O(\psi, I) = \int_{\psi'} \int_{\epsilon} H(\psi', \epsilon) X(\psi', \psi, \epsilon, I) d\psi' d\epsilon, \quad (2.31)$$

where $H(\psi', \epsilon)$ represents the intrinsic source spectral distribution, which denotes the number of source photons with energies between ϵ and $\epsilon + d\epsilon$, and polarization angles between ψ' and $\psi' + d\psi'$. The function $X(\psi', \psi, \epsilon, I)$ describes the instrument response, representing the probability of detecting a photon emitted with intrinsic energy ϵ and polarization angle ψ' in energy channel I and polarization angle ψ , assuming perfect (100%) polarization sensitivity along ψ . It may be noted that, for a well-calibrated polarimeter, the observed angular distribution of counts (ψ) in any given energy channel sharply peaks around the intrinsic polarization angle ψ' .

Further, to characterize the spectro-polarimetric properties, it is convenient to employ the Stokes parameter formalism as before. Thus, the intrinsic source spectrum $H(\epsilon, \psi')$ can be decomposed as,

$$H(\epsilon, \psi') = F(\epsilon) + W(\epsilon) + Z(\epsilon), \quad (2.32)$$

where $F(\epsilon)$ represents the total intensity spectrum, whereas $W(\epsilon)$ and $Z(\epsilon)$ describe the linear polarization characteristics. Using this, the modulation curve given in Eq. 2.31 can be expressed in terms of the Stokes spectra as,

$$I(I) = \int_{\epsilon} F(\epsilon) G(\epsilon) R(\epsilon, I) d\epsilon, \quad (2.33a)$$

$$U(I) = \int_{\epsilon} W(\epsilon) \mu(\epsilon) G(\epsilon) R(\epsilon, I) d\epsilon, \quad (2.33b)$$

$$Q(I) = \int_{\epsilon} Z(\epsilon) \mu(\epsilon) G(\epsilon) R(\epsilon, I) d\epsilon, \quad (2.33c)$$

where $G(\epsilon)$ characterizes the effective area of the detector, $R(\epsilon, I)$ is the energy redistribution matrix, and $\mu(\epsilon)$ is the energy dependent modulation factor, which represents the response of the detector to the polarized emission. Furthermore, the functions

$W(\epsilon)$ and $Z(\epsilon)$ can be expressed in terms of the intrinsic polarization properties of the source as,

$$W(\epsilon) = F(\epsilon) a(\epsilon) \sin 2\psi'_0(\epsilon), \quad (2.34a)$$

$$Z(\epsilon) = F(\epsilon) a(\epsilon) \cos 2\psi'_0(\epsilon), \quad (2.34b)$$

where $a(\epsilon)$ and $\psi'_0(\epsilon)$ denote the energy dependent intrinsic polarization fraction and position angle, respectively.

It is worth mentioning that, based on a prior model assumption for the source intensity and polarimetric information in Eq. 2.33, and using χ^2 statistics, we perform simultaneous spectro-polarimetric modeling, following a similar approach discussed in §2.3.3. Based on this, the polarization properties, namely the polarization degree and position angle, are estimated as the best-fitted model parameters. For this, the I , Q , and U Stokes spectra, along with the corresponding response files, are generated from the polarimetric data of *IXPE* for a given source using the software routine *IXPEOBSSIMv31.0.3*, which are then read into *XSPEC* for modeling. In general, the physical models commonly employed in spectral studies can also be used to fit the intensity Stokes spectra (Eq. 2.33a). In contrast, for polarimetric modeling, various forms of energy-dependency in $a(\epsilon)$ and $\psi'_0(\epsilon)$ are generally considered. Below, we present the details of some commonly used polarimetric models that will be incorporated into the spectro-polarimetric study in later chapters.

- **Polconst**: This is a simple multiplicative model for constant polarization. Depending on the nature of the Stokes spectrum (Q and/or U), the multiplication factors $A \cos 2\psi_{\text{rad}}$ and/or $A \sin 2\psi_{\text{rad}}$ are used in the model, where ψ_{rad} is the polarization angle expressed in radians. The model returns two parameters for polarization measurements: the polarization fraction (A) and the polarization angle (ψ in degrees).
- **Polpow**: This model describes the polarization properties with a power-law dependency on energy. The polarization fraction $A(\epsilon)$ and angle $\psi(\epsilon)$ as functions of energy are given by the following relations

$$A(\epsilon) = A_{\text{norm}} \times \epsilon^{-A_{\text{index}}}, \quad (2.35)$$

$$\psi(\epsilon) = \psi_{\text{norm}} \times \epsilon^{-\psi_{\text{index}}}. \quad (2.36)$$

The model parameters are defined as: A_{norm} is the polarization fraction normalized at 1 keV, A_{index} is the power-law index of polarization fraction, ψ_{norm} , the polarization angle normalized at 1 keV (in degrees) and ψ_{index} is the power-law index of polarization angle.

- **Pollin**: Unlike **Polpow**, the model **Pollin** describes the polarization properties with a linear dependence on energy. The polarization fraction and angle are given by the following expressions:

$$A(\epsilon) = A_1 + (\epsilon - 1) \times A_{\text{slope}}, \quad (2.37)$$

$$\psi(\epsilon) = \psi_1 + (\epsilon - 1) \times \psi_{\text{slope}}, \quad (2.38)$$

where model parameters are defined as: A_1 is the polarization fraction at 1 keV, A_{slope} is the slope of the polarization fraction, ψ_1 represents polarization angle at 1 keV (in degrees), ψ_{slope} denotes the slope of the polarization angle.

To conclude, this chapter presents a comprehensive overview of the X-ray observatories, data reduction procedures, and analysis techniques that form the methodological foundation of this thesis. These tools and frameworks are essential for extracting physical insights from high energy X-ray observational data. In the subsequent chapters, we use these methods to study accretion processes and emission geometry in black hole systems.



Exploring Spectro-temporal Variability Across Diverse Timescales in Galactic BH-XRBs

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BH-XRBs generally exhibit fast timing variabilities on different time scales across diverse spectral states. Therefore, in the study of timing variabilities of BH-XRBs, it becomes important to consider the various characteristic time scales that may arise from different physical processes within the system (Nowak et al., 1999a,b). These include, but are not limited to, the radial light crossing time, radial sound crossing time, free fall time, viscous time, and thermal diffusion time (Belloni, 2010). However, extracting these specific time scales directly from X-ray timing data often appears to be complex. Typically, BH-XRBs exhibit aperiodic broadband noise variability, with the total fractional *rms* sometimes reaching as high as 40 – 50%, particularly during their hard spectral states (Remillard and McClintock, 2006). When analyzed in the Fourier frequency domain, this variability is commonly decomposed into a set of broad Lorentzian components.

On the other hand, during the hard/intermediate states, BH-XRBs frequently display strong aperiodic variability in the form of narrow QPOs, each characterized by

a distinct frequency. These frequencies correspond to more deterministic variability time scales, potentially linked to specific physical processes in the accretion flow. Thus, QPOs are considered one of the most powerful tools to probe the accretion dynamics around black holes. Despite rigorous observational and theoretical efforts, the physical mechanisms responsible for QPOs remain an open question. Two main explanations have been proposed for their origin: a geometric origin involving processes such as Lense-Thirring precession of the inner accretion flow (Stella and Vietri, 1998, Ingram et al., 2009), and a physical origin related to intrinsic oscillations or instabilities in the accretion disc or corona (Tagger and Pellat, 1999, Molteni et al., 1996, Chakrabarti et al., 2008, Das et al., 2014a). However, the geometric model often faces challenges, including difficulties in explaining the continuous evolution of QPO frequencies and their close association with spectral state changes. This suggests that the accretion dynamics of BH-XRBs possibly play a crucial role in the generation of QPOs. In addition, the spectral dependence of QPO characteristics implies a potential association between these features and the physical processes governing the observed spectra. Keeping these persistent challenges into consideration, in this Chapter, we focus on the investigation of the spectro-temporal variability of BH-XRBs over various timescales and their intrinsic connection to the underlying emission mechanisms.

The content of this Chapter is based on Majumder et al. (2022), Nandi et al. (2024) and Majumder et al. (2025b).

3.1 Evolving Low-frequency QPOs of Swift J1727.8-1613 in Hard X-rays

In this work, we study the spectro-temporal variability properties of the transient BH-XRB source Swift J1727.8 – 1613 using archival *AstroSat* and *NICER* observations. While doing so, for the first time, we study the energy resolved LFQPOs in hard X-rays (~ 100 keV) during HIMS of Swift J1727.8 – 1613. Needless to mention that the large effective area of *AstroSat*/*LAXPC* makes it possible to study the variability of LFQPO at high energies. We also investigate the systematic evolution of LFQPO frequencies using *AstroSat* observations (augmented with *NICER* and *Swift* detections) during the remarkable outburst of the source in 2023. Furthermore, we perform a detailed investigation of the spectral distribution of the source in 0.6 – 40 keV energy range and examine its connection to the underlying physical mechanisms driving the observed LFQPO features.

3.1.1 Brief Description of the Source

Swift J1727.8–1613 is a new galactic transient detected on August 23, 2023, following a sharp rise in its X-ray flux, which peaked at ~ 7.6 Crab in the 15 – 50 keV energy range (Palmer and Parsotan, 2023). Follow-up multi-wavelength observations revealed the nature of the source to be typical of a black hole transient in X-rays (Nakajima et al., 2023, Draghis et al., 2023, Peng et al., 2024a), optical bands (Castro-Tirado et al., 2023, Wang et al., 2023), and radio frequencies (Miller-Jones et al., 2023). Recent measurements estimate the source distance as ~ 2.7 kpc, with a spin of ~ 0.98 and an inclination of $\sim 40^\circ$ (Mata Sánchez et al., 2024, Peng et al., 2024a). Further, Nandi et al. (2024) reported the detection of evolving type-C LFQPOs in hard X-rays (up

to ~ 100 keV) using *AstroSat* observations. LFQPOs are also detected in hard X-rays with *Insight-HXMT* observations (Yu et al., 2024, Chatterjee et al., 2024, Bollemeijer et al., 2025). Interestingly, *NICER* observations suggest a vertically elongated, jet-like corona based on the evolution of type-C QPOs (Liao et al., 2024). Veledina et al. (2023) reported the first significant detection of X-ray polarization for this source in the hard intermediate state (HIMS). Following this, Ingram et al. (2024) studied the evolution of X-ray polarization through different spectral states of the source during its outburst. Notably, a dramatic drop in the polarization degree is observed during the soft state of the source (Svoboda et al., 2024a). Interestingly, Wood et al. (2024) reported the largest resolved radio jet in Swift J1727.8 – 1613. Further, it has been found that the X-ray polarization angle, detected in the HIMS of the source, remains aligned along the radio jet of the source. This suggests the presence of X-ray corona in the equatorial plane (Ingram et al., 2024).

3.1.2 Outline of the Targeted Observations

AstroSat observed Swift J1727.8–1613 on 02 September, 2023 (MJD 60189) for the first time during a slew mode operation with an offset of ~ 0.9 degree from the pointing (RA = 261.13° , DEC = -16.01°) for 11 sec ($T_{\text{start}} = 14:18$ UT) exposure only. The source was further observed by *AstroSat* as a part of Target of Opportunity (ToO)¹ campaign during 08 September, 2023 (MJD 60195) to 14 September, 2023 (MJD 60201) for a total exposure of ~ 207 ksec. During slew mode, *LAXPC20* was operational, although it was switched off during ToO observations for safety reasons to avoid detector saturation due to very high source count rates. *LAXPC10* was operational in a low-gain mode for ToO observations. As *LAXPC10* operates at low gain mode, the channel to energy mapping remains uncertain. Hence, we obtain energy-channel relation using the 60 keV calibration peak in the veto anode A8 (Antia et al., 2017) and a feature in background spectrum (observed before ToO observation) around 30 keV. These peaks were attributed around channels 70 and 35, respectively, in 1024 channel space of *LAXPC10*, suggesting an approximately linear response. Employing this scaling, we estimate the low energy threshold to be around 20 keV. With this, we adopt a linear relation to obtain an energy-resolved light curve. Lighcurves are generated using single event, all layers data of *LAXPC10* (Sreehari et al., 2020, Katoch et al., 2021). In this work, *LAXPC10* data are employed for temporal analysis, while *LAXPC20* data are used for spectral analysis, when available.

Swift J1727.8 – 1613 is also observed with *NICER* almost on a daily basis since its discovery. In this work, we analyze the *NICER* observations on 2th, 8th, and 13th September, 2023 quasi-simultaneous with *AstroSat* observations. Two more observations on 25th August and 2nd October, 2023 in different phases of the outburst are also analysed.

The analyses of *AstroSat* and *NICER* data are performed following the techniques discussed in Chapter 2.

3.1.3 Luminous Outburst of Swift J1727.8-1613

We study the outburst profile of Swift J1727.8–1613 using data from multiple instruments (*MAXI*, *BAT*, *VLITE*) in different energy bands. Since its detection on 24th

¹https://astrobrowse.issdc.gov.in/astro_archive/archive/Home.jsp

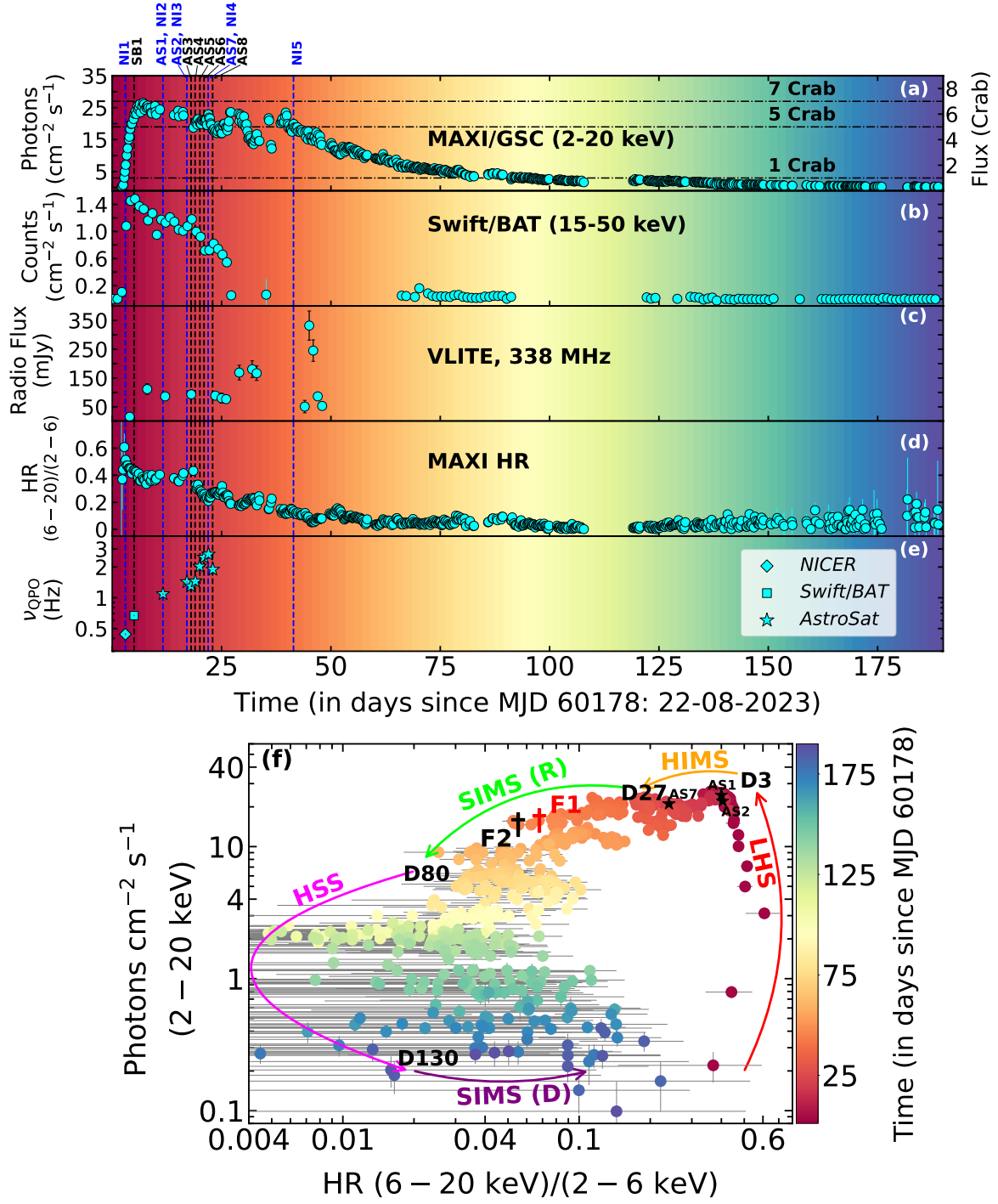


Figure 3.1: Long term monitoring of Swift J1727.8–1613 with multiple instruments in different energy bands. In panel (a) and (b), variation of *MAXI/GSC* and *Swift/BAT* count rates in 2 – 20 keV and 15 – 50 keV energy ranges are shown. Panel (c) represents radio flux with *VLITE* at 338 MHz. Variation of hardness ratio obtained from *MAXI/GSC* is plotted in panel (d). Evolution of ν_{QPO} in Swift J1727.8–1613 detected from different instruments is shown in panel (e). Hardness intensity diagram obtained from *MAXI/GSC* observations in 2 – 20 keV energy band is shown in panel (f). Colorbar indicates day number since source discovery.

August 2023, the source seems to exhibit a canonical outburst profile with a sudden rise from quiescence followed by a slow decay. In Fig. 3.1a-c, we present the results obtained from (a) 0.2 day averaged monitoring with *MAXI/GSC* (2 – 20 keV), (b) 1 day binned light curve from *Swift/BAT* (15 – 50 keV), and (c) radio detections using *VLITE* (at 338 MHz), respectively. During the initial phase of the outburst (~ 27 days), the source is observed with ‘compact’ radio emission of flux ~ 80 mJy. However, a significant increase of radio emission ~ 150 mJy is observed during the transition from HIMS to SIMS, which is followed by a strong radio flare with flux ~ 350 mJy after ~ 15 days (Peters et al., 2023). In panel (d), we depict the variation of hardness ratio (HR) defined as the ratio of photon counts in 6 – 20 keV to 2 – 6 keV energy bands of *MAXI/GSC*. We show the evolution of detected type-C QPO frequency (ν_{QPO}) during the onset phase of outburst observed with *NICER*, *Swift* and *AstroSat* in panel (e).

In Fig. 3.1f, we present the hardness intensity diagram (HID) obtained from the *MAXI/GSC* monitoring, where the variation of intensity (photons $\text{cm}^{-2} \text{s}^{-1}$) in 2 – 20 keV energy range is plotted with HR . The obtained results are plotted using color-coded filled circles, where the colorbar indicates the day number since the discovery of the source (see also panels Fig. 3.1a-d). As the outburst progresses, the source traces different spectral states, namely LHS with $HR \sim 0.6 - 0.47$ (D0-D3), HIMS with $HR \sim 0.47 - 0.19$ (D3-D27), SIMS(R) with $HR \sim 0.19 - 0.02$ (D27-D80), a long-lived HSS with $HR \lesssim 0.02$ (D80-D130), respectively. The source probably evolved through the decay phase of SIMS (from D130) with $HR \gtrsim 0.02$ and flux level ~ 70 mCrab during the outburst. Note that the observed radio detection, which is strongly correlated with the spectral states, further confirms the transition from HIMS to SIMS ($\sim$ D27) of the source along with a strong radio flare detected during SIMS.

3.1.4 Detection of LFQPOs in Hard X-rays

We examine the power density spectra (PDS) using the archival *LAXPC10* data during the outburst phase (see Fig. 3.1a-b). While doing so, 0.01 s time binned lightcurves in 20–100 keV energy range are used to generate PDS up to the Nyquist frequency (50 Hz) using ftool *powspec*² within *HEASOFT* V6.32.1³. We choose 4096 newbins per interval, which results in 2048 frequency points in the unbinned PDS. These 2048 frequency points are further geometrically rebinned with a factor of 1.03 to obtain the resultant PDS with 140 frequency bins in units of rms^2/Hz (Sreehari et al., 2019a). Accordingly, each frequency bin contains ~ 15 data points, which are averaged out. Because of this, the underlying likelihood function tends to follow a Gaussian distribution (van der Klis, 1989a, Vaughan, 2010) in accordance with the central limit theorem, and therefore, the chi-square statistics remain valid for PDS modeling (Papadakis and Lawrence, 1993).

Each PDS is modeled with a combination of multiple Lorentzian (van der Klis, 1994a,b, Nowak, 2000, Belloni et al., 2002, Belloni et al., 2005, Kushwaha et al., 2021) and a powerlaw component within *XSPEC* environment. In Fig. 3.2, we present the various model components to describe the PDS continuum and QPO features of Epoch AS2 (MJD 60195) in 20 – 100 keV energy range. While doing so, we use two zero-centred Lorentzian (ZCL; dot-dashed in grey), two bump-like features (BLF; dashed in blue) at ~ 0.2 Hz and ~ 4 Hz and one powerlaw component (PL; dotted in cyan) to

²<https://heasarc.gsfc.nasa.gov/xanadu/xronos/examples/powspec.html>

³https://heasarc.gsfc.nasa.gov/lheasoft/release_notes.html

Table 3.1: All the model parameters obtained from the best fitted PDS of Epoch AS2 (MJD 60195) in different energy bands. Here, Γ_{PL} , $norm_{\text{PL}}$ and L_{tor}^i ($i = 1, 2, 3, 4, 5, 6, 7, 8, 9$) represent the powerlaw index, normalization and Lorentzian components used in the fitting, respectively. f_{cen} , ΔF and N_{tor} are the Lorentzian centroid frequency, FWHM and normalization, respectively. A constant component (instead of powerlaw) is used for the modeling of 60 – 80 keV and 80 – 100 keV energy band PDS. $\Delta\chi^2_{\text{dof}}$ represents the improvement in χ^2 per degrees of freedom due to the inclusion of respective model components. Parameters in bold font indicate the fundamental QPO components. See the text for details.

Energy (keV)	Γ_{PL}	PL <i>norm</i> _{PL} ($\times 10^{-4}$)	ZCL		BLF		QPO (Additional)			LFQPO (Harmonic)			LFQPO (Fundamental)			$\chi^2/\text{d.o.f}$
			L^1_{tor}	L^2_{tor}	L^3_{tor}	L^4_{tor}	L^5_{tor}	L^6_{tor}	L^7_{tor}	L^8_{tor}	L^9_{tor}					
20 – 100 0.46 $^{+0.08}_{-0.09}$	–	5.05 $^{+1.02}_{-0.89}$	$\Delta\chi^2_{\text{dof}}$	30	18	62	4	46	41	18	12	103	131/117			
			f_{cen}	0.0	0.0	3.94 $^{+0.13}_{-0.15}$	0.19 $^{+0.04}_{-0.05}$	19.46 $^{+0.02}_{-0.06}$	2.76 $^{+0.02}_{-0.02}$	1.27 $^{+0.01}_{-0.01}$	1.34 $^{+0.01}_{-0.01}$	1.43 $^{+0.02}_{-0.02}$				
			ΔF	2.88 $^{+0.37}_{-0.38}$	0.30 $^{+0.05}_{-0.05}$	3.05 $^{+0.31}_{-0.30}$	0.2 †	0.1 †	0.69 $^{+0.09}_{-0.09}$	0.1 †	0.06 †	0.20 $^{+0.03}_{-0.01}$				
			N_{tor}	0.015 $^{+0.002}_{-0.002}$	0.007 $^{+0.001}_{-0.001}$	0.0027 $^{+0.0005}_{-0.0004}$	0.0009 $^{+0.0004}_{-0.0003}$	0.00013 $^{+0.00001}_{-0.00001}$	0.0012 $^{+0.0002}_{-0.0002}$	0.0019 $^{+0.0003}_{-0.0003}$	0.0027 $^{+0.0006}_{-0.0006}$	0.00915 $^{+0.00071}_{-0.00169}$				
20 – 40 0.31 $^{+0.04}_{-0.05}$	–	5.00 $^{+0.85}_{-0.75}$	$\Delta\chi^2_{\text{dof}}$	54	56	42	3	29	41	43	20	158	128/116			
			f_{cen}	0.0	0.0	3.94 $^{+0.13}_{-0.15}$	0.22 $^{+0.02}_{-0.02}$	19.28 $^{+0.13}_{-0.12}$	2.76 $^{+0.02}_{-0.02}$	1.27 $^{+0.01}_{-0.01}$	1.38 $^{+0.01}_{-0.02}$	1.42 $^{+0.02}_{-0.02}$				
			ΔF	2.82 $^{+0.24}_{-0.25}$	0.32 $^{+0.02}_{-0.02}$	3.01 $^{+0.29}_{-0.28}$	0.1 †	0.33 $^{+0.15}_{-0.16}$	0.72 $^{+0.11}_{-0.09}$	0.07 †	0.1 †	0.22 $^{+0.02}_{-0.02}$				
			N_{tor}	0.019 $^{+0.001}_{-0.001}$	0.0097 $^{+0.0006}_{-0.0006}$	0.0035 $^{+0.0007}_{-0.0006}$	0.00033 $^{+0.00016}_{-0.00015}$	0.00015 $^{+0.00003}_{-0.00003}$	0.0017 $^{+0.0003}_{-0.0003}$	0.0028 $^{+0.0003}_{-0.0006}$	0.0055 $^{+0.0009}_{-0.0009}$	0.00943 $^{+0.00153}_{-0.00146}$				
40 – 60 0.21 $^{+0.04}_{-0.04}$	–	17.61 $^{+2.29}_{-2.23}$	$\Delta\chi^2_{\text{dof}}$	105	–	60	9	–	–	–	–	457 $^{\square}$	135/127			
			f_{cen}	0.0	–	2.87 $^{+0.10}_{-0.13}$	0.72 $^{+0.03}_{-0.03}$	–	–	–	–	1.38 $^{+0.01}_{-0.01}$				
			ΔF	0.45 $^{+0.02}_{-0.02}$	–	2.76 $^{+0.52}_{-0.43}$	0.28 $^{+0.17}_{-0.12}$	–	–	–	–	0.23 $^{+0.02}_{-0.02}$				
			N_{tor}	0.013 $^{+0.001}_{-0.001}$	–	0.007 $^{+0.001}_{-0.001}$	0.0009 $^{+0.0004}_{-0.0003}$	–	–	–	–	0.01291 $^{+0.00064}_{-0.00056}$				
60 – 80 –	–	constant ($\times 10^{-4}$)	$\Delta\chi^2_{\text{dof}}$	87	–	9	–	16	–	–	–	38	153/129			
			f_{cen}	0.0	–	1.51 $^{+0.81}_{-0.79}$	–	19.34 $^{+0.15}_{-0.22}$	–	–	–	1.37 $^{+0.01}_{-0.01}$				
			ΔF	0.43 $^{+0.06}_{-0.06}$	–	4.18 $^{+2.68}_{-1.27}$	–	0.1 †	–	–	–	0.24 $^{+0.04}_{-0.04}$				
			N_{tor}	0.0036 $^{+0.0004}_{-0.0005}$	–	0.0033 $^{+0.0013}_{-0.0012}$	–	0.0007 $^{+0.0001}_{-0.0001}$	–	–	–	0.00243 $^{+0.00040}_{-0.00031}$				
80 – 100 –	–	16.31 $^{+0.26}_{-0.26}$	$\Delta\chi^2_{\text{dof}}$	10	–	–	–	–	–	–	–	3	77/91			
			f_{cen}	0.0	–	–	–	–	–	–	–	–		1.37 $^{+0.04}_{-0.05}$		
			ΔF	0.61 $^{+0.39}_{-0.22}$	–	–	–	–	–	–	–	–		0.17 $^{+0.13}_{-0.07}$		
			N_{tor}	0.00104 $^{+0.00031}_{-0.00026}$	–	–	–	–	–	–	–	–		0.00042 $^{+0.00014}_{-0.00013}$		

† Frozen at best fitted values as errors are not constrained.

$^{\square}$ Higher $\Delta\chi^2_{\text{dof}}$ signifies very strong fundamental LFQPO (L_{tor}^9 component) in absence of L_{tor}^7 and L_{tor}^8 components.

model the entire continuum in 0.1 – 50 Hz frequency range. In addition, in modeling the complex nature of LFQPO feature (see also Dotani et al., 1989, Belloni et al., 2002), we use three Lorentzian (dotted in red) at three distinct nearby frequencies of ~ 1.27 Hz, ~ 1.34 Hz and ~ 1.43 Hz. Further, one additional Lorentzian (solid in green) profile is required to model the harmonic feature at ~ 2.76 Hz. Finally, one more Lorentzian (dotted in magenta) is needed to model a possible QPO-like feature at ~ 20 Hz. With this, we obtain best fit PDS with a χ^2_{red} ($\chi^2/\text{d.o.f}$) of $131/117 = 1.12$ that yields a strong LFQPO feature of frequency $\nu_{\text{QPO}} \sim 1.43$ Hz in 20 – 100 keV energy band. We present the best fitted residuals variation in the bottom panel of Fig. 3.2. Following the above approach, we further carry out the modeling of the energy-dependent PDS of Epoch AS2 (MJD 60195). The best fitted model parameters associated to individual model components used in the PDS fitting are tabulated in Table 3.1. Similar model combinations are also used to fit the PDS (20 – 100 keV) of Epoch AS7 (MJD 60199) with the exception that the bump-like features (~ 1 Hz, ~ 5 Hz and ~ 8 Hz) and complex LFQPO features (~ 2.17 Hz, ~ 2.66 Hz and ~ 3.29 Hz) are present at different frequencies.

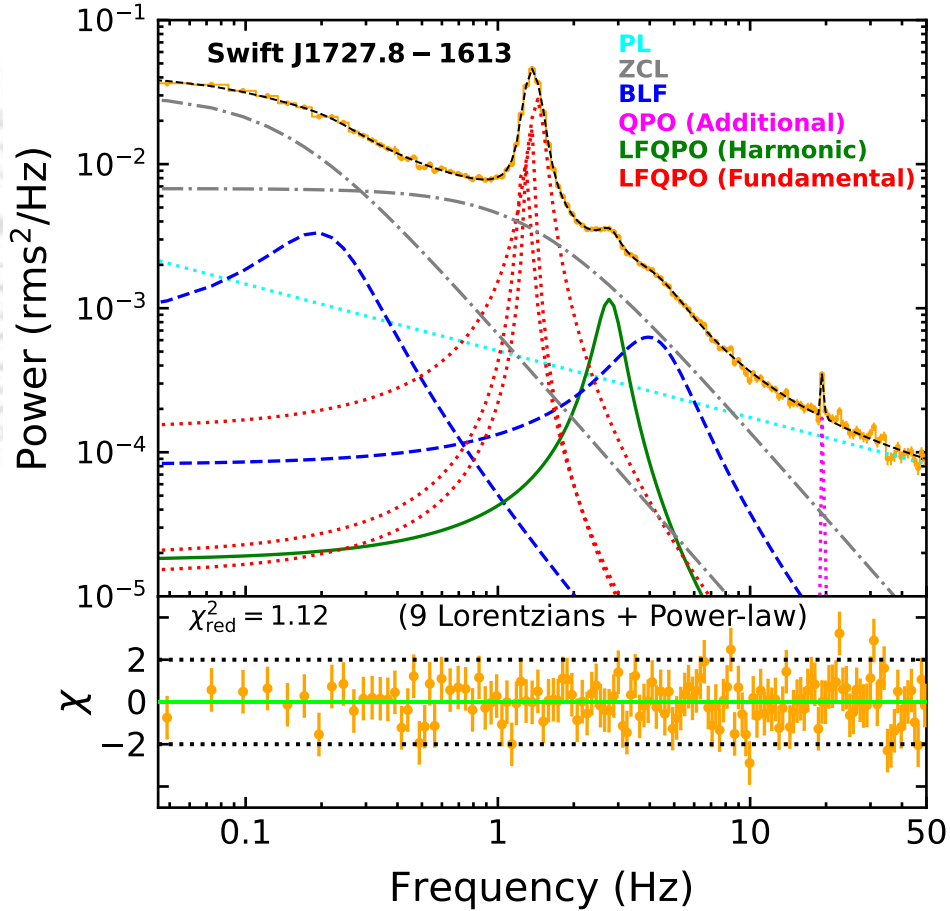


Figure 3.2: Best fitted PDS of AS2 observation (MJD 60195) of Swift J1727.8 – 1613 in 20 – 100 keV energy band. The different model components (nine Lorentzian and one powerlaw) corresponding to different characteristics are used to fit the entire PDS. The variation of residuals is shown in the bottom panel. See the text for details.

We verify the significance of the LFQPO features by comparing the chi-square statistics obtained from the best fit due to the inclusion of respective Lorentzian components. We also examine χ^2 statistics of the PDS modeling with and without

QPO feature. Towards this, we compute the change in fitted chi-square value per degrees of freedom (defined as $\Delta\chi_{\text{dof}}^2 = (\chi_b^2 - \chi_a^2)/\Delta\text{dof}$) using best fitted chi-square value before (χ_b^2) and after (χ_a^2) the inclusion of respective **Lorentzian** component corresponding to the difference in degrees of freedom (Δdof). Accordingly, the best fit statistics is realized with the improvement of $\Delta\chi_{\text{dof}}^2$ due to the inclusion of respective **Lorentzian** components, which are presented in Table 3.1. As an example, in 20 – 100 keV, $\Delta\chi_{\text{dof}}^2$ are computed due to the difference of best fitted PDS for L1-L8 components and L1-L9 components, which renders $\Delta\chi_{\text{dof}}^2 = 309/3 = 103$. A similar approach is followed in determining the chi-square statistics for other energy bands. The estimated $\Delta\chi_{\text{dof}}^2$ due to the inclusion of respective **Lorentzian** components are presented in Table 3.1 for all PDS of AS2. Needless to mention that the requirement of the different model components to obtain the best fit PDS is clearly justified as $\Delta\chi_{\text{dof}}^2$ improves significantly. We continue to carry out the analyses for AS7 as well, however, we refrain from presenting it to avoid repetition.

Following the standard approach (Belloni and Altamirano, 2013, Sreehari et al., 2019a, Majumder et al., 2022, 2023, and references therein), we estimate the significance of detection (σ_{QPO}), and quality factor ($Q\text{-}fac$) for QPO features (see Chapter 2 also). We obtain σ_{QPO} and $Q\text{-}fac$ for fundamental LFQPO as 5.46σ (22.97σ) and 7.14 (5.02) for Epoch AS2 (AS7), respectively. We further estimate the percentage rms amplitude (rms_{QPO} ; Ribeiro et al., 2019, Sreehari et al., 2020) of the detected LFQPO and obtained as 10.95% (9.21%) for Epoch AS2 (AS7). Note that in both AS2 and AS7 Epochs, we consider the centroid frequency of LFQPO that renders maximum power. Subsequently, the LFQPO parameters are computed for this component only. All the best-fit model and estimated parameters are tabulated in Table 3.2. In Fig. 3.1e, we present the evolution of ν_{QPO} (1.09 – 2.66 Hz) during the entire *AstroSat* campaign along with *NICER* and *Swift/BAT* detection in 0.44 – 0.8 Hz frequency range.

We further study the energy-dependent properties of the detected LFQPO features. Towards this, we generate PDS in different energy bands, namely 20 – 40 keV, 40 – 60 keV, 60 – 80 keV and 80 – 100 keV. We detect strong type-C LFQPO features in all the aforementioned energy bands (see Table 3.2) and observe that the centroid frequency (ν_{QPO}) remains independent of X-ray photon energy as shown in Fig. 3.3 (AS2 and AS7 Epochs). It may be noted that only a ZCL component, along with an additional **Lorentzian** at ν_{QPO} , are used to fit the PDS in the higher energy band (80 – 100 keV). In order to confirm the detection significance of QPO, we perform simulation using `simftest` inside `XPSEC` (Athulya et al., 2022, Bhuvana et al., 2023, Sharma et al., 2023, Li et al., 2023) to obtain the probability of best fit without the LFQPO features in 80 – 100 keV energy band. In Fig. 3.3(c-d), we present the distribution of the difference of chi-square values with and without LFQPO feature for 1000 simulated power spectra. The change of the chi-square value obtained from the real observed data ($\Delta\chi_{\text{obs}}^2$) by modeling the LFQPO feature is found outside the distribution of the change in chi-square value ($\Delta\chi_{\text{sim}}^2$) obtained from the simulation. These findings evidently indicate that the detected ν_{QPO} is directly associated with the hard X-ray emissions. The energy-dependent model fitted and estimated parameters, along with fit statistics, are tabulated in Table 3.2.

Furthermore, we study the variation of energy-resolved rms amplitude (rms_{QPO}) of the LFQPOs as function of *SWIFT/BAT* (B) and *MAXI/GSC* (M) fluxes. The obtained results are shown in Fig. 3.4, where filled colored circles, triangle and squares denote the type-C LFQPO of $\nu_{\text{QPO}} = 1.43$ Hz (AS2), 2.03 Hz (AS5) and 2.66 Hz (AS7)

Table 3.2: Best fitted QPO and harmonic characteristics obtained from different observations with *LAXPC90* (AS1) and *LAXPC10* (AS2 and AS7) of *AstroSat*. All the quantities mentioned in the table have their usual meanings. See the text for details.

		Fundamental QPO characteristics					Harmonic characteristics						
Epoch (Date)	Energy Range	ν_{QPO} (Hz)	Δ_{F} (Hz)	$Q\text{-}fac$	σ_{QPO}	rms_{QPO} (%)	ν_{har} (Hz)	Δ_{F} (Hz)	$Q\text{-}fac$	σ_{har}	rms_{har} (%)	rms_{total} (%)	χ^2_{red} ($\chi^2/\text{d.o.f}$)
AS1 (02-09-2023)	3 – 100	$1.09^{+0.02}_{-0.02}$	$0.05^{+0.03}_{-0.04}$	21.80	2.20	9.84 ± 5.84	$2.16^{+0.25}_{-0.11}$	$0.79^{+0.56}_{-0.27}$	2.73	3.42	10.02 ± 5.25	22.27 ± 10.39	1.00 (44/44)
	3 – 20	$1.09^{+0.04}_{-0.02}$	$0.05^{+0.02}_{-0.03}$	21.80	2.16	11.42 ± 6.27	$2.24^{+0.34}_{-0.25}$	$0.70^{+0.45}_{-0.32}$	3.20	3.38	10.09 ± 5.05	19.11 ± 11.94	1.02 (45/44)
AS2 (08-09-2023)	20 – 100	$1.43^{+0.02}_{-0.02}$	$0.20^{+0.03}_{-0.01}$	7.14	5.46	10.95 ± 2.14	$2.76^{+0.04}_{-0.04}$	$0.69^{+0.16}_{-0.14}$	4.00	6.67	6.64 ± 0.31	21.88 ± 1.71	1.12 (131/117)
	20 – 40	$1.42^{+0.02}_{-0.02}$	$0.22^{+0.02}_{-0.02}$	6.45	6.51	12.62 ± 2.04	$2.76^{+0.03}_{-0.04}$	$0.73^{+0.18}_{-0.15}$	3.78	6.37	7.75 ± 0.63	24.82 ± 1.94	1.10 (128/116)
	40 – 60	$1.38^{+0.01}_{-0.01}$	$0.23^{+0.02}_{-0.02}$	6.00	23.11	10.44 ± 1.28	$3.01^{+0.20}_{-0.25}$	$1.54^{+1.37}_{-0.74}$	1.95	2.47	11.49 ± 2.05	28.65 ± 5.18	1.06 (135/127)
	60 – 80	$1.37^{+0.01}_{-0.01}$	$0.24^{+0.04}_{-0.04}$	5.71	7.84	5.30 ± 1.22	—	—	—	—	—	26.44 ± 3.06	1.19 (153/129)
AS7 (13-09-2023)	80 – 100	$1.37^{+0.07}_{-0.07}$	$0.17^{+0.12}_{-0.07}$	8.06	3.23	2.98 ± 1.10	—	—	—	—	—	28.78 ± 3.63	0.85 (77/91)
	20 – 100	$2.66^{+0.01}_{-0.01}$	$0.53^{+0.03}_{-0.02}$	5.02	22.97	9.21 ± 1.35	—	—	—	—	—	17.55 ± 1.69	1.13 (130/115)
	20 – 40	$2.66^{+0.01}_{-0.01}$	$0.53^{+0.04}_{-0.02}$	5.02	23.90	11.87 ± 2.17	—	—	—	—	—	22.95 ± 0.92	1.37 (157/115) [⊠]
	40 – 60	$2.66^{+0.04}_{-0.03}$	$0.63^{+0.12}_{-0.06}$	4.22	11.26	9.57 ± 1.76	—	—	—	—	—	26.46 ± 2.61	1.07 (134/125)
	60 – 80	$2.69^{+0.06}_{-0.07}$	$0.69^{+0.23}_{-0.18}$	3.90	5.41	5.27 ± 1.24	—	—	—	—	—	24.32 ± 2.98	1.19 (159/134)
80 – 100	$2.64^{+0.24}_{-0.08}$	$0.41^{+0.33}_{-0.15}$	6.44	3.81	4.17 ± 1.25	—	—	—	—	—	26.62 ± 3.65	0.88 (80/91)	

[⊠]Higher χ^2_{red} is observed due to the excess residuals at ~ 2 Hz and ~ 35 Hz (AS7), and we refrain using additional Lorentzian for modelling.

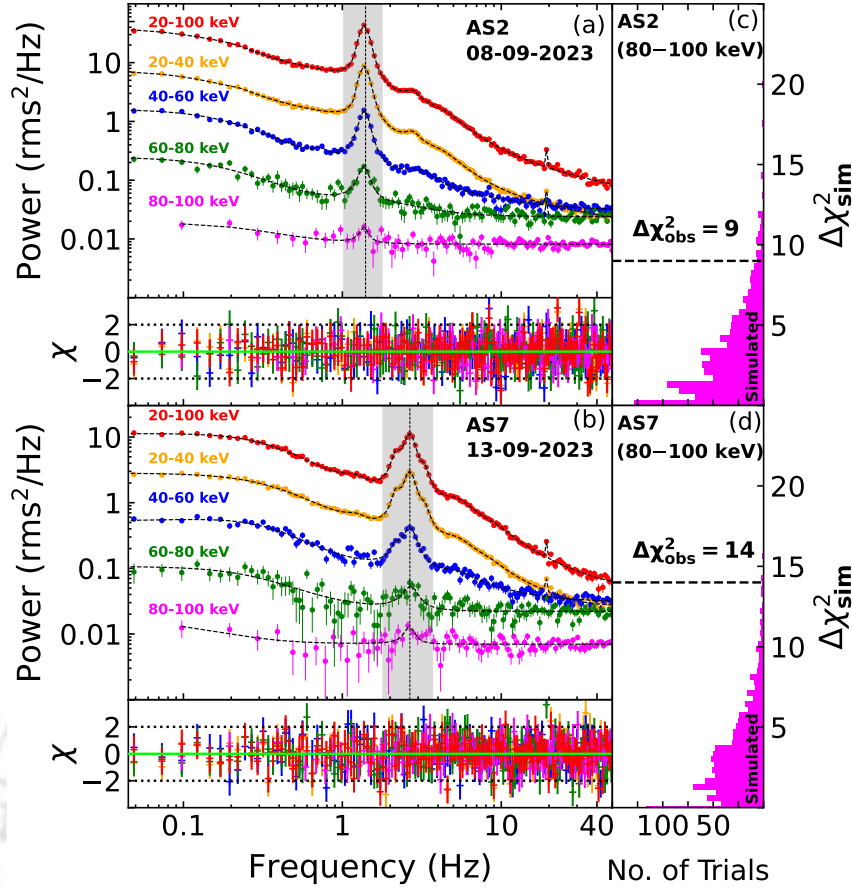


Figure 3.3: Best fitted power spectra of Swift J1727.8 – 1613 in different energy bands (obtained from *AstroSat/LAXPC10* observations). Panels (a) and (b) are for Epoch AS2 and AS7 and residual variations are shown at the bottom of each panel. For clarity, power spectra in 20 – 100 keV, 20 – 40 keV, 40 – 60 keV, 60 – 80 keV and 80 – 100 keV energy bands are scaled by multiplying with constant 950, 150, 40, 20, and 5. Panels (c) and (d) show the results obtained from *simfittest* in 80 – 100 keV energy band of both observations. See the text and [Nandi et al. \(2024\)](#) for details.

observed with *AstroSat* in different energy bands. In the figure, all points marked with ‘B’ and ‘M’ are shifted horizontally for better clarity. The horizontal and vertical colorbars demonstrate the quasi-simultaneous *SWIFT/BAT* (counts in $\text{cm}^{-2} \text{s}^{-1}$ within 15 – 50 keV) and *MAXI/GSC* (photons in $\text{cm}^{-2} \text{s}^{-1}$ within 2 – 20 keV) fluxes. We observe $rms_{\text{QPO}} \sim 13\%$ at 20 – 40 keV, which drops down around $\sim 2.5\%$ at 80 – 100 keV for all Epochs under consideration. It is noteworthy that *SWIFT/BAT* flux anti-correlates with ν_{QPO} in all energy band, whereas *MAXI/GSC* flux increases with ν_{QPO} .

3.1.5 Study of Spectral Energy Distribution

We investigate the spectral properties of Swift J1727.8–1613 using combined *NICER/XTI* and *AstroSat/LAXPC20* observations in 0.6 – 40 keV energy range. The spectral analysis is carried out for quasi-simultaneous *NICER* and *AstroSat* observations during Epoch AS1 and NI2. In addition, the spectral distribution of the source is studied using *NICER* observations NI1, NI3, NI4 and NI5 in 0.6 – 10 keV energy range, when *AstroSat/LAXPC20* monitoring were not available.

Spectra are modeled using XSPEC in HEASOFT V6.32.1. We adopt a model combination `const*Tbabs*(gaussian+diskbb+smedge*nthcomp)` to describe the spectral

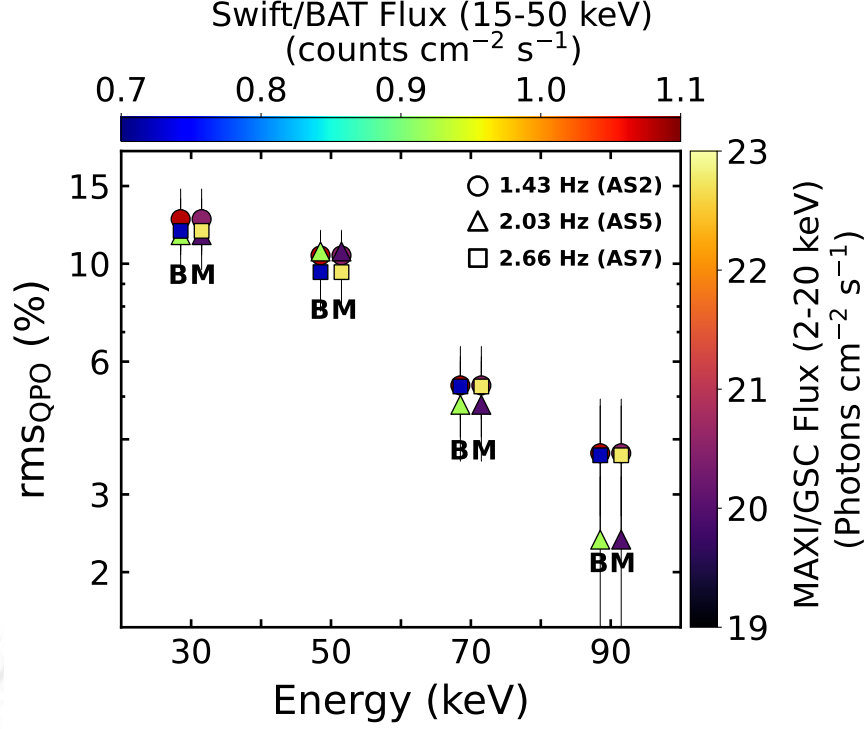


Figure 3.4: Plot of rms_{QPO} with energy visualized in terms of *SWIFT*/*BAT* (B) and *MAXI*/*GSC* (M) fluxes. Color-coded filled circles, triangles and squares denote frequency of LFQPO of $\nu_{\text{QPO}} = 1.43$ Hz (AS2), 2.03 Hz (AS5) and 2.66 Hz (AS7), respectively. Points marked with ‘B’ and ‘M’ are horizontally shifted for better visibility. Horizontal and vertical colorbars denote *Swift*/*BAT* and *MAXI*/*GSC* fluxes.

distribution. Here, `const` takes care of the cross calibration between the spectra of different instruments and `Tbabs` is used for the galactic absorption. The models `diskbb` (Makishima et al., 1986) and `nthcomp` (Zdziarski et al., 1996) represent the standard accretion disc and thermal Comptonization components. The `gaussian` is incorporated in the spectral fitting to model the iron line emission at ~ 6.4 keV. Additionally, a `smedge` component is used at ~ 9.94 keV to improve the residual variations only for AS1+NI2 observations. It may be noted that *NICER* spectra showed two instrument lines at 1.8 keV and 2.2 keV, which are modeled using two additional `gaussian`. With this, we obtain an acceptable fit with χ^2_{red} of 0.99. The resultant fit indicates the presence of a weak disc signature having a temperature ($k_{\text{B}}T_{\text{in}}$) of 0.36 ± 0.01 keV. Moreover, a hard Comptonized spectral tail of photon index (Γ_{nth}) 1.84 ± 0.01 and electron temperature ($k_{\text{B}}T_{\text{e}}$) $6.83^{+0.30}_{-0.29}$ keV are obtained. We compute the flux associated with different spectral components as well as total bolometric flux using the convolution model `cflux` in 0.5 – 50 keV energy range. Following Zdziarski et al. (1996), Majumder et al. (2022), we estimate the optical depth (τ) and Compton y-parameter (y_{par}). We find that the *NICER* spectra are well described with the aforementioned model without the `smedge` component. All the model fitted and estimated spectral parameters are tabulated in Table 3.3. The best fit spectra obtained from *NICER* and *AstroSat* observations and the corresponding residuals are shown in Fig. 3.5.

3.1.6 Understanding the Physical Origin of LFQPOs

The most fascinating results we report in this work are the significant detection of energy dependent LFQPO features above 40 keV, particularly in the energy range of

Table 3.3: Best fitted and estimated spectral parameters obtained from the fitting of energy spectra with *NICER* and *AstroSat* in 0.6 – 40 keV energy range. All notations have their usual meanings. The errors are computed with 90% confidence level.

Model Components	Model Parameters	NI1	AS1+NI2	NI3	NI4	NI5
Fitted Parameters						
Tbabs	$n_{\text{H}} (\times 10^{22}) \text{ cm}^{-2}$	$0.19^{+0.01}_{-0.01}$	$0.21^{+0.01}_{-0.01}$	$0.20^{+0.01}_{-0.01}$	$0.22^{+0.02}_{-0.01}$	$0.19^{+0.01}_{-0.01}$
diskbb	$k_{\text{B}}T_{\text{in}} \text{ (keV)}$	$0.32^{+0.01}_{-0.02}$	$0.36^{+0.01}_{-0.01}$	$0.40^{+0.02}_{-0.02}$	$0.60^{+0.01}_{-0.02}$	$0.70^{+0.01}_{-0.01}$
	$N_{\text{diskbb}} (\times 10^5)$	$0.82^{+0.26}_{-0.14}$	$1.54^{+0.16}_{-0.13}$	$1.01^{+0.18}_{-0.13}$	$0.13^{+0.02}_{-0.01}$	$0.09^{+0.01}_{-0.01}$
nthcomp	$k_{\text{B}}T_{\text{e}} \text{ (keV)}$	$3.93^{+0.69}_{-0.42}$	$6.83^{+0.30}_{-0.29}$	$4.26^{+0.49}_{-0.26}$	$4^{\S}$	$4.61^{\S}$
	Γ_{nth}	$1.60^{+0.01}_{-0.02}$	$1.84^{+0.01}_{-0.01}$	$1.80^{+0.02}_{-0.02}$	$1.96^{+0.01}_{-0.01}$	$2.65^{+0.02}_{-0.02}$
gaussian	$E_{\text{gauss}} \text{ (keV)}$	—	$6.41^{+0.06}_{-0.06}$	—	$6.71^{+0.02}_{-0.01}$	—
	FWHM (keV)	—	$0.7^{\S}$	—	$0.30^{+0.13}_{-0.11}$	—
	$norm_{\text{gauss}}$	—	$0.117^{+0.008}_{-0.008}$	—	$0.016^{+0.007}_{-0.006}$	—
Estimated Parameters						
	$F_{\text{disc}} (\times 10^{-7}) \text{ erg cm}^{-2} \text{ s}^{-1}$	$0.13^{+0.01}_{-0.01}$	$0.35^{+0.01}_{-0.01}$	$0.36^{+0.01}_{-0.01}$	$0.30^{+0.02}_{-0.01}$	$0.37^{+0.01}_{-0.01}$
	$F_{\text{nth}} (\times 10^{-7}) \text{ erg cm}^{-2} \text{ s}^{-1}$	$1.27^{+0.02}_{-0.01}$	$3.52^{+0.01}_{-0.01}$	$1.83^{+0.02}_{-0.02}$	$2.41^{+0.02}_{-0.02}$	$1.69^{+0.02}_{-0.01}$
	$F_{\text{bol}} (\times 10^{-7}) \text{ erg cm}^{-2} \text{ s}^{-1}$	$1.41^{+0.02}_{-0.02}$	$3.98^{+0.01}_{-0.01}$	$2.20^{+0.02}_{-0.01}$	$2.73^{+0.01}_{-0.02}$	$2.06^{+0.03}_{-0.02}$
	Disc contribution (%)	9.22	8.79	16.36	10.99	17.96
	Compt. contribution (%)	90.07	88.44	83.18	88.24	82.04
	$L_{\text{bol}} \text{ (in } L_{\text{Edd}})$	0.09 ± 0.01	0.28 ± 0.01	0.15 ± 0.01	0.19 ± 0.01	0.14 ± 0.01
	τ	12.03 ± 1.20	6.97 ± 0.22	9.49 ± 0.64	8.66 ± 1.88	5.26 ± 1.05
	y_{par}	4.45 ± 0.21	2.60 ± 0.05	2.99 ± 0.11	2.34 ± 0.15	1.01 ± 0.08
	$\chi^2/\text{d.o.f.} (\chi^2_{\text{red}})$	135/136 (0.99)	223/225 (0.99)	137/135 (1.01)	124/142 (0.87)	159/161 (0.99)

§ Frozen parameter. $L_{\text{Edd}} = 1.26 \times 10^{39} \text{ erg s}^{-1}$ for a $10M_{\odot}$ black hole.

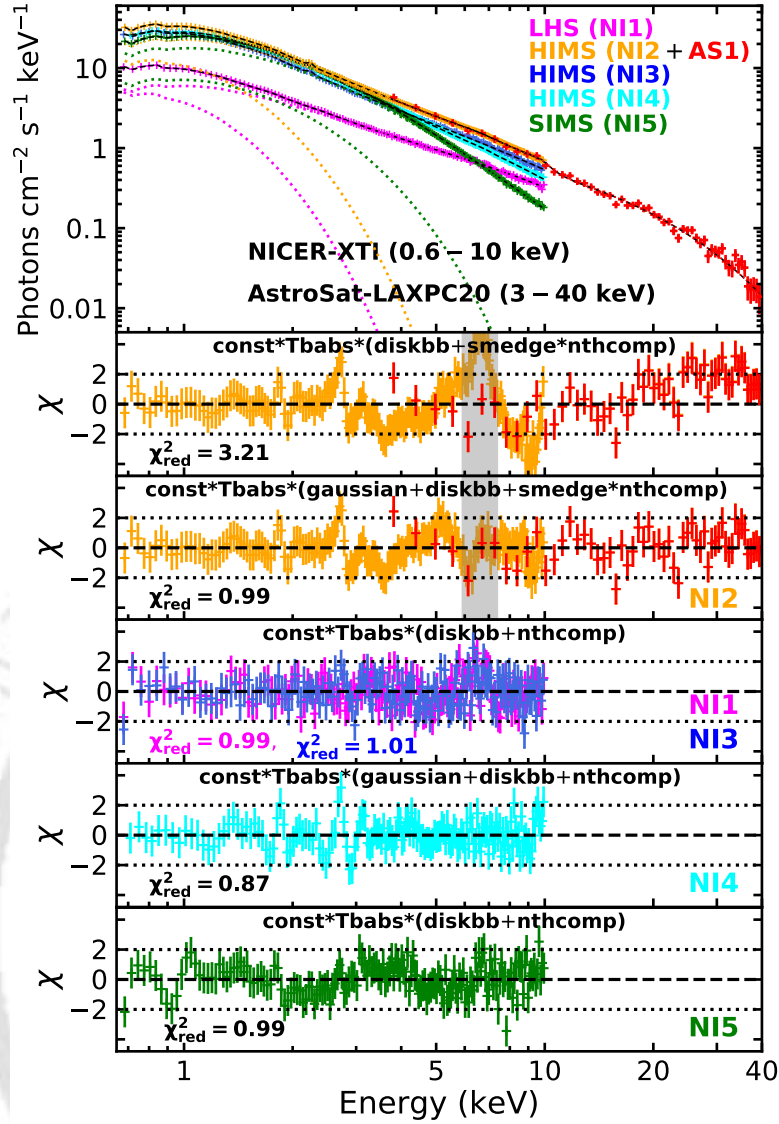


Figure 3.5: *Upper panel:* Best fit energy spectra of Swift J1727.8–1613 with *NICER* and *AstroSat* observations during the onset phase of the outburst. *Lower panels:* Residuals variations obtained from the fitting with different model combinations.

80 – 100 keV with $Q\text{-}fac > 6$ and $\sigma_{\text{QPO}} > 3\sigma$ (see Table 3.2 and Fig. 3.3), when the source was in HIMS. We observe that as the outburst progresses, ν_{QPO} is evolved from ~ 0.44 Hz to 2.66 Hz during LHS (*NICER* and *Swift/BAT*) and HIMS (*AstroSat*) (see Fig. 3.1e). The detection of LFQPO ($\nu_{\text{QPO}} < 1$ Hz) at high energies (> 100 keV) was earlier reported for few BH-XRBs (MAXI J1820+070, Ma et al. (2021) and MAXI J1803–298, Wang et al. (2021)), however strong LFQPO ($\nu_{\text{QPO}} \sim 1 - 10$ Hz) at energies < 100 keV were observed in MAXI J1535–571 (Huang et al., 2018) and MAXI J1631–479 (Bu et al., 2021) sources. It was suggested that the Lense-Thirring (LT) precession of the inner hot flow can account for the possible origin of type-C LFQPO of BH-XRBs (see Ingram et al., 2016, for details). Considering this, efforts were further given to investigate the type-C LFQPOs using LT precession of a small scale jet, where jet rotates and twists around the spin axis of BH resulting the modulation of the observed flux (Ma et al., 2021). However, this scenario bears limitations as it requires steady increase of jet precession in order to explain the evolution of LFQPO of $\nu_{\text{QPO}} \sim$

1.09–2.66 Hz as detected in Swift J1727.8–1613 at high energies > 40 keV. In addition, while explaining the evolution of ν_{QPO} considering the jet precession model for low inclination source ($\theta_{\text{inc}} \sim 29^\circ$), Bu et al. (2021) claimed that the frequency of type-C LFQPO generally increases with the decrease of jet height. However, jets are unlikely to be decoupled in LHS/HIMS (Fender et al., 2004, 2009) and hence, this model also suffers shortcomings to explain the evolution of QPO for Swift J1727.8–1613, although the orbital inclination of this source is recently reported as 40° (Peng et al., 2024a). Moreover, as there is no energy dependence of ν_{QPO} observed for this source (see Table 3.2), it is implausible that any differential precession is involved in exhibiting the LFQPO (Ingram et al., 2016). Needless to mention that the evolution of the type-C LFQPO ($\nu_{\text{QPO}} \sim 0.1 - 30$ Hz) is observed in the BH-XRBs having a time scale of 5–20 days (Remillard and McClintock, 2006, Nandi et al., 2012, Radhika and Nandi, 2014, Radhika et al., 2016), which remains challenging to explain till date.

Meanwhile, alternate possibilities are also suggested that comprehend the local inhomogeneity in accretion disk yielded the time varying modulation of the inner ‘hot’ flow and hence, it contributes in resulting ν_{QPO} (Huang et al., 2018, Bu et al., 2021). In reality, this conjecture resembles the corona oscillation scenario caused due to the undulation of the ‘hot’ and ‘dense’ downstream flow in the vicinity of the black holes (Molteni et al., 1996). Since ν_{QPO} is comparable to the inverse of the infall time scale (t_{infall}) (Chakrabarti and Manickam, 2000) and t_{infall} strongly depends on corona geometry, it is more likely that ν_{QPO} increases as the region occupied by the down-stream flow decreases (Chakrabarti et al., 2008, Nandi et al., 2012, Iyer et al., 2015). Indeed, the dynamics of the downstream flow can be regulated by tuning the accretion parameters, namely accretion rate and viscosity (Chakrabarti and Molteni, 1993, Das et al., 2014a). When the soft photons from the upstream are up-scattered at the inner ‘hot’ flow, high-energy X-ray emissions are produced because of the inverse-Comptonization process (Chakrabarti and Titarchuk, 1995, Mandal and Chakrabarti, 2005). Accordingly, LFQPO is likely to be observed at high energies whenever the source remains in a harder spectral state dominated by the Comptonized emission in the presence of a ‘weak’ disc signature.

To summarize, in this work, we report the first detection of evolving LFQPO features of Swift J1727.8–1613 above 40 keV in HIMS observed with *AstroSat*, which are possibly associated with the modulation of the inner Comptonizing corona.

3.2 High-frequency QPOs in GRS 1915+105: Insights from Spectro-temporal Diagnostics

In the previous section, we conducted a detailed study on the LFQPOs of BH-XRB source Swift J1727.8–1613. Apart from these variability signatures, BH-XRBs occasionally exhibit high-frequency Quasi-periodic Oscillations (HFQPOs). Being a rare phenomenon, HFQPOs have been observed in only eight BH-XRBs, including GRS 1915 + 105 (see Remillard and McClintock 2006, Belloni and Altamirano 2013 for details). Among these, the HFQPOs in GRS 1915 + 105 are of particular interest due to their relatively stable nature and strong association with rapid temporal variability occurring close to the black hole. These features are widely considered to be potential signatures of strong gravitational effects in the vicinity of the compact object. Motivated by these aspects, in this section, we aim to explore the HFQPO features of GRS

1915 + 105. We begin by providing a brief description of the source, followed by an overview of the previous studies conducted for this source.

3.2.1 GRS 1915+105: The Enigmatic BH-XRB

GRS 1915+105 is a well-known galactic microquasar (Mirabel and Rodríguez, 1994), notable for being one of the brightest black hole X-ray binaries (BH-XRBs), discovered in 1992 by the *WATCH* instrument onboard *GRANAT* (Castro-Tirado et al., 1992). The binary system consists of a K-M III-type giant star with a mass of $1.4 M_{\odot}$ and a black hole as the primary compact object, with an orbital period of 34 days (Greiner et al., 2001a). Based on the fast variability properties of GRS 1915+105, the black hole mass was initially estimated to lie within $\sim 10 - 33 M_{\odot}$ (Morgan et al., 1997). A more robust mass measurement was later obtained from radial velocity studies of the binary system, yielding a black hole mass of $\sim 14 M_{\odot}$ (Greiner et al., 2001b). Using parallax distance measurements, Reid et al. (2014) proposed a more accurate estimate of the black hole mass as $\sim 12.4 M_{\odot}$. Further, initial radio observations of the source predicted a kinematic distance of about 12.5 kpc (Rodríguez et al., 1995). However, *MERLIN* observations of multiple relativistic radio ejections of the source placed an upper limit on the distance as 11.2 kpc (Fender et al., 1999). The recent measurements predict that the source is located near the galactic plane at a distance of 8.6 kpc (Reid et al., 2014). Several indirect measurements indicate that GRS 1915 + 105 hosts a rapidly spinning black hole (Middleton et al., 2006, Miller et al., 2013, Mills et al., 2021, Wang et al., 2023), and suggest a moderate inclination for the binary system (Fender et al., 1999, Reid et al., 2014). Notably, broadband spectral modeling of the source using *AstroSat* observations constrained the black hole mass to lie within $12.4 - 13.1 M_{\odot}$ and the spin parameter in the range of $0.990 - 0.997$ (Sreehari et al., 2020).

Interestingly, GRS 1915+105 exhibits a broad range of structured and rapid X-ray variability on timescales of seconds to minutes. Based on the morphology of its light curves and the corresponding shape in the color-color diagrams (CCDs), these variability properties can be classified into 16 distinct classes ($\alpha, \beta, \gamma, \delta, \theta, \kappa, \lambda, \mu, \nu, \rho, \phi, \chi, \omega, \xi, \psi, \tau$) as observed with *RXTE*, *IXAE*, *AstroSat* and *Insight-HXMT* (Paul et al. 1997, 1998, Yadav et al. 1999, Munro et al. 1999, Belloni et al. 2000, Klein-Wolt et al. 2002, Hannikainen et al. 2005, Athulya et al. 2021, Majumder et al. 2022, Shi et al. 2023, Majumder et al. 2025b) along with ϵ (Pahari and Pal, 2009), a sub-set of the canonical ω class. So far, *AstroSat* observations identified nine distinct variability classes ($\beta, \theta, \chi, \omega, \delta, \rho, \kappa, \gamma, \tau$) (see Yadav et al. 2016, Athulya et al. 2021, Majumder et al. 2022, 2025b and §3.3 for details) during its 5-years long observational campaign on GRS 1915+105. In addition, a few intraclass variants including ρ' , χ_1 , χ_2 , χ_3 and χ_4 class variability are also observed (Athulya et al. 2021; Majumder et al. 2025, In preparation). Over more than three decades of activity, GRS 1915+105 has exhibited diverse timing features, including both LFQPOs (Nandi et al., 2001, Vadawale et al., 2001, Belloni et al., 2012) and HFQPOs (Morgan et al., 1997, Strohmayer, 2001a, Belloni et al., 2006, Belloni and Altamirano, 2013) observed with *RXTE*. Among these, stable HFQPOs in 63 – 71 Hz range have been detected across multiple classes ($\kappa, \gamma, \mu, \delta, \omega, \rho$, and ν) (Belloni and Altamirano, 2013) along with simultaneous features at ~ 34 Hz and ~ 41 Hz for a few instances (Strohmayer, 2001b). In addition, several studies focusing on detailed fast spectro-temporal variabilities are also carried out to

investigate HFQPO features at ~ 70 Hz in GRS 1915+105 using *AstroSat* observations (Belloni et al., 2019, Sreehari et al., 2020, Majumder et al., 2025c, Harikesh et al., 2025).

In addition to timing characteristics, the wideband spectral properties of GRS 1915+105 have been extensively studied using several missions. For example, simultaneous modeling of *RXTE* and *CGRO/OSSE* broadband (3 – 600 keV) spectra revealed a powerlaw-like spectral shape without any break (Zdziarski et al., 2001). Specifically, it was found that the broadband spectrum cannot be explained by either thermal or bulk-motion Comptonization and is best described by Comptonization in thermal/nonthermal plasmas. Similar wideband spectra from *RXTE* and *CGRO/OSSE* in ω classes are found to be described by a strong blackbody component Comptonized by thermal electrons and a weak non-thermal tail (Zdziarski et al., 2005). In addition, broadband energy spectra (3 – 300 keV) with *RXTE* and *INTEGRAL* in different variability classes (ν , λ , β and χ) are also studied and found to be dominated by thermal/non-thermal Comptonization at higher energies (Hannikainen et al., 2005, Rodriguez et al., 2008). Meanwhile, low (< 1 keV) to high ($\gtrsim 50$ keV) energy X-ray spectra of the source have been studied in several variability classes with *AstroSat* (Sreehari et al., 2020, Athulya et al., 2021, Majumder et al., 2025c, Harikesh et al., 2025), revealing the emission properties of the source.

In summary, these studies highlight GRS 1915 + 105 as one of the most promising candidates for investigating fast spectro-temporal variabilities in galactic BH-XRBs. Moreover, the stable HFQPO features exhibited by this source offer the opportunity to study the effects of strong gravity near black holes. However, the origin of these features is still not well understood, and significant challenges persist in explaining their underlying characteristics. This motivates us to undertake an in-depth spectro-temporal investigation of the HFQPOs in GRS 1915 + 105 using high-quality *AstroSat* observations.

3.2.2 Archival Data Acquisition

GRS 1915+105 was observed by *AstroSat* for 47 pointed observations (termed as ObsID) during different time periods between 2016–2021. In this work, we examine all 47 ObsIDs that include 38 Guaranteed Time (GT) data, 4 Announcement of Opportunity (AO) cycle data, and 5 Target of Opportunity (TOO) cycle data of *LAXPC* and *SXT* instruments. Throughout the 5-year *AstroSat* campaign targeting GRS 1915 + 105, several distinct variability classes reappear across multiple observations. To minimize redundancy in our analysis, we consider the data corresponding to 24 orbits drawn from 17 ObsIDs, as summarized in Table 3.4. The extraction and analysis of both *LAXPC* and *SXT* data is carried out following the procedures outlined in Chapter 2.

3.2.3 Characterization of Variability Classes

We generate 1 s binned light curve in the energy range 3 – 60 keV, after combining the data from *LAXPC10* and *LAXPC20* while studying the structured variability in different classes. Following Agrawal et al. (2018), Sreehari et al. (2019a, 2020), we correct the dead-time effect in all the light curves and calculate the average incident and detected count rates in 3 – 60 keV energy range as tabulated in Table 3.4. The light curves are generated in 3 – 6 keV, 6 – 15 keV and 15 – 60 keV energy ranges to plot the CCDs. We define the soft color and hard color following Sreehari et al. (2020) as

Table 3.4: Observation details of the source GRS 1915+105 observed by *AstroSat* during 2016 to 2021 in seven ‘softer’ and one ‘harder’ variability classes. In the table, ObsID along with MJD, Orbit number and exposure time are mentioned. The detected (r_{det}) and incident (r_{in}) count rate of the *LAXPC* detector along with hardness ratios are also tabulated. MJD 57451 corresponds to 4th March, 2016. See the text for details.

ObsID	MJD	Orbit	Effective	r_{det}	r_{in}	$HR1$	$HR2$	Variability	HFQPO
			Exposure (s)	(cts/s)	(cts/s)	(B/A)*	(C/A)*	Class	
T01_030T01_9000000358	57451.89	2351	3459	7252	8573	0.68	0.07	θ	No
	57452.82	2365	3148	4376	4825	0.69	0.09	χ	No
	57453.35	2373	1099	8915	10997	0.69	0.09	θ	No
G05_214T01_9000000428	57504.02	3124	2533	7308	8651	0.76	0.04	ω	Yes
G05_189T01_9000000492	57552.56	3841	3027	7965	9588	0.75	0.03	δ	No
	57553.88	3860	2381	6744	7872	0.87	0.06	δ	Yes
G06_033T01_9000000760	57689.10	5862	2674	5359	6047	0.62	0.04	β	No
G06_033T01_9000000792	57705.22	6102	3633	6712	7829	0.68	0.02	δ	No
G07_028T01_9000001232	57891.88	8863	3228	1431	1476	0.73	0.11	ρ'	No
G07_046T01_9000001236	57892.74	8876	3627	1292	1328	0.61	0.09	ρ	No
G07_028T01_9000001370	57943.69	9629	977	2814	2993	0.76	0.04	κ	No
	57943.69	9633	3442	2701	2866	0.75	0.04	κ	Yes
G07_046T01_9000001374	57946.10	9666	1093	3115	3335	0.79	0.04	κ	Yes
	57946.34	9670	2735	3160	3387	0.79	0.04	κ	Yes
G07_028T01_9000001406	57961.39	9891	1323	3642	3947	0.86	0.07	κ	No
	57961.39	9894	2451	4415	4872	0.87	0.05	κ	Yes
G07_046T01_9000001408	57961.59	9895	3590	4726	5254	0.87	0.05	κ	Yes
G07_028T01_9000001500	57995.30	10394	3036	5719	6511	0.90	0.06	ω	Yes
G07_046T01_9000001506	57996.46	10411	3632	6160	7088	0.88	0.05	ω	Yes
G07_046T01_9000001534	58007.80	10579	1729	6968	8180	0.84	0.05	ω	Yes
	58008.08	10583	1898	7392	8769	0.88	0.05	γ	Yes
A04_180T01_9000001622	58046.36	11154	2059	7312	8657	0.66	0.02	δ	No
A04_180T01_9000002000	58209.13	13559	2632	1403	1445	0.87	0.19	χ	No
A05_173T01_9000002812	58565.82	18839	3626	300	302	1.02	0.28	χ	No

* A, B and C are the count rates in 3 – 6 keV, 6 – 15 keV and 15 – 60 keV energy ranges, respectively (see [Sreehari et al., 2020](#)).

$HR1 = B/A$ and $HR2 = C/A$, where A , B and C are the photon count rates in 3 – 6 keV, 6 – 15 keV and 15 – 60 keV energy bands, respectively. The CCDs are obtained by plotting $HR1$ against $HR2$. It may be noted that the combined *LAXPC10* and *LAXPC20* background count rate (~ 225 cts/s) is negligible ($\sim 2.5\%$) compared to the combined source count rate (~ 10000 cts/s). Accordingly, we incorporate the background correction while carrying out the color-color and spectral analyses. However, power spectra are generated without background correction of light curves.

Following the classification scheme of [Belloni et al. \(2000\)](#), the light curves and CCDs indicate the presence of seven ‘softer’ variability classes as θ , β , δ , ρ , κ , ω and γ with an additional variant (ρ') of ρ class ([Athulya et al., 2021](#)), and one ‘harder’ variability class (χ). The hardness ratios $HR1$ and $HR2$ for each class are tabulated in Table 3.4. It is clearly seen that the soft color $HR1$ and the hard color $HR2$ are

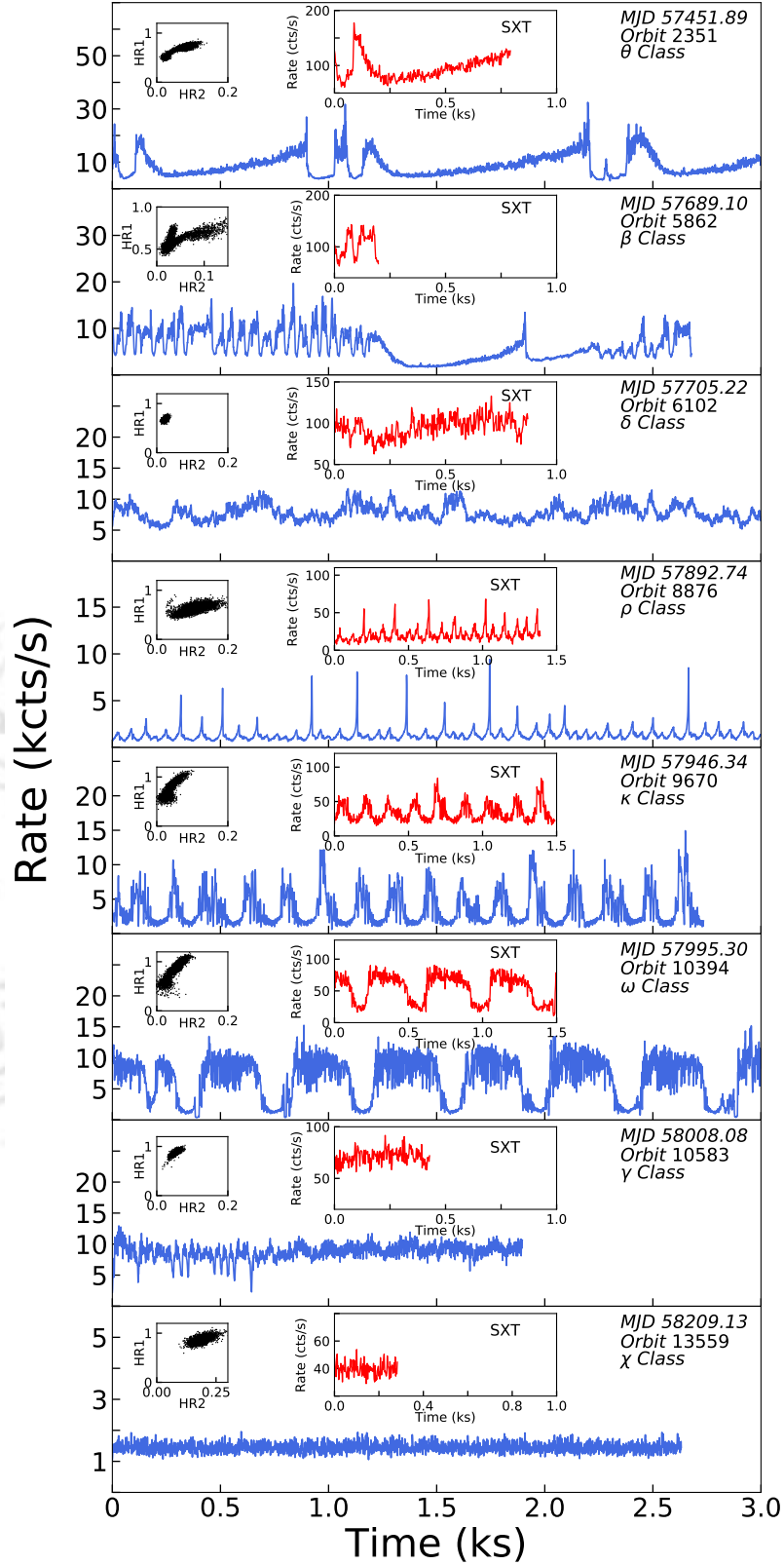


Figure 3.6: Background subtracted and dead-time corrected 1 s binned light curves of GRS 1915+105 observed with *AstroSat*. Light curves corresponding to eight different variability classes, namely θ , β , δ , ρ , κ , ω , γ and χ are depicted from top to bottom panels. Each light curve is obtained by combining *LAXPC10* and *LAXPC20* data in 3 – 60 keV energy band. In every panel, the CCD and the *SXT* light curves (0.5 – 7 keV) are also shown at the top-left and top-middle insets, respectively. See the text for details.

generally less than 0.9 and 0.1, respectively, which imply the ‘softer’ variability classes. In Fig. 3.6, we present background subtracted and dead-time corrected *LAXPC* light curves of eight different variability classes (θ , β , δ , ρ , κ , ω , γ and χ) with the CCD at the top-left inset of each panel. Different structured variability patterns along with the variations in the CCDs are observed in various classes.

During the *AstroSat* campaign, the source was initially observed in θ variability class (see Banerjee et al., 2021), where the count rate went up to 20 kcts/s and both colors are softened as observed in the CCD. Further, the source was found in ω , δ and β variability classes (see Table 3.4.) Subsequently, the source was found in a variability class ρ on MJD 57892.74. In this period, we see a ‘flare’ like nature in the light curve, and in the CCD, the points are distributed more towards the harder range. Next, the source displayed κ class variability, in which the count rates were high as 15 kcts/s and multiple ‘dips’ (low counts) of few tens to hundred seconds of duration are observed. In addition, small duration ($\sim$ few seconds) ‘non-dips’ (high counts) are also present between the two ‘dips’. The CCD shows a uniform C-shaped distribution of points. In ω class, the duration of ‘non-dips’ between two ‘dips’ increases up to a few hundred of seconds, and the CCD shows a similar pattern as observed in κ class. In γ class, the long duration ‘dips’ are absent instead of small ‘dips’ with a few seconds of duration are observed along with high counts. A diagonally elongated distribution of points is found in the CCD. Finally, the source was found in ‘harder’ variability class (χ) with count rate less than 1.5 kcts/s (Athulya et al., 2021). In each panel of Fig. 3.6, we show the *SXT* light curves of the same observations in the energy range of 0.5 – 7 keV at the top-middle inset. Similar structured variabilities are also observed in *SXT* light curves as seen in *LAXPC* observations.

3.2.4 Investigation of Power Density Spectra: Detection of HFQPOs

We generate light curves of 1 ms resolution corresponding to each variability class with combined data from *LAXPC10* and *LAXPC20*. We generate power density spectra (PDS) for each observation, considering the Nyquist frequency of 500 Hz with these light curves. We choose 32768 bins per interval for generating the respective PDS, which are further averaged to obtain the final PDS. A geometric binning factor of 1.03 is used for the power spectral analysis. Finally, the dead-time corrected power spectra are obtained following Agrawal et al. (2018), Sreehari et al. (2019a, 2020).

Each PDS is then modeled using multiple Lorentzians and a constant component in the wide frequency range of 0.01 – 500 Hz. In Fig. 3.7, we present the model fitted PDS of δ , κ , ω and γ variability classes with the detected HFQPO feature as depicted in the inset of each panel. The variability class and the observation details are marked in each panel. First, we begin with the modeling of the power spectrum of γ class observation using the model combination of a constant and four Lorentzians. Initially, two zero-centroid Lorentzians and one Lorentzian with centroid frequency at 2.25 Hz, along with a constant component, are used to fit the entire PDS. The fit is resulted in a χ^2_{red} of 310/234 = 1.32. Further, to model the HFQPO feature, we include an additional Lorentzian with the centroid frequency of $\sim$ 72 Hz. We emphasize that while modeling the entire PDS and estimating the errors associated with the model parameters, all the model parameters are kept free. The best fit is obtained with a χ^2_{red} of 133/231 = 0.58 (see also Sreehari et al., 2020). We follow the above procedure to fit the PDS in the presence of HFQPO features for δ , κ and ω

Table 3.5: Details of the best fitted PDS parameters from *LAXPC* observations of GRS 1915+105 in 3 – 60 keV energy range in different variability classes. Results are obtained with combined data from *LAXPC10* and *LAXPC20*. CO and L_{ior}^i ($i = 1, 2, 3, 4$) denote the **constant** and multiple **Lorentzians** used to obtain the best fit. σ_{QPO} denotes the significance of HFQPOs. $rms_{\text{QPO}}\%$ and $rms_{\text{total}}\%$ represent the rms percentage of the HFQPO feature and the entire PDS. The centroid frequency ($f_{\text{cen}} = \nu_{\text{QPO}}$), FWHM (ΔF) and normalization (N_{lor}) of the detected HFQPOs are highlighted in bold font. All the errors are computed with 68% confidence level. See the text for details.

Model Parameters										Estimated Parameters			
MJD (Orbit)	CO (10^{-4})	L_{lor}^1	L_{lor}^2	L_{lor}^3	L_{lor}^4	$\chi^2/\text{d.o.f}$	σ_{QPO}	$rms_{\text{QPO}}\%$	$rms_{\text{total}}\%$	Class			
57451.89 (2351) [†]	$1.58_{-0.01}^{+0.01}$	f_{cen}	0.0	0.0	$5.05_{-0.07}^{+0.05}$	—	—	—	—	θ			
		ΔF	$5.47_{-0.43}^{+0.57}$	$0.90_{-0.11}^{+0.14}$	$1.09_{-0.12}^{+0.23}$	—	—	—	—				
		N_{lor}	$0.0034_{-0.0007}^{+0.0007}$	$0.033_{-0.004}^{+0.004}$	$0.0010_{-0.0001}^{+0.0001}$	—	—	—	—				
57452.82 (2365) [†]	$1.34_{-0.01}^{+0.01}$	f_{cen}	0.0	0.0	$3.25_{-0.01}^{+0.02}$	$6.11_{-0.11}^{+0.08}$	—	—	—	χ			
		ΔF	$3.94_{-0.49}^{+0.53}$	$0.85_{-0.21}^{+0.24}$	$0.44_{-0.01}^{+0.03}$	$2.36_{-0.31}^{+0.38}$	168/232	—	—				
		N_{lor}	$0.0037_{-0.0007}^{+0.0008}$	$0.0055_{-0.0008}^{+0.0007}$	$0.019_{-0.001}^{+0.002}$	$0.00077_{-0.00004}^{+0.00005}$	—	—	—				
57453.35 (2373) [†]	$1.53_{-0.01}^{+0.01}$	f_{cen}	0.0	0.0	$6.19_{-0.16}^{+0.14}$	—	—	—	—	θ			
		ΔF	$7.87_{-1.81}^{+3.23}$	$1.37_{-0.18}^{+0.19}$	$1.75_{-0.39}^{+0.61}$	—	137/235	—	—				
		N_{lor}	$0.0011_{-0.0006}^{+0.0009}$	$0.0303_{-0.0031}^{+0.0036}$	$0.00046_{-0.00008}^{+0.00009}$	—	—	—	—				
57504.02 (3124)	$1.86_{-0.01}^{+0.01}$	f_{cen}	0.0	$1.71_{-0.21}^{+0.20}$	$71.52_{-0.29}^{+0.36}$	—	—	—	—	ω			
		ΔF	$0.26_{-0.03}^{+0.04}$	$2.71_{-0.22}^{+0.23}$	$1.25_{-0.55}^{+0.62}$	—	151/233	3.67	1.48 ± 0.36				
		N_{lor}	$0.21_{-0.04}^{+0.05}$	$0.00097_{-0.00013}^{+0.00016}$	0.00011 $_{-0.00003}^{+0.00004}$	—	—	—	—				
57552.56 (3841) [†]	$1.39_{-0.01}^{+0.01}$	f_{cen}	0.0	0.0	$0.75_{-0.05}^{+0.06}$	$2.73_{-0.18}^{+0.21}$	—	—	—	δ			
		ΔF	$8.45_{-2.25}^{+1.84}$	$0.33_{-0.05}^{+0.06}$	$0.77_{-0.11}^{+0.14}$	$4.05_{-1.24}^{+0.98}$	165/231	—	—				
		N_{lor}	$0.00004_{-0.00001}^{+0.00001}$	$0.012_{-0.001}^{+0.002}$	$0.0014_{-0.0002}^{+0.0003}$	$0.00023_{-0.00004}^{+0.00004}$	—	—	—				

[†] Non-detection of HFQPO.

Table 3.5: Continued.

		Model Parameters				Estimated Parameters				
MJD (Orbit)	CO (10^{-4})	L^1_{lor}	L^2_{lor}	L^3_{lor}	L^4_{lor}	$\chi^2/\text{d.o.f}$	σ_{QPO}	$rms_{\text{QPO}}\%$	$rms_{\text{total}}\%$	Class
57553.88 (3860)	f_{cen}	0.0	$1.62^{+0.23}_{-0.20}$	$0.83^{+0.04}_{-0.05}$	$\mathbf{69.31^{+0.11}_{-0.16}}$	134/228	2.75	1.54 ± 0.48	9.69 ± 2.23	δ
	Δ_{F}	$0.018^{+0.005}_{-0.004}$	$3.10^{+0.19}_{-0.16}$	$1.05^{+0.24}_{-0.19}$	$\mathbf{1.39^{+0.94}_{-1.06}}$					
	N_{lor}	$0.29^{+0.03}_{-0.02}$	$0.0012^{+0.0003}_{-0.0003}$	$0.0021^{+0.0003}_{-0.0003}$	$\mathbf{0.00011^{+0.00004}_{-0.00004}}$					
57689.10 (5862) [†]	f_{cen}	0.0	0.0	$3.59^{+0.32}_{-0.34}$	$3.35^{+0.39}_{-0.28}$	129/231	—	—	26.30 ± 6.12	β
	Δ_{F}	$0.023^{+0.001}_{-0.002}$	$1.34^{+0.15}_{-0.14}$	$6.41^{+0.49}_{-0.46}$	$0.98^{+0.26}_{-0.23}$					
	N_{lor}	$5.05^{+1.45}_{-1.21}$	$0.013^{+0.002}_{-0.002}$	$0.00071^{+0.00008}_{-0.00008}$	$0.0012^{+0.0003}_{-0.0003}$					
57705.22 (6102) [†]	f_{cen}	0.0	0.0	$1.73^{+0.33}_{-0.26}$	—	154/231	—	—	11.68 ± 2.71	δ
	Δ_{F}	$1.68^{+0.71}_{-0.61}$	$0.06^{+0.02}_{-0.01}$	$4.21^{+0.15}_{-0.16}$	—					
	N_{lor}	$0.0019^{+0.0006}_{-0.0003}$	$0.16^{+0.08}_{-0.03}$	$0.00092^{+0.00021}_{-0.00023}$	—					
57891.88 (8863) [†]	f_{cen}	0.0	0.0	$5.14^{+0.04}_{-0.02}$	$10.33^{+0.18}_{-0.21}$	183/232	—	—	27.38 ± 5.69	ρ'
	Δ_{F}	$13.47^{+1.41}_{-1.66}$	$0.18^{+0.04}_{-0.03}$	$1.15^{+0.12}_{-0.11}$	$3.47^{+1.43}_{-0.89}$					
	N_{lor}	$0.0011^{+0.0001}_{-0.0001}$	$0.42^{+0.16}_{-0.12}$	$0.0032^{+0.0003}_{-0.0002}$	$0.00042^{+0.00006}_{-0.00004}$					
57892.74 (8876) [†]	f_{cen}	0.0	0.0	$5.74^{+0.06}_{-0.05}$	$10.63^{+0.28}_{-0.23}$	144/222	—	—	23.53 ± 2.70	ρ
	Δ_{F}	$3.80^{+0.81}_{-0.67}$	$0.13^{+0.05}_{-0.03}$	$1.54^{+0.15}_{-0.14}$	$8.43^{+1.18}_{-0.93}$					
	N_{lor}	$0.0016^{+0.0004}_{-0.0003}$	$0.71^{+0.21}_{-0.18}$	$0.0019^{+0.0002}_{-0.0001}$	$0.00043^{+0.00005}_{-0.00002}$					
57943.69 (9629) [†]	f_{cen}	0.0	—	—	—	149/239	—	—	35.49 ± 5.35	κ
	Δ_{F}	$0.14^{+0.02}_{-0.01}$	—	—	—					
	N_{lor}	$1.26^{+0.28}_{-0.24}$	—	—	—					

[†] Non-detection of HFQPO.

Table 3.5: Continued.

Model Parameters										Estimated Parameters			
MJD (Orbit)	CO (10^{-4})	L_{tor}^1	L_{tor}^2	L_{tor}^3	L_{tor}^4	$\chi^2/\text{d.o.f}$	σ_{qpo}	$rms_{\text{qpo}}\%$	$rms_{\text{total}}\%$	Class			
57943.69 (9633)	$1.59^{+0.01}_{-0.01}$	$f_{\text{cen}} 0.0$ $\Delta_F 0.13^{+0.01}_{-0.01}$ $N_{\text{tor}} 1.36^{+0.24}_{-0.21}$	0.0 $2.21^{+0.15}_{-0.13}$ $0.016^{+0.002}_{-0.002}$	$71.55^{+0.96}_{-0.96}$ $5.67^{+2.76}_{-2.17}$ $0.000052^{+0.000019}_{-0.000014}$	— — —	172/234	3.71	2.14 ± 0.50	38.32 ± 6.67	κ			
57946.10 (9666)	$1.55^{+0.01}_{-0.01}$	$f_{\text{cen}} 0.0$ $\Delta_F 0.17^{+0.02}_{-0.01}$ $N_{\text{tor}} 1.12^{+0.26}_{-0.22}$	$69.76^{+0.89}_{-0.74}$ $5.01^{+2.93}_{-2.29}$ $0.000085^{+0.000042}_{-0.000026}$	— — —	— — —	146/237	3.27	2.55 ± 0.71	37.28 ± 6.31	κ			
57946.34 (9670)	$1.67^{+0.01}_{-0.01}$	$f_{\text{cen}} 0.0$ $\Delta_F 0.13^{+0.01}_{-0.01}$ $N_{\text{tor}} 1.55^{+0.25}_{-0.22}$	$6.79^{+1.38}_{-1.05}$ $7.43^{+1.69}_{-1.98}$ $0.000078^{+0.000021}_{-0.000014}$	$70.45^{+0.54}_{-0.53}$ $4.67^{+1.56}_{-1.07}$ $0.000086^{+0.000018}_{-0.000017}$	— — —	142/234	5.06	2.49 ± 0.37	37.98 ± 5.35	κ			
57961.39 (9891) [†]	$5.46^{+0.01}_{-0.01}$	$f_{\text{cen}} 0.0$ $\Delta_F 0.29^{+0.04}_{-0.02}$ $N_{\text{tor}} 0.44^{+0.12}_{-0.08}$	— — —	— — —	— — —	147/240	—	—	31.51 ± 4.35	κ			
57961.39 (9894)	$1.57^{+0.01}_{-0.01}$	$f_{\text{cen}} 0.0$ $\Delta_F 2.14^{+0.02}_{-0.01}$ $N_{\text{tor}} 0.04^{+0.01}_{-0.01}$	0.0 $0.09^{+0.03}_{-0.02}$ $1.70^{+0.84}_{-0.53}$	$2.14^{+0.48}_{-0.42}$ $1.25^{+0.36}_{-0.31}$ $0.0042^{+0.0011}_{-0.0011}$	$71.68^{+0.84}_{-0.75}$ $4.70^{+2.60}_{-2.21}$ $0.000072^{+0.000038}_{-0.000021}$	156/232	3.43	2.28 ± 0.63	42.31 ± 8.66	κ			
57961.59 (9895)	$2.11^{+0.01}_{-0.01}$	$f_{\text{cen}} 0.0$ $\Delta_F 0.13^{+0.02}_{-0.01}$ $N_{\text{tor}} 1.59^{+0.36}_{-0.28}$	$0.72^{+0.02}_{-0.01}$ $4.01^{+0.66}_{-0.62}$ $0.00105^{+0.00069}_{-0.00033}$	$70.47^{+0.69}_{-0.65}$ $3.86^{+1.69}_{-1.32}$ $0.000066^{+0.000017}_{-0.000015}$	— — —	171/234	4.40	1.98 ± 0.41	39.38 ± 7.30	κ			

[†] Non-detection of HFQPO.

Table 3.5: Continued.

		Model Parameters			Estimated Parameters					
MJD (Orbit)	CO (10 ⁻⁴)	L ¹ _{lor}	L ² _{lor}	L ³ _{lor}	L ⁴ _{lor}	χ ² /dof	σ _{QPO}	rms _{QPO} %	rms _{total} %	Class
57995.30 (10394)	f _{cen}	0.0	0.32 ^{+0.04} _{-0.02}	6.79 ^{+0.34} _{-0.24}	68.14 ^{+0.65} _{-0.61}	165/231	5.55	2.25 ± 0.31	34.27 ± 9.76	ω
	Δ _F	0.08 ^{+0.02} _{-0.01}	0.61 ^{+0.03} _{-0.02}	2.46 ^{+0.91} _{-1.10}	5.42 ^{+1.49} _{-1.11}					
	N _{lor}	1.23 ^{+0.59} _{-0.39}	0.05 ^{+0.01} _{-0.01}	0.00012 ^{+0.00004} _{-0.00003}	0.000061 ^{+0.000012} _{-0.000011}					
57996.46 (10411)	f _{cen}	0.0	0.11 ^{+0.02} _{-0.03}	70.01 ^{+0.56} _{-0.49}	—	193/234	7.01	2.66 ± 0.29	26.45 ± 7.47	ω
	Δ _F	0.03 ^{+0.01} _{-0.01}	0.57 ^{+0.07} _{-0.05}	5.96 ^{+1.22} _{-0.99}	—					
	N _{lor}	1.75 ^{+0.44} _{-0.23}	0.08 ^{+0.01} _{-0.01}	0.000077 ^{+0.000012} _{-0.000011}	—					
58007.80 (10579)	f _{cen}	0.0	1.89 ^{+0.23} _{-0.31}	72.22 ^{+0.49} _{-0.39}	—	128/234	4.95	1.86 ± 0.37	19.01 ± 3.66	ω
	Δ _F	0.25 ^{+0.05} _{-0.03}	3.04 ^{+0.42} _{-0.40}	2.25 ^{+0.77} _{-1.48}	—					
	N _{lor}	0.18 ^{+0.07} _{-0.03}	0.00068 ^{+0.00011} _{-0.00009}	0.000099 ^{+0.000032} _{-0.000020}	—					
58008.08 (10583)	f _{cen}	0.0	0.0	2.25 ^{+0.06} _{-0.05}	72.32 ^{+0.23} _{-0.21}	133/231	11.00	2.46 ± 0.19	12.98 ± 3.72	γ
	Δ _F	9.71 ^{+4.19} _{-2.66}	0.27 ^{+0.03} _{-0.03}	1.52 ^{+0.23} _{-0.21}	3.61 ^{+0.48} _{-0.45}					
	N _{lor}	0.00021 ^{+0.00016} _{-0.00009}	0.062 ^{+0.013} _{-0.011}	0.0010 ^{+0.0001} _{-0.0001}	0.00011 ^{+0.00001} _{-0.00001}					
58046.36 (11154) [†]	f _{cen}	0.0	0.0	0.61 ^{+0.04} _{-0.02}	—	166/234	—	—	7.91 ± 1.77	δ
	Δ _F	4.66 ^{+0.32} _{-0.32}	0.21 ^{+0.05} _{-0.04}	0.43 ^{+0.09} _{-0.06}	—					
	N _{lor}	0.00086 ^{+0.00011} _{-0.00009}	0.013 ^{+0.004} _{-0.003}	0.0018 ^{+0.0003} _{-0.0002}	—					
58209.13 (13559) [†]	f _{cen}	0.0	0.0	3.26 ^{+0.02} _{-0.02}	6.32 ^{+0.07} _{-0.06}	171/232	—	—	24.02 ± 4.23	χ
	Δ _F	6.18 ^{+0.42} _{-0.35}	0.84 ^{+0.13} _{-0.11}	0.64 ^{+0.04} _{-0.04}	1.24 ^{+0.23} _{-0.21}					
	N _{lor}	0.0059 ^{+0.0006} _{-0.0008}	0.018 ^{+0.002} _{-0.002}	0.016 ^{+0.001} _{-0.001}	0.00104 ^{+0.00012} _{-0.00011}					
58565.82 (18839) [†]	f _{cen}	0.0	0.0	2.20 ^{+0.01} _{-0.01}	4.42 ^{+0.03} _{-0.03}	130/232	—	—	21.14 ± 5.13	χ
	Δ _F	7.76 ^{+1.29} _{-0.81}	0.57 ^{+0.27} _{-0.15}	0.15 ^{+0.03} _{-0.01}	0.39 ^{+0.11} _{-0.09}					
	N _{lor}	0.0045 ^{+0.0007} _{-0.0009}	0.014 ^{+0.003} _{-0.002}	0.031 ^{+0.004} _{-0.003}	0.0048 ^{+0.0009} _{-0.0008}					

[†] Non-detection of HFQPO.

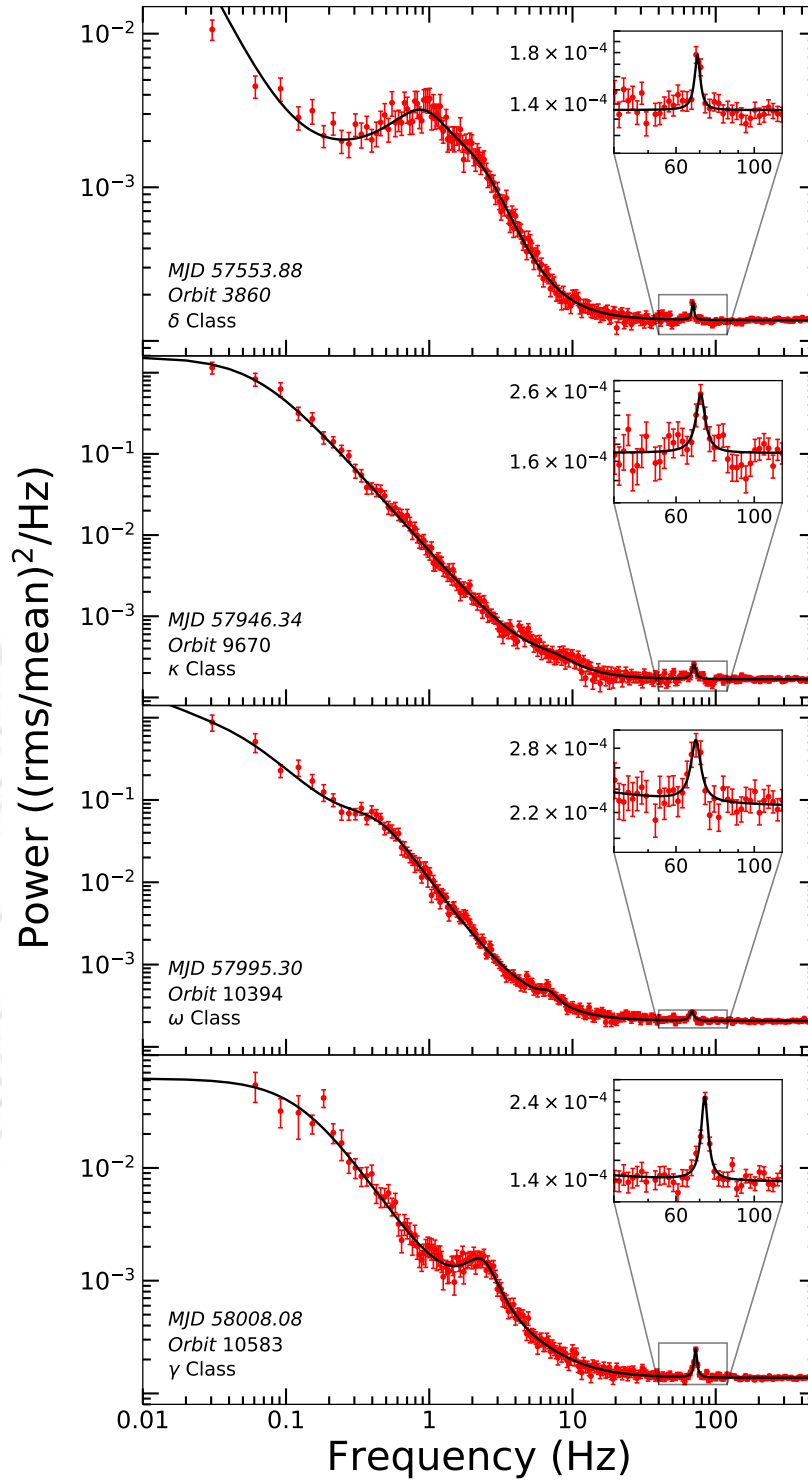


Figure 3.7: Power density spectra of four different variability classes in the presence of HFQPOs. Each PDS is obtained in 3 – 60 keV energy range by combining *LAXPC10* and *LAXPC20* observations. In each panel, variability classes are marked, and the detected HFQPO features (zoomed view) are shown in the inset. See the text and [Majumder et al. \(2022\)](#) for details.

classes, and the best fitted model parameters along with errors are tabulated in Table 3.5. In addition, we also note the presence of a broad feature in the PDS of δ and γ class observations at ~ 1 Hz and 2 Hz, respectively, which is absent in κ and ω classes.

The presence of a HFQPO feature in the power spectra is determined by means of

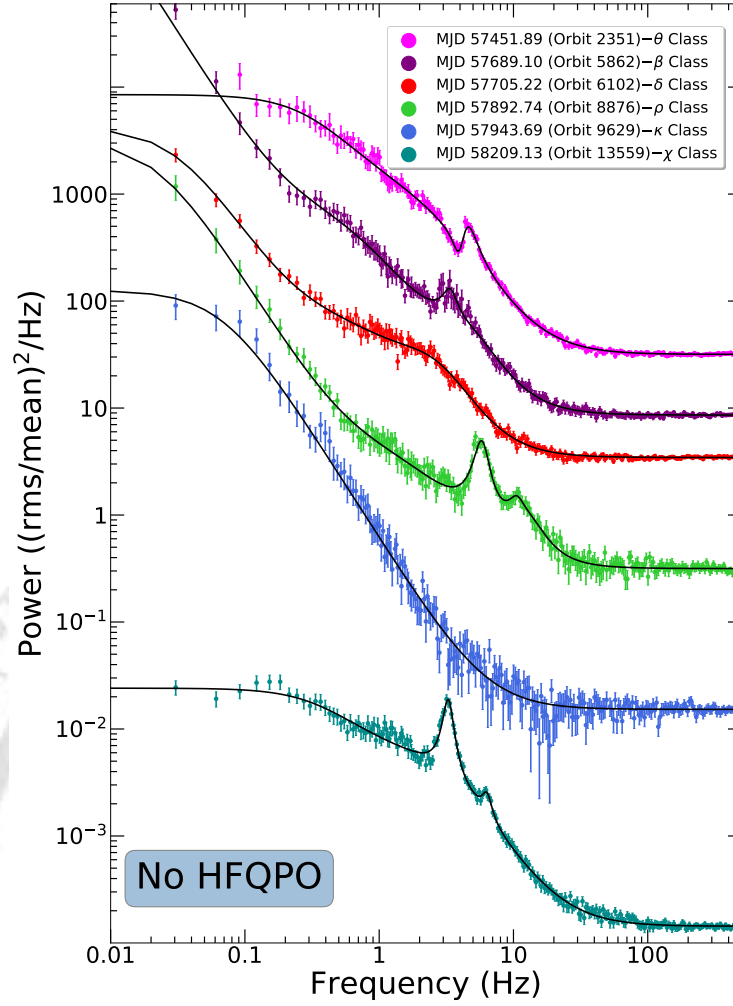


Figure 3.8: Power density spectra of six different observations in 3 – 60 keV energy band, where HFQPO is absent. Magenta, purple, red, green, blue, and dark cyan filled circles denote the PDS corresponding to θ , β , δ , ρ , κ , and χ classes, respectively. The power corresponding to θ , β , δ , ρ and κ class observations are scaled by multiplying 200000, 50000, 25000, 2000 and 100 for the purpose of clarity. See the text for details.

quality factor (Q - fac) and detection significance (σ_{QPO}) (see Chapter 2). Best fitted PDS of γ class observation shows a strong signature of HFQPO feature of centroid frequency $72.32^{+0.23}_{-0.21}$ Hz with significance of 11σ as shown in the inset of the bottom panel of Fig. 3.7. We calculate the percentage rms of the HFQPO by taking the square root of the definite integral of Lorentzian function (van der Klis, 1989b, Ribeiro et al., 2019, Sreehari et al., 2020, and references therein) with the HFQPO fitted parameters (ν_{QPO} , Δ_F , N_{lor}) and obtain as $2.46 \pm 0.19\%$. Further, we calculate the percentage rms of the entire PDS in the wide frequency range 0.01 – 500 Hz and for γ class observation, we obtain its value as $12.98 \pm 3.72\%$. We detect 11 such HFQPO features in four variability classes (*i.e.*, δ , κ , ω , γ) with centroid frequencies in the range of 68.14 – 72.32 Hz, significance in the range of 2.75 – 11.0 σ and the percentage rms in the range of 1.48 – 2.66. The model fitted as well as estimated parameters of all observations are tabulated in Table 3.5.

To address the non-detection of the HFQPO features, we compute the percentage rms amplitude ($rms\%$) of the most significant peak near the observed HFQPO frequency for all the observations. We find the highest value of the percentage rms amplitude as 0.94 ± 0.15 ($rms\%$ less than this value considered as ‘insignificant QPO

rms') for non-detection of HFQPO feature (see Table 3.6, Fig. 3.8 for PDS of κ class). On the contrary, we obtain the lowest value of $rms_{QPO}\%$ for the confirmed HFQPO detection as 1.48 ± 0.36 in the power spectra. Accordingly, we identify thirteen observations in θ , β , δ , ρ , κ and χ variability classes that do not exhibit the signature of HFQPO feature as presented in Table 3.6. Further, for reconfirmation (Belloni et al., 2001, Sreehari et al., 2020), we include one additional Lorentzian in the PDS of Orbit 9629 (κ class, as an example) by freezing the centroid frequency at 69.76 Hz and width at 5.01 Hz, similar to the HFQPO characteristics obtained in Orbit 9666 (κ class) having similar exposure. The significance of the best fitted Lorentzian feature is found to be 1.21 at 1σ unit, which indicates the non-detection of HFQPO. All the model fitted parameters of the power spectra are presented in Table 3.5. In Fig. 3.8, we show the model fitted PDS corresponding to θ , β , δ , ρ , κ and χ classes, modeled with Lorentzians and a constant. Note that in the wide frequency band, the power spectra of δ class observation (Orbit 6102) shows a bump-like feature near 2 Hz, whereas the PDS corresponding to κ class (Orbit 9629) is completely featureless. We find a strong type-C LFQPO at ~ 5.05 Hz, ~ 5.74 Hz and ~ 3.2 Hz for θ , ρ and χ classes, respectively, whereas the LFQPO feature at ~ 3.35 Hz is found broader for β variability class. Here, we avoid the discussion on LFQPOs as it is beyond the scope of the present work.

3.2.5 HFQPOs: Energy-Dependent Phenomena

We study the energy dependent PDS for all the 'softer' variability classes to examine the HFQPO features. While doing so, we divide 3 – 60 keV energy band into different energy intervals and search for HFQPO features following the same method as discussed in §3.2.4. We find that for γ class observation, the HFQPOs are present only in 6 – 25 keV energy range with higher rms amplitude ($\sim 3.64\%$) and higher significance ($\sigma_{QPO} \sim 12$) at 1σ unit compared to that in 3 – 60 keV energy band (see Table 3.5 and 3.6). What is more is that the PDS corresponding to 3 – 6 keV and 25 – 60 keV energy bands are found to be featureless (see Fig. 3.9) as the $rms\%$ corresponding to the most significant peak are obtained as ~ 0.92 and ~ 0.74 , respectively. In addition, we model the PDS in 3 – 6 keV and 25 – 60 keV energy bands using Lorentzian function with centroid fixed at ~ 72.32 Hz for γ class (see Belloni et al., 2001, Sreehari et al., 2020). The highest values of the significance of the fitted Lorentzian are found to be 1.6σ and 0.7σ in 3 – 6 keV and 25 – 60 keV energy bands, respectively. These results clearly indicate the non-detection of HFQPO feature as the percentage rms are insignificant. We follow same methodology for all the observations under consideration and find that the prominent HFQPO features are present only in 6 – 25 keV energy range (see Fig. 3.9 and Table 3.6). In Fig. 3.9, the HFQPO feature (6 – 25 keV) is shown in each panel along with the non-detection cases (3 – 6 keV and 25 – 60 keV) at the insets of the respective panels.

3.2.6 Dynamical Behavior of HFQPOs

The power spectra in different variability classes reveal that HFQPOs are not persistent but rather sporadic in nature. Therefore, we examine the dynamic nature of the power spectrum, where we search for HFQPO in each segment of duration 32 s of the entire light curve of 1 ms resolution. The Leahy power spectrum (Leahy et al., 1983) for each

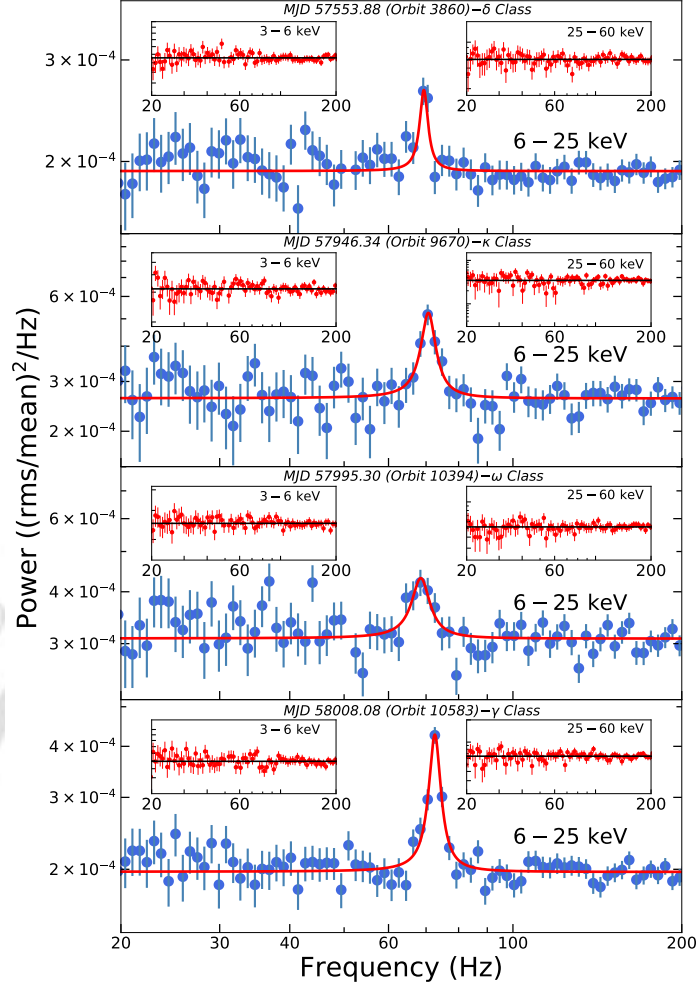


Figure 3.9: Energy-dependent power density spectra depicted in 20 – 200 Hz frequency range. PDS corresponding to δ , κ , ω and γ class observations are presented in sequence from top to bottom panels. Energy ranges are marked in each panel, including insets. The PDS corresponding to 3 – 6 keV and 25 – 60 keV energy ranges are modelled with a **constant**, whereas the PDS in 6 – 25 keV energy range is modelled using a **constant** and a **Lorentzian**. See the text for details.

segment of the light curve is computed and plotted as a vertical slice corresponding to each time bin using the `stingray` package⁴ (Huppenkothen et al., 2019). The frequency bin size is chosen as 2 Hz. We use `bicubic` interpolation (Huppenkothen et al., 2019) to improve clarity and smooth the dynamic power spectrum. The power corresponding to each frequency is color coded such that yellow indicates minimum power and red indicates maximum power as shown in the colorbar of Fig. 3.10.

In the top panel of Fig. 3.10, we present the light curve of Orbit 10411, generated by combining *LAXPC10* and *LAXPC20* light curves along with the corresponding dynamic power spectrum. The light curve corresponds to the ω class variability (see Fig. 3.6). It is observed that the power at frequencies around 70 Hz is significant during ‘non-dips’ (high counts) and is insignificant during the ‘dips’ (low counts). The percentage rms amplitude of the HFQPO during high counts and low counts are obtained as 2.38 ± 0.29 and 0.67 ± 0.18 for ω class observation, respectively. This clearly suggests that the HFQPO of frequencies around 70 Hz are generated when the count rate is high. We also observe similar behavior during γ class observation. From

⁴<https://pypi.org/project/stingray/>

Table 3.6: Estimated percentage rms amplitudes of HFQPOs in different energy bands. All the errors are computed with 68% confidence level. See the text for details.

MJD (Orbit)	HFQPO rms amplitude (%)			Non-detection of HFQPO	Detection of HFQPO	Class
	energy band	energy band	energy band	<i>rms</i> %	<i>rms</i> _{QPO} %	
	(3 – 6 keV)	(6 – 25 keV)	(25 – 60 keV)	(3 – 60 keV)	(3 – 60 keV)	
57451.89 (2351) [†]	–	–	–	0.54 ± 0.23	–	θ
57452.82 (2365) [†]	–	–	–	0.38 ± 0.11	–	χ
57453.35 (2373) [†]	–	–	–	0.44 ± 0.16	–	θ
57504.02 (3124)	0.39 ± 0.11	2.33 ± 0.25	0.81 ± 0.32	–	1.48 ± 0.36	ω
57552.56 (3841) [†]	–	–	–	0.61 ± 0.23	–	δ
57553.88 (3860)	0.79 ± 0.28	2.12 ± 0.22	0.88 ± 0.25	–	1.54 ± 0.48	δ
57689.10 (5862) [†]	–	–	–	0.16 ± 0.09	–	β
57705.22 (6102) [†]	–	–	–	0.86 ± 0.15	–	δ
57891.88 (8863) [†]	–	–	–	0.23 ± 0.12	–	ρ'
57892.74 (8876) [†]	–	–	–	0.77 ± 0.26	–	ρ
57943.69 (9629) [†]	–	–	–	0.94 ± 0.15	–	κ
57943.69 (9633)	0.38 ± 0.14	3.65 ± 0.31	0.56 ± 0.12	–	2.14 ± 0.50	κ
57946.10 (9666)	0.75 ± 0.18	3.34 ± 0.48	0.62 ± 0.21	–	2.55 ± 0.71	κ
57946.34 (9670)	0.83 ± 0.22	4.29 ± 0.54	0.71 ± 0.13	–	2.49 ± 0.37	κ
57961.39 (9891) [†]	–	–	–	0.82 ± 0.24	–	κ
57961.39 (9894)	0.79 ± 0.15	2.86 ± 0.29	0.77 ± 0.11	–	2.28 ± 0.63	κ
57961.59 (9895)	0.19 ± 0.07	3.12 ± 0.63	0.84 ± 0.33	–	1.98 ± 0.41	κ
57995.30 (10394)	0.72 ± 0.21	3.30 ± 0.55	0.67 ± 0.12	–	2.25 ± 0.31	ω
57996.46 (10411)	0.84 ± 0.24	4.01 ± 0.37	0.81 ± 0.15	–	2.66 ± 0.29	ω
58007.80 (10579)	0.68 ± 0.12	3.21 ± 0.42	0.89 ± 0.19	–	1.86 ± 0.37	ω
58008.08 (10583)	0.92 ± 0.16	3.64 ± 0.24	0.74 ± 0.21	–	2.46 ± 0.19	γ
58046.36 (11154) [†]	–	–	–	0.42 ± 0.14	–	δ
58209.13 (13559) [†]	–	–	–	0.76 ± 0.13	–	χ
58565.82 (18839) [†]	–	–	–	0.69 ± 0.11	–	χ

[†] Non-detection of HFQPO.

the bottom panel of Fig. 3.10, it is evident that the source emits at high count rate of about 9000 cts/s throughout the observation during γ class. As a result, HFQPO is seen to be present in almost every 32 s interval, although its power amplitude reduces during the narrow dips (500 – 700 s) present in the light curve. Overall, by analyzing the dynamic PDS, we infer that within the ‘softer’ variability classes (κ , ω and γ), high count rate (non-dips) seems to be associated with the generation of HFQPOs.

3.2.7 Decoding the Spectrum: Insights into Emission Mechanisms

For each variability class, we generate the corresponding wideband energy spectra combining the *SXT* and *LAXPC20* data. We consider 0.7 – 7 keV energy range for *SXT* spectra, whereas *LAXPC* spectra are extracted in the energy range of 3 – 50 keV (see Sreehari et al., 2019a, 2020, for details). The dead-time corrections are applied

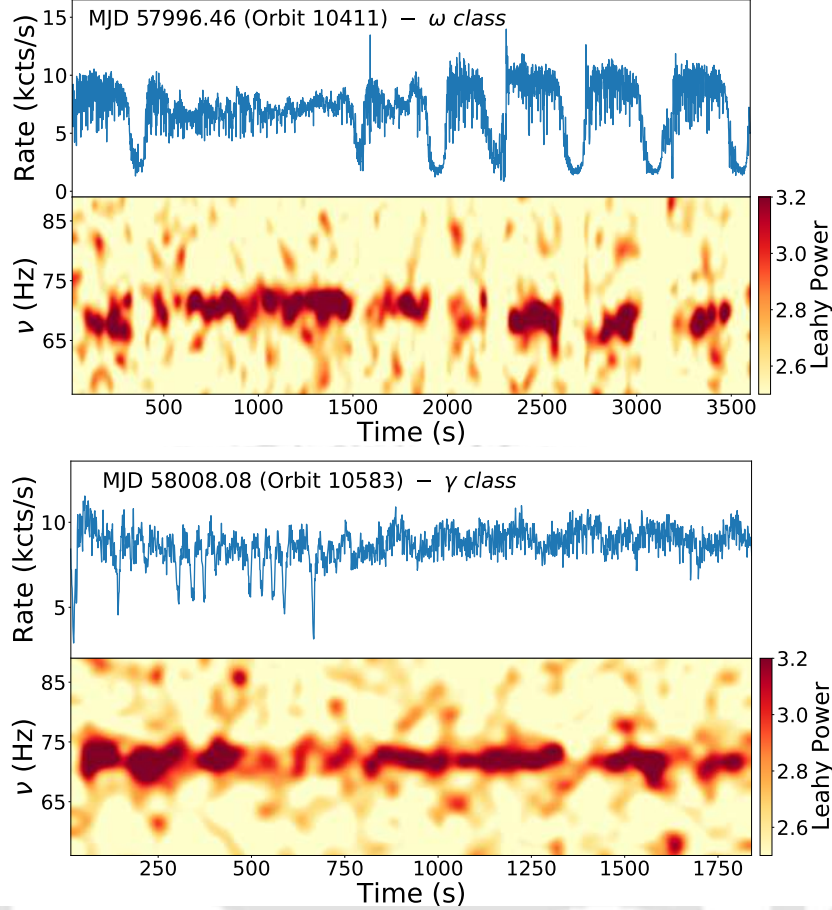


Figure 3.10: The light curves (3 – 60 keV) of ω and γ classes are depicted in the top panels of each plot. In the bottom panels of each plot, the dynamical power spectra generated from the high-resolution (1 ms) light curve are presented. Here, 32 s segment size and 2 Hz frequency bin are used to represent the dynamical power spectra. The obtained results are presented using color code, where colorbars are marked in the right of the bottom panels. See the text for details.

to the *LAXPC* spectra while extracting with *LaxpcSoftv3.4*⁵ software (Antia et al., 2017).

We model the wideband energy spectra using *XSPEC V12.10.1f* in *HEASOFT V6.26.1* to understand the radiative emission processes active around the source. While modeling the energy spectra, we consider a systematic error of 2% for both *SXT* and *LAXPC* data (Antia et al., 2017, Leahy and Chen, 2019, Sreehari et al., 2020). We use the *gain fit* command in *XSPEC* to take care of the instrumental features at 1.8 keV and 2.2 keV in *SXT* spectra. While applying gain fit, we allow the offset to vary and fix the slope at 1. The hydrogen column density (nH) is kept fixed at 6×10^{22} atoms/cm² following Yadav et al. (2016), Sreehari et al. (2020).

To begin with, we adopt a model *Tbabs* × *nthcomp* × *constant* to fit the wideband energy spectrum of γ class observation (Orbit 10583) for which the strongest HFQPO feature is seen in the PDS (bottom panel of Fig. 3.7). Here, the model *Tbabs* (Wilms et al., 2000) takes care of the galactic absorption between the source and the observer. The model *nthcomp* (Zdziarski et al., 1996) represents the thermally Comptonized continuum. A *constant* parameter is used to account for the offset between the spectra from two different instruments, *SXT* and *LAXPC*. The obtained fit yields a

⁵http://www.tifr.res.in/~astrosat_laxpc/LaxpcSoft.html

poor reduced χ^2 ($\chi^2_{\text{red}} = \chi^2/\text{d.o.f}$) of $2095/546 = 3.83$ as there are large residuals left at the higher energies beyond 30 keV. Hence, we include a **powerlaw** along with one Xenon **edge** component at 32 keV (Sreehari et al., 2019a) to fit the high energy part of the spectrum. The Xenon **edge** is required for all the energy spectra to account for the instrumental absorption feature at 32 – 35 keV. Also, one **smedge** component is used at ~ 9 keV to obtain the best fit. The model **Tbabs** $\times$ (**smedge** $\times$ **nthcomp** + **powerlaw**) $\times$ **constant** provides statistically acceptable fit with $\chi^2_{\text{red}} = \chi^2/\text{d.o.f}$ of $563/533 = 1.08$. In the left side of Fig. 3.11, we present the best fitted unfolded energy spectrum of γ class observation for representation.

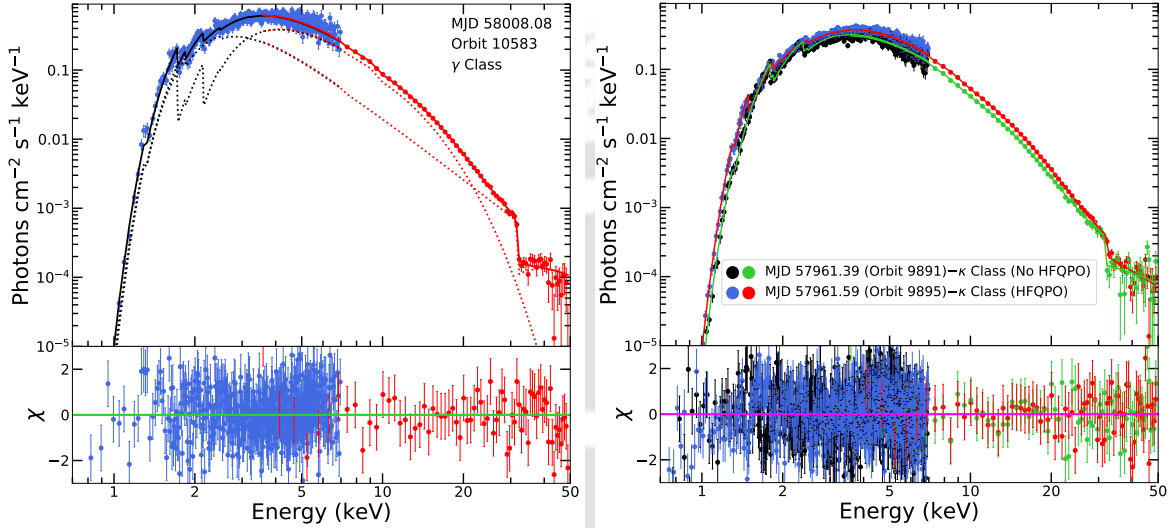


Figure 3.11: Unfolded wideband (0.7 – 50 keV) energy spectra of the source GRS 1915 + 105. The spectra are modelled with **Tbabs** $\times$ (**smedge** $\times$ **nthcomp** + **powerlaw**) $\times$ **constant**. The spectra of γ class observation on MJD 58008.08 (Orbit 10583) are presented on the left. The two best-fitted spectra of κ class variabilities without (MJD 57961.39; Orbit 9891) and with (MJD 57961.59; Orbit 9895) HFQPO are depicted on the right. The bottom panels of each plot show the residuals in units of σ . See the text and Majumder et al. (2022) for details.

The best fitted model parameters of the **nthcomp** component for γ class observation (Orbit 10583) are obtained as electron temperature ($k_B T_e$) = $2.62^{+0.10}_{-0.12}$ keV, photon index (Γ_{nth}) = $2.02^{+0.06}_{-0.07}$ with normalization ($norm_{\text{nth}}$) = 15 ± 2 . The seed photon temperature ($k_B T_{\text{bb}}$) is kept fixed at 0.1 keV during the fitting. The best fitted value for the **powerlaw** photon index is obtained as $\Gamma_{\text{PL}} = 3.00^{+0.05}_{-0.06}$ with **powerlaw** normalization $norm_{\text{PL}} = 21^{+4}_{-3}$. Following the same approach, we carry out the spectral modeling for all other observations of various variability classes (*i.e.*, θ , β , δ , ρ , κ , ω , γ and χ) irrespective to the presence or absence of HFQPOs. The best fitted model parameters are tabulated in Table 3.7. It is found that in all observations, the model **Tbabs** $\times$ (**smedge** $\times$ **nthcomp** + **powerlaw**) $\times$ **constant** satisfactorily describes the energy spectra except for ρ and χ class observations. For ρ class, the acceptable fit is obtained without **powerlaw** component, whereas in χ class observation, an additional **diskbb** component is required along with **nthcomp**. Note that we are unable to constrain the electron temperature for the observations of ρ , ρ' and two χ classes and hence we fix the electron temperature $k_B T_e = 10$ keV and 20 keV, respectively (see Table 3.7). In the right side of Fig. 3.11, we present the wideband energy spectra of two κ class observations on MJD 57961.39 (Orbit 9891) and MJD 57961.59 (Orbit 9895) without and with HFQPO feature, respectively. We point out that the best fitted energy spectrum of orbit 9891 (without HFQPO) has a weak **nthcomp** contribution ($norm_{\text{nth}} \sim 7$), whereas in orbit 9895 (with HFQPO), the **nthcomp** contribution (

$norm_{nth} \sim 16$) is relatively higher. We also find relatively high electron temperatures in those observations that ascertain the detection of HFQPOs except one observation in θ class (Orbit 2351).

Further, we estimate the flux in the energy range $0.7 - 50$ keV associated with different model components used for the spectral fitting. While doing so, the convolution model `cflux` in `XSPEC` is used. For γ class observation, the fluxes associated with `nthcomp` and `powerlaw` components are estimated as 2.49 and 1.37 in units of 10^{-8} erg $\text{cm}^{-2} \text{s}^{-1}$, respectively (see Table 3.7). We also calculate bolometric flux (F_{bol}) in the energy range $0.3 - 100$ keV using the `cflux` model. Considering the mass (M_{BH}) and the distance (d) of the source as $M_{BH} = 12.4M_{\odot}$ and $D = 8.6$ kpc (Reid et al., 2014), we calculate the bolometric luminosity in units of Eddington luminosity (L_{Edd})⁶ as $L_{bol} = F_{bol} \times 4\pi D^2$. The luminosity is found to vary in the range of $3 - 34\%$ L_{Edd} . The calculated flux values and bolometric luminosities for all the observations are given in Table 3.7.

In order to understand the nature of the Comptonizing medium in the vicinity of the source, we calculate the optical depth (τ) of the medium. Following Zdziarski et al. (1996), Chatterjee et al. (2021), the relation among the optical depth (τ), `nthcomp` spectral index ($\Gamma = \Gamma_{nth} - 1$), and electron temperature ($k_B T_e$) is given by,

$$\Gamma = \left[\frac{9}{4} + \frac{1}{\left(\frac{k_B T_e}{m_e c^2} \right) \tau \left(1 + \frac{\tau}{3} \right)} \right]^{1/2} - \frac{3}{2}, \quad (3.1)$$

where m_e is the electron mass, k_B is the Boltzmann constant and c refers to the speed of light. Using Eq. 3.1, the optical depth (τ) is calculated and found in the range $2 \lesssim \tau \lesssim 14$ for all the observations. This implies that an optically thick corona is present as a Comptonizing medium in the vicinity of the source. Moreover, we calculate the Compton y-parameter (y_{par}), which measures the degree of Compton up-scattering of soft photons in the underlying accretion flow by the Comptonizing medium. Following Agrawal et al. (2018), Chatterjee et al. (2021), the Compton y-parameter ($y_{par} = 4k_B T_e \tau^2 / m_e c^2$) in the optically thick medium is found to be in the range of $0.63 \pm 0.08 - 3.12 \pm 0.35$. In Table 3.7, we tabulate the obtained optical depth (τ) and Compton y-parameter values for all the observations.

3.2.8 Correlation Among Spectral and Timing Properties

In this section, we examine the spectro-temporal correlation in different variability classes of GRS 1915+105. While doing so, we consider four variability classes, namely δ , κ , ω and γ , and study the variation of the percentage rms amplitude ($rms_{QPO}\%$) of HFQPO features as function of energy shown in the top panel of Fig. 3.12. The results corresponding to δ , κ , ω and γ classes are denoted by the filled triangles (blue), asterisks (yellow), squares (green) and circles (red), respectively. We find that $rms_{QPO}\%$ increases with energy up to ~ 17 keV and then sharply decreases. Further, to correlate the evolution of $rms_{QPO}\%$ with the Comptonized flux (*i.e.*, `nthcomp`), we present the variation of the estimated `nthcomp` flux in the respective energy bands as shown in the bottom panel of Fig. 3.12. We notice that `nthcomp` flux decreases with energy and it

⁶Eddington luminosity $L_{Edd} = 1.26 \times 10^{38} (M_{BH}/M_{\odot})$ erg s^{-1} for a compact object of mass M_{BH} (Frank et al., 2002).

Table 3.7: Best fitted parameters of the wideband (0.7 – 50 keV) energy spectra of GRS 1915+105 with the model $\text{tbabs} \times (\text{smedge} \times \text{nthcomp} + \text{powerlaw}) \times \text{constant}$ for different observations as mentioned in Table 3.4. In the table, $k_B T_e$ is the electron temperature in keV, Γ_{nth} is the `nthcomp` photon index, norm_{nth} is the `nthcomp` normalization. Γ_{PL} and norm_{PL} are the `powerlaw` photon index and normalization, respectively. F_{nth} and F_{PL} are the flux in $\text{erg cm}^{-2} \text{s}^{-1}$ associated with `nthcomp` and `powerlaw` components, respectively. F_{bol} , L_{bol} , τ and y_{par} are the bolometric flux, bolometric luminosity in units of $\%L_{\text{Edd}}$, optical depth and Compton y -parameter, respectively. All the errors are computed with 90 per cent confidence level. See the text for details.

Model fitted parameters						Estimated parameters							
MJD (Orbit)	$k_{\rm B}T_e$ (keV)	$\Gamma_{\rm nth}$	$norm_{\rm nth}$	$\Gamma_{\rm PL}$	$norm_{\rm PL}$	$\chi^2_{\rm red}$	$F_{\rm nth}$ (0.7 – 50 keV)	$F_{\rm PL}$ (0.7 – 50 keV)	$F_{\rm bol}$ (0.3 – 100 keV) $\boxplus$	$L_{\rm bol}$ (% $L_{\rm Ed}$)	τ	$y_{\rm par}$	Class
							$(10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1})$	$(10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1})$	$(10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1})$				
57451.89 (2351) [†]	$3.66^{+0.11}_{-0.12}$	$2.89^{+0.08}_{-0.05}$	34^{+3}_{-2}	$2.85^{+0.07}_{-0.07}$	42^{+4}_{-3}	1.14	2.51	2.84	5.38	30	6	0.83 ± 0.06	θ
57452.82 (2365) ^{†,¶}	$23.92^{+7.54}_{-4.72}$	$2.57^{+0.03}_{-0.03}$	18^{+1}_{-1}	—	—	1.06	2.45	—	3.03	17	2	0.63 ± 0.08	χ
57453.35 (2373) [†]	$3.10^{+0.08}_{-0.07}$	$2.47^{+0.03}_{-0.02}$	29^{+4}_{-2}	$2.59^{+0.03}_{-0.03}$	23^{+2}_{-2}	1.08	2.85	3.14	6.05	34	7	1.29 ± 0.04	θ
57504.02 (3124)	$2.37^{+0.12}_{-0.11}$	$1.97^{+0.06}_{-0.05}$	16^{+3}_{-2}	$2.65^{+0.09}_{-0.08}$	4^{+2}_{-1}	1.18	4.46	0.44	5.06	28	12	2.47 ± 0.21	ω
57552.56 (3841) [†]	$1.94^{+0.04}_{-0.05}$	$1.83^{+0.06}_{-0.08}$	16^{+3}_{-4}	$3.27^{+0.05}_{-0.06}$	34^{+6}_{-7}	1.19	3.52	1.71	5.24	29	14	3.12 ± 0.35	δ
57553.88 (3860)	$2.53^{+0.10}_{-0.11}$	$2.08^{+0.09}_{-0.11}$	19^{+5}_{-5}	$3.18^{+0.05}_{-0.04}$	32^{+4}_{-3}	1.12	3.57	1.15	4.73	27	10	2.11 ± 0.31	δ
57689.10 (5862) [†]	$1.82^{+0.11}_{-0.09}$	$2.13^{+0.06}_{-0.06}$	12^{+4}_{-3}	$2.83^{+0.07}_{-0.07}$	20^{+4}_{-5}	1.11	1.64	1.91	3.85	22	12	2.06 ± 0.16	β
57705.22 (6102) [†]	$1.93^{+0.06}_{-0.04}$	$1.90^{+0.05}_{-0.05}$	15^{+4}_{-2}	$3.21^{+0.04}_{-0.03}$	24^{+3}_{-2}	1.08	2.37	1.67	4.26	24	14	2.80 ± 0.21	δ
57891.88 (8863) [†]	10^*	$2.30^{+0.04}_{-0.02}$	9^{+2}_{-1}	—	—	1.22	1.03	—	1.05	6	—	—	ρ'
57892.74 (8876) [†]	10^*	$2.86^{+0.04}_{-0.07}$	13^{+3}_{-2}	—	—	1.17	1.02	—	1.16	7	—	—	ρ

$\boxminus$ *SXT* response extends from 0.3 keV. [†] No detection of HFOPO. [*] Frozen at 10 and 20 keV, below this value the spectral fitting is affected yielding higher χ^2_{red} . [¶] Modelled with `diskbb` and `nthcomp` component. Inner disc temperature, $k_B T_{\text{in}} \sim 0.25$ keV.

Table 3.7: Continued.

Model fitted parameters										Estimated parameters				
MJD (Orbit)	$k_B T_e$ (keV)	Γ_{nth}	$norm_{nth}$	Γ_{PL}	$norm_{PL}$	χ^2_{red}	F_{nth} (0.7 – 50 keV) (10^{-8} erg cm $^{-2}$ s $^{-1}$)	F_{PL} (0.7 – 50 keV) (10^{-8} erg cm $^{-2}$ s $^{-1}$)	F_{bol} (0.3 – 100 keV) $^{\boxplus}$ (10^{-8} erg cm $^{-2}$ s $^{-1}$)	L_{bol} ($\%L_{Edd}$)	τ	y_{par}	Class	
57943.69 (9629) †	$2.38^{+0.06}_{-0.06}$	$1.96^{+0.08}_{-0.07}$	6^{+1}_{-1}	$2.73^{+0.05}_{-0.05}$	2^{+1}_{-1}	1.02	1.04	0.59	1.65	9	12	2.51 ± 0.29	κ	
57943.69 (9633)	$2.36^{+0.06}_{-0.05}$	$2.11^{+0.07}_{-0.09}$	7^{+1}_{-2}	$3.26^{+0.04}_{-0.03}$	15^{+3}_{-1}	1.18	1.06	0.52	1.57	9	11	2.04 ± 0.21	κ	
57946.10 (9666)	$2.39^{+0.11}_{-0.08}$	$2.03^{+0.06}_{-0.05}$	7^{+2}_{-1}	$3.13^{+0.04}_{-0.04}$	13^{+3}_{-2}	1.03	1.21	0.54	1.76	10	11	2.27 ± 0.19	κ	
57946.34 (9670)	$2.50^{+0.07}_{-0.06}$	$2.06^{+0.04}_{-0.04}$	7^{+1}_{-1}	$3.24^{+0.03}_{-0.03}$	16^{+1}_{-1}	1.17	1.10	0.55	1.78	10	11	2.17 ± 0.12	κ	
57961.39 (9891) †	$2.48^{+0.09}_{-0.08}$	$1.97^{+0.06}_{-0.06}$	7^{+1}_{-1}	$2.80^{+0.05}_{-0.06}$	6^{+1}_{-2}	1.23	1.03	0.84	2.03	12	11	2.46 ± 0.21	κ	
57961.39 (9894)	$2.64^{+0.10}_{-0.07}$	$2.10^{+0.07}_{-0.05}$	10^{+1}_{-1}	$3.05^{+0.05}_{-0.04}$	14^{+1}_{-1}	1.12	1.52	0.83	2.48	14	10	2.04 ± 0.19	κ	
57961.59 (9895)	$2.77^{+0.11}_{-0.12}$	$2.23^{+0.07}_{-0.12}$	16^{+3}_{-2}	$3.12^{+0.05}_{-0.05}$	18^{+1}_{-1}	1.06	1.53	0.98	2.53	14	9	1.72 ± 0.25	κ	
57995.30 (10394)	$3.06^{+0.13}_{-0.08}$	$2.44^{+0.05}_{-0.08}$	33^{+4}_{-5}	$3.12^{+0.04}_{-0.03}$	26^{+4}_{-2}	1.06	1.74	1.37	3.23	18	8	1.33 ± 0.12	ω	
57996.46 (10411)	$3.07^{+0.11}_{-0.11}$	$2.36^{+0.05}_{-0.05}$	27^{+3}_{-3}	$3.13^{+0.04}_{-0.04}$	24^{+1}_{-1}	1.17	1.94	1.36	3.43	19	8	1.46 ± 0.08	ω	
58007.80 (10579)	$2.67^{+0.09}_{-0.11}$	$2.17^{+0.06}_{-0.11}$	21^{+3}_{-4}	$3.10^{+0.03}_{-0.04}$	26^{+2}_{-1}	0.98	2.24	1.31	3.85	22	9	1.86 ± 0.14	ω	
58008.08 (10583)	$2.62^{+0.10}_{-0.12}$	$2.02^{+0.06}_{-0.07}$	15^{+2}_{-2}	$3.00^{+0.05}_{-0.06}$	21^{+4}_{-3}	1.08	2.49	1.37	4.16	23	11	2.27 ± 0.22	γ	
58046.36 (11154) †	$2.03^{+0.08}_{-0.06}$	$1.84^{+0.05}_{-0.05}$	15^{+3}_{-2}	$2.99^{+0.07}_{-0.06}$	14^{+2}_{-1}	1.25	3.36	1.68	5.12	29	14	3.05 ± 0.24	δ	
58209.13 (13559) †,¶	20*	$2.19^{+0.04}_{-0.04}$	8^{+1}_{-1}	—	—	0.93	2.21	—	2.34	13	—	—	χ	
58565.82 (18839) †,¶	20*	$1.88^{+0.02}_{-0.02}$	$0.71^{+0.03}_{-0.02}$	—	—	1.03	0.51	—	0.53	3	—	—	χ	

[‡] *SXT* response extends from 0.3 keV. [†] No detection of HFQPO. [*] Frozen at 10 and 20 keV, below this value the spectral fitting is affected yielding higher χ^2_{red} . [†] Modelled with `diskbb` and `nthcomp` component. Inner disc temperature, $k_B T_{in} \sim 0.25$ keV.

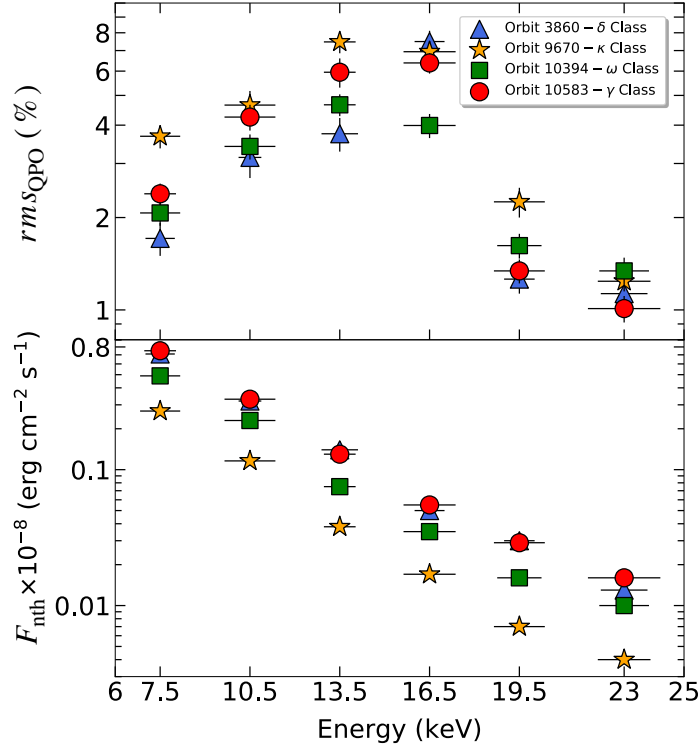


Figure 3.12: *Top*: Variation of percentage rms amplitudes ($rms_{QPO}\%$) of HFQPOs with energy for δ , κ , ω and γ variability classes. *Bottom*: Variation of **nthcomp** flux (F_{nth}) with energy corresponding to the variability classes as marked in the inset of the top panel. See the text for details.

becomes negligible beyond ~ 25 keV ($\sim 2\%$ of the total **nthcomp** flux in $3 - 60$ keV; see also Fig. 3.11).

In Fig. 3.13, we present the variation of photon index (Γ_{nth}) with the **nthcomp** flux (F_{nth}) for observations in δ , ρ , κ , ω , γ , β , and θ variability classes. Here, the variation of the percentage rms amplitude ($rms\%$) of the detected HFQPOs, as well as the $rms\%$ of the non-detection of HFQPOs (see Table 3.6) are shown using color code. We find that $rms\%$ of HFQPOs lies in the range $\gtrsim 1.5\%$ and it drops below 1% when HFQPOs are not seen. Further, we notice that in ω class observations, Γ_{nth} decreases with the increase of **nthcomp** flux in the range $1.8 \times 10^{-8} \lesssim \text{Flux}_{nth} \text{ (erg cm}^{-2} \text{ s}^{-1}) \lesssim 4.5 \times 10^{-8}$. In κ variability classes, marginal variations are observed in the **nthcomp** flux, unlike ω class observation, although photon indices remain $\Gamma_{nth} \gtrsim 2$ when HFQPOs are present. For δ variability classes, we find $3.5 \times 10^{-8} \lesssim \text{Flux}_{nth} \text{ (erg cm}^{-2} \text{ s}^{-1}) \lesssim 4.58 \times 10^{-8}$ and $\Gamma_{nth} \gtrsim 1.9$ for HFQPOs. In addition, we point out that HFQPOs are not seen for θ , β and ρ class observations, although they belong to the ‘softer’ variability classes.

3.2.9 On the Origin of HFQPOs

In this work, we investigate the in-depth spectro-temporal properties of GRS 1915+105 in the presence of its HFQPO feature at ~ 70 Hz. We find the signatures of HFQPOs in δ , ω , κ , and γ variability classes in $3 - 60$ keV energy range. The energy-dependent power spectral study confirms that $6 - 25$ keV energy band photons are responsible for the origin of the HFQPOs (see Fig. 3.9). Moreover, we find that the significance and percentage rms amplitudes of the HFQPOs are higher in $6 - 25$ keV energy band

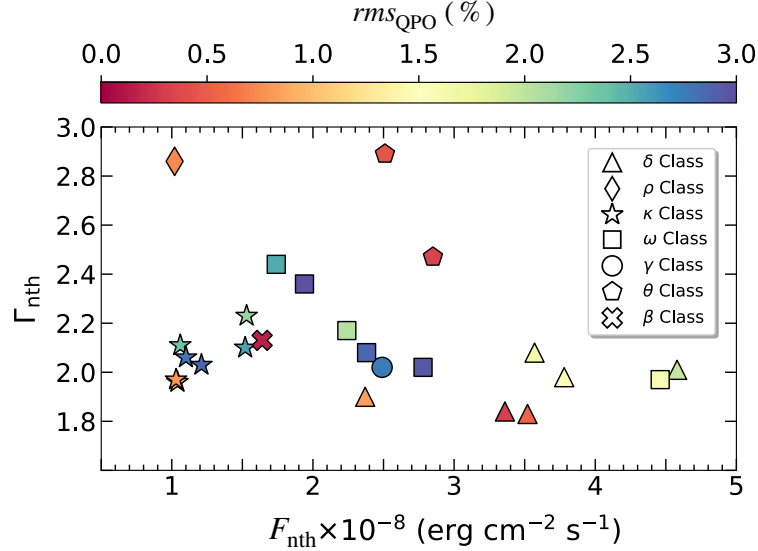


Figure 3.13: Variation of photon index (Γ_{nth}) as a function of Comptonized flux associated with **nthcomp** (see Table 3.7) for δ , ρ , κ , ω , γ , θ and β variability classes. The color codes denote the rms amplitudes ($\text{rms}_{\text{QPO}}\%$) corresponding to the detection and non-detection of HFQPOs. The obtained results for different variability classes are presented using different symbols, which are marked in the inset. See the text for details.

compared to 3–60 keV energy band (see Table 3.6). Notably, κ and ω class variabilities exhibit different durations of ‘non-dips’ (high counts ~ 9600 cts/s) and ‘dips’ (low counts ~ 1250 cts/s) features. While studying the dynamic PDS for these classes, it is found that the HFQPO is generally present during ‘non-dips’ period with relatively higher rms amplitude (2.38% and 2.35% for ω and κ classes).

Notably, wideband energy spectra (0.7 – 50 keV) of θ , β , δ , κ , ω and γ class observations are satisfactorily described by the thermal Comptonization **nthcomp** along with a **powerlaw** component (see Fig. 3.11 and Table 3.7). On the contrary, the **nthcomp** component seems to be adequate to fit the energy spectra of ρ class observations. From the spectral modeling, we obtain the range of **nthcomp** photon index as $1.83 \lesssim \Gamma_{\text{nth}} \lesssim 2.89$, and electron temperature as $1.82 \lesssim k_{\text{B}}T_{\text{e}} \lesssim 3.66$ keV (see Table 3.7). In addition, we obtain a steep **powerlaw** photon index (Γ_{PL}) as 2.59 – 3.27 for all the variability classes under consideration. Similar steep Γ_{PL} is also reported in the previous studies carried out for θ (Belloni et al., 2006) and δ (Sreehari et al., 2020) variability classes of the source. We estimate the optical depth (τ) of the surrounding medium and obtain its value as $2 \lesssim \tau \lesssim 14$. This evidently indicates the presence of a cool and optically thick corona around the source, which presumably acts as a Comptonizing medium that reprocesses the soft seed photons. The Compton y-parameter is obtained in the range 0.63 – 3.12, which implies that the soft photons are substantially reprocessed via Comptonization at the optically thick corona.

Furthermore, we examine the energy dependent (6 – 25 keV) $\text{rms}_{\text{QPO}}\%$ of HFQPOs in δ , κ , ω , and γ variability classes, and find that $\text{rms}_{\text{QPO}}\%$ increases (1 – 8%) with energy up to ~ 17 keV and then decreases (see Fig. 3.12). Subsequently, we observe that the Comptonized flux (F_{nth}) decreases with energy, which tends to become negligible beyond ~ 25 keV. This possibly happens when the soft photons emitted from the disc are Comptonized by the ‘hot’ electrons from an optically thick corona ($8 \lesssim \tau \lesssim 12$) and produce the aforementioned Comptonized continuum. In

order to elucidate the spectra above ~ 25 keV, an additional `powerlaw` component with photon index $\Gamma_{\text{PL}} \sim 3$ is required. This eventually indicates that there could be an extended corona present surrounding the central corona, which is responsible for these high-energy emissions (Titarchuk and Seifina, 2009, Sreehari et al., 2020, Harikesh et al., 2025). We further notice that for intermediate range of `nthcomp` photon index ($1.97 \lesssim \Gamma_{\text{nth}} \lesssim 2.44$) along with the large variation of `nthcomp` flux ($1.06 \times 10^{-8} \lesssim F_{\text{nth}} \text{ (erg cm}^{-2} \text{ s}^{-1}) \lesssim 4.46 \times 10^{-8}$) generally yields HFQPO signature in δ , κ , ω and γ variability classes (see Fig. 3.13). With this, we argue that the Comptonization process plays a viable role in exhibiting HFQPO. Overall, based on the findings presented above, we conjecture that HFQPOs in GRS 1915+105 are perhaps manifested due to the modulation of the ‘Comptonizing corona’ surrounding the central source (Méndez et al., 2013, Aktar et al., 2017, Aktar et al., 2018, Dihingia et al., 2019, Sreehari et al., 2020).

3.3 Discovery of a New Class with Twin Peak HFQPO in GRS 1915 + 105

In the preceding section, we discuss the characteristics of eight previously known variability classes of GRS 1915 + 105 as observed during the *AstroSat* monitoring of the source. These classes are consistent with those previously reported in the literature. However, during a thorough and systematic investigation of the complete *AstroSat* archival dataset spanning over five years, we have discovered a variability pattern in GRS 1915 + 105 that does not correspond to any of the 15 known classes found so far. In the following section, we present a comprehensive spectro-temporal characterization of this ‘unknown’ variability class.

3.3.1 Distinct Variability Signature of ‘unknown’ Class

MAXI/GSC Monitoring of GRS 1915+105

We study the evolution of the source GRS 1915 + 105 with daily MAXI/GSC monitoring. In Fig. 3.14a, we present the light curve in 2 – 20 keV energy range during MJD 57711 – 58061. In Fig. 3.14b, we show the variation of hardness ratio (HR) defined as the ratio of counts in 6 – 20 keV and 2 – 6 keV energy bands. The dashed vertical lines in brown, black, green and magenta denote the Epochs corresponding to *AstroSat* and *NuSTAR* observations under consideration. Further, we carry out a correlation study between HR and count rates for two distinct regions of the MAXI/GSC light curves, represented by orange (Seg 1) and blue (Seg 2) colors in Fig. 3.14. The variation of HR against the count rates for each of these two segments is shown in the insets of Fig. 3.14b. While computing the Pearson correlation coefficient (p) of these distributions, we consider all the data points in Seg 1, whereas count rates exceeding 5 counts $\text{cm}^{-2} \text{ s}^{-1}$ are excluded for Seg 2. With this, we find a moderate negative (positive) correlation between HR and count rate for Seg 1 (Seg 2), with $p = -0.7(+0.7)$.

Moreover, we note that the *AstroSat* observations considered in this study fall within the Seg 2 region. This suggests that, during this period, the source was exhibiting ‘softer’ spectral characteristics with a ~ 2.5 times increase in the count rate and a marginal variation in the HR. The detection of ‘softer’ variability classes (‘unknown’, δ , and κ) during this period further supports the softening behavior of the

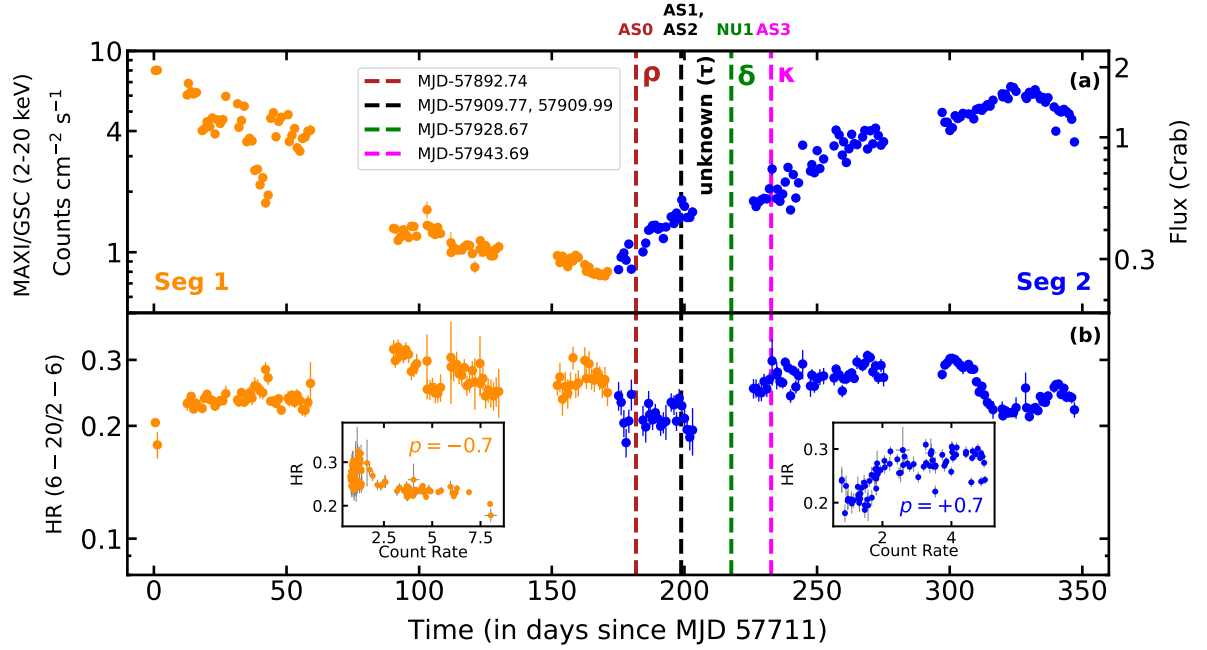


Figure 3.14: (a) *MAXI/GSC* daily light curve in the energy band of 2 – 20 keV in flux units of counts cm⁻² s⁻¹. (b) The variation of the hardness ratio is defined as the ratio of 6 – 20 keV to 2 – 6 keV count rates with the time of observation. In panel (b), the insets show the variation of the hardness ratio with the corresponding count rates, indicated by distinct colors (orange and blue). p denotes the Pearson correlation coefficient between the count rate and hardness ratio distributions. Different colored vertical dashed lines represent the Epochs of observations with *AstroSat* and *NuSTAR*, respectively. See the text for details.

source. At the initial phase of Seg 2 the *MAXI/GSC* count rate was $\lesssim 1$ counts cm⁻² s⁻¹, during which ρ class variability characterized by quasi-periodic flares with relatively harder characteristics in the CCD (see Belloni et al. 2000) was detected. It is important to note that the canonical χ class variability of harder spectral characteristics in GRS 1915 + 105 is generally associated with the less variable quiescent state C, often persisting over longer timescales ranging from hours to months (Belloni et al., 2000). In contrast, the ϕ class, which resembles a typical soft state variability pattern, is seen to be connected with the outbursting state A of the source (Belloni et al., 2000). Notably, the ‘softer’ variability classes (‘unknown’, δ , and κ) remain in between these two and correspond to rapid transitions between the outbursting states and the short-lived quiescent state C on much smaller timescales of a few tens of seconds.

Temporal Variability

We generate 1 s binned background subtracted *LAXPC10* and *LAXPC20* combined light curves in 3 – 60 keV energy range to investigate the variability properties of the source. The dead-time corrected average incident and detected count rates estimated in 3 – 60 keV energy range are given in Table 3.8. We generate the CCDs of each *AstroSat/LAXPC* observation following the definitions of *HR1* and *HR2* mentioned in the previous section (see §3.2). Similarly, the CCD of *NuSTAR* observation is calculated considering the same energy bands. The average of *HR1* and *HR2* for each observation are listed in Table 3.8. We present the light curves (*SXT* in grey, and *LAXPC* in blue and red) of AS1 and AS2 Epochs in Fig. 3.15a and Fig. 3.15c along with the CCDs at top right insets. The variation of hardness ratio ($HR = D/A$)

Table 3.8: Observation details of GRS 1915 + 105 observed by *AstroSat* and *NuSTAR* during June, 2017. Column 1, 2, 4, 5 and 6 are for ObsID, Epoch, Orbit number, MJD and exposure time. In column 3, ‘Seg.’ denotes the light curve segments for Epochs AS1 and AS2. The detected (r_{det}) and incident (r_{in}) count rates along with hardness ratios (HRs) for each variability classes are tabulated in column 7 – 10. In column 11 – 12, the variability classes and the presence of Low/High-frequency QPO features in respective observations are given. See the text for details.

ObsID	Epoch	Seg.	Orbit	MJD (Start)	Effective Exposure (ks)	r_{det} (cts/s)	r_{in} (cts/s)	HR1 (B/A)*	HR2 (C/A)*	HR1 _{var} (%)	HR2 _{var} (%)	$r_{\text{det_var}}$ (%)	Class	LF/HF QPO
10408-01-30-00	RX0	2	–	50313.31	3.4	16919	–	0.68	0.09	2	7	7	χ_3	LF
20402-01-33-00	RX1	2	–	50617.61	3.3	14676	–	1.14	0.11	24	27	60	κ	LF
20402-01-53-01	RX2	1	–	50757.21	3.2	21288	–	1.02	0.08	17	21	27	μ	–
G07_046T01_9000001236	AS0	–	8876	57892.74	3.63	1292	1328	0.61	0.09	13	28	42	ρ	LF
G07_028T01_9000001272	AS1	1a	9127	57909.77	2.43	2156	2259	0.62	0.04	16	37	60	unknown	–
		1b	9127 – 9128	57909.83	3.36	2236	2348	0.62	0.04	16	44	62	unknown	HF
		1c	9130	57909.89	2.95	2235	2346	0.62	0.04	17	49	72	unknown	–
		1d	9130 – 9131	57909.98	0.94	2133	2235	0.60	0.04	15	30	48	unknown	–
G07_046T01_9000001274	AS2	2a	9131 – 9136	57909.99	6.53	2135	2236	0.61	0.04	15	29	47	unknown	–
		2b	9136 – 9139	57910.43	9.03	2167	2272	0.60	0.04	14	31	45	unknown	HF
30302018002	NU1	–	–	57928.67	18.4	572	–	0.78	0.02	7	31	4	δ	–
G07_028T01_9000001370	AS3	–	9629	57943.69	0.98	2814	2993	0.76	0.04	21	43	47	κ	–

* A, B and C are the count rates in 3 – 6 keV, 6 – 15 keV and 15 – 60 keV energy ranges, respectively.

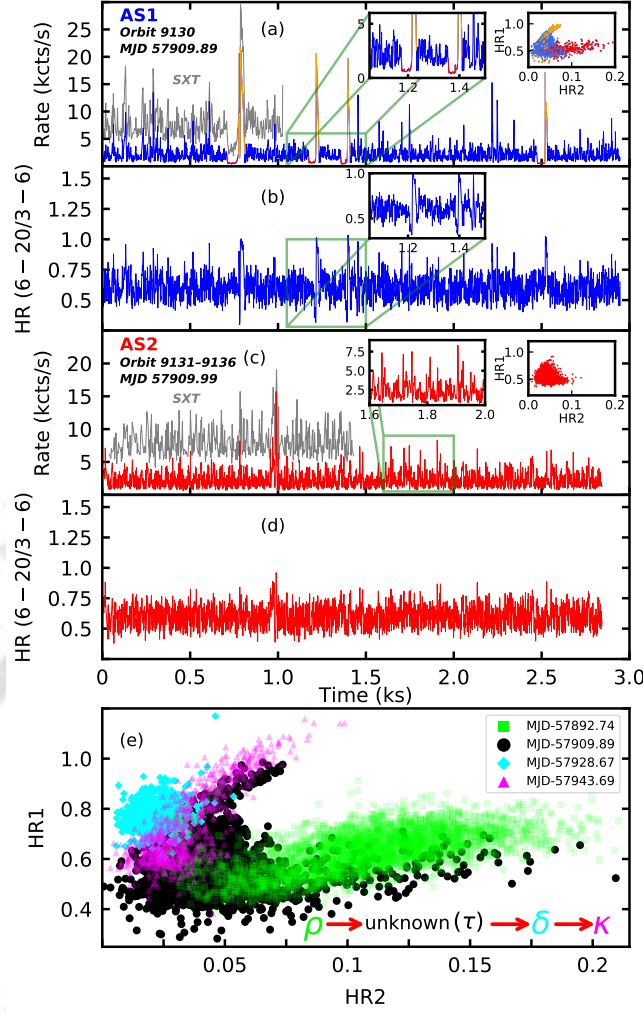


Figure 3.15: Background subtracted and dead-time corrected 1 s binned light curves (*LAXPC* in 3 – 60 keV) of GRS 1915+105 observed with *AstroSat* during Epoch AS1 (a) and AS2 (c), respectively. The *SXT* light curves of AS1 and AS2, simultaneous with *LAXPC* is shown with gray color. The CCD of the same observations are shown at the top right insets, respectively. The variation of the corresponding hardness ratios are shown in panel (b) and (d). The comparison of CCDs in different variability classes under consideration is shown in panel (e). See the text and Majumder et al. (2025b) for details.

corresponding to AS1 and AS2 is depicted in Fig. 3.15b and Fig. 3.15d, respectively, where D is the count rates in the 6 – 20 keV energy band.

Investigation of the variability patterns observed in the *LAXPC* light curve of AS1 reveals the appearance of several irregular ‘dips’ (low counts) of maximum ~ 60 s duration (Fig. 3.15a) between two consecutive ‘non-dip’ (steady counts) segments. In addition, a ‘flare’ like feature is also seen immediately after the ‘dip’. However, Epoch AS2 exhibits almost steady light curves (Fig. 3.15c) similar to the ‘non-dip’ duration of AS1. The pattern of the CCD of AS2 (Fig. 3.15c) resembles with that of AS1 (‘C’ shape pattern, see Fig. 3.15a) without its two elongated branches. Further, we investigated the variability properties of AS1 and AS2 observation across different energy bands. For this, in Fig. 3.16, we present the light curves of AS1 and AS2 observations in 3 – 6 keV, 6 – 15 keV, and 15 – 60 keV energy bands, focusing on the time interval (0.6 – 1.5 ks) during which the repetitive dip and spike-like features are observed (see Fig. 3.15). Interestingly, we find that the overall structured variability pattern remains broadly similar across all energy bands, with only the count rate varying

between them. More specifically, we observe that the low-count ‘dip’ features in the light curve are most prominent and pronounced in the 3 – 6 keV and 6 – 15 keV energy bands, but they disappear in the 15 – 60 keV band. In contrast, the characteristics of the spike-like features remain similar across all energy bands. In addition, during the AS2 observation, the structured variability shows marginal differences in different energy bands.

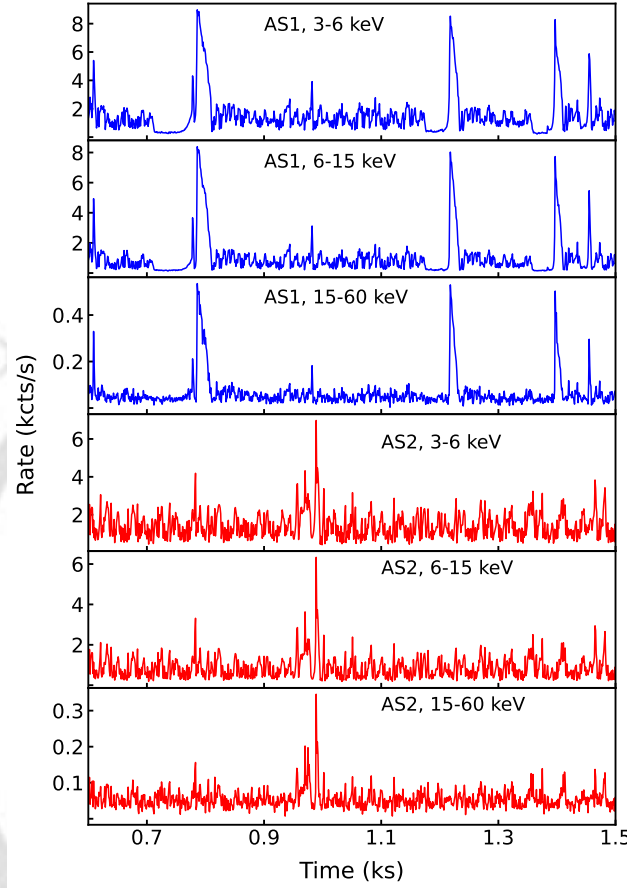


Figure 3.16: Light curves from the AS1 and AS2 observations in the 3 – 6 keV, 6 – 15 keV, and 15 – 60 keV energy ranges are shown in the top, middle, and bottom panels, respectively. These segments correspond to the 0.6 – 1.5 ks interval of the full light curves shown in Fig. 3.15, highlighting the structured variability. See text for details.

The observed variability pattern seems to be different from the known 15 variability classes of GRS 1915+105. Indeed, the overall shape of the CCD in AS1 is coarsely similar to the λ class; however, the variability pattern and the duration of ‘dip’ and ‘non-dip’ segments are distinctly different from the λ and κ classes. Further, the ‘flare’ like features observed just after the ‘dips’ in AS1 seem to be similar to ρ class (Belloni et al., 2000, Athulya et al., 2022). In a preceding observation with *AstroSat* (AS0 in Fig. 3.14, see Table 3.8) 16 days before AS1, the source was in ρ class (Athulya et al., 2022). In addition, the source was observed in κ class (Epoch AS3 in Fig. 3.14, see Table 3.8) after 33 days of AS2. Interestingly, the *NuSTAR* observation (NU1 in Fig. 3.14, see Table 3.8) which is 15 days prior to AS3 shows δ class variability. All the above findings clearly indicate that the source exhibits multiple class transitions within a months timescale during Epoch AS0 to AS3. Therefore, we infer that possibly GRS 1915 + 105 went through an ‘unknown’ variability class rather than the previously known 15 distinct classes. However, we also note that due to the lack of continuous

observations of the source, we are unable to track all possible class transitions that might have occurred on timescales of hours to days, as is typically seen for GRS 1915+105 (Chakrabarti et al., 2005).

In Fig. 3.15e, we compare the CCDs generated from Epochs AS0, AS1, NU1 and AS3 (Table 3.8). It is evident that the source underwent transition from ρ to κ class via an ‘unknown’ and δ class variabilities. A detailed investigation of the CCDs indicates that the ‘harder’ tail (black filled circles with $HR1 \lesssim 0.6$ and $HR2 \gtrsim 0.07$) and the ‘softer’ branch ($HR1 \gtrsim 0.6$ and $HR2 \lesssim 0.07$) of AS1 overlap with the distributions of a ρ (filled green squares) and κ (filled magenta triangles) classes, respectively. We observe that δ class (filled cyan diamonds), generally ‘softer’ in nature, appears in between AS0 and AS3, and it makes the ‘unknown’ class more complex as the CCD shows the mixed properties of both ρ and κ classes. This further corroborates the appearance of an ‘unknown’ variability class which is characterized by the irregular soft ‘dips’ along with ‘flare’ like spikes in the light curve between two consecutive steady count rates.

Comparison with χ_3 , κ and μ classes

In this section, we perform a comparative study between the variability properties of the ‘unknown’ class (AS1 and AS2) and the canonical χ_3 , κ and μ classes observed with *RXTE/PCA* (see Table 3.8). In doing so, we present 1 s time binned light curves of the χ_3 , κ , and μ classes in Fig. 3.17 with CCDs at the insets, obtained from the *RXTE/PCA* data in 3 – 60 keV energy band. Note that, to compare with AS1 and AS2 observations, we obtain the CCDs of χ_3 , κ and μ classes using the definition of soft color and hard color as $HR1 = B/A$ and $HR2 = C/A$, respectively, where A , B and C represent the light curves in 3 – 6 keV, 6 – 15 keV and 15 – 60 keV energy bands, respectively. It is important to note that the observed structured variability pattern in the light curve and the shape of the CCD for a given class largely depend on both the effective area of the instruments used and, to some extent, the overall flux level of the source. For instance, the *AstroSat/LAXPC* observations were conducted at a relatively lower source intensity of ~ 555 mCrab and with a much larger effective area beyond ~ 10 keV (Beri et al., 2019). In contrast, the *RXTE/PCA* observations were performed during a much brighter phase of the source (~ 1.2 Crab). Because of that, despite the sharply declining effective area of *RXTE/PCA* beyond ~ 10 keV, the count rates at higher energies may increase significantly, thereby altering the hardness ratios. Keeping these limitations in mind, in this section, we focus solely on a qualitative comparison between the CCDs of different classes observed with *RXTE/PCA* and the ‘unknown’ variability class observed with *AstroSat/LAXPC*.

In Fig. 3.15 and Fig. 3.17, we observe that the structured variability in the ‘unknown’ class remains different from the individual variability patterns of χ_3 and μ classes mainly due to the appearance of irregular small duration dips followed by high count spikes in AS1. Interestingly, these dip features appear somewhat similar to the low-count dips of varying durations observed in the κ class (see Fig. 3.17). However, we find that the typical duration of these dips is about ~ 60 s in AS1, whereas it varies between $\sim 50 - 90$ s in the κ class. Moreover, the fractional noise amplitudes (defined as the standard deviation normalized by the mean count rate) of these dip intervals are found to be $\sim 9.3\%$ and $\sim 15.2 - 17.4\%$ for the ‘unknown’ and κ variability classes observed with *AstroSat* and *RXTE*, respectively. This suggests that although an ap-

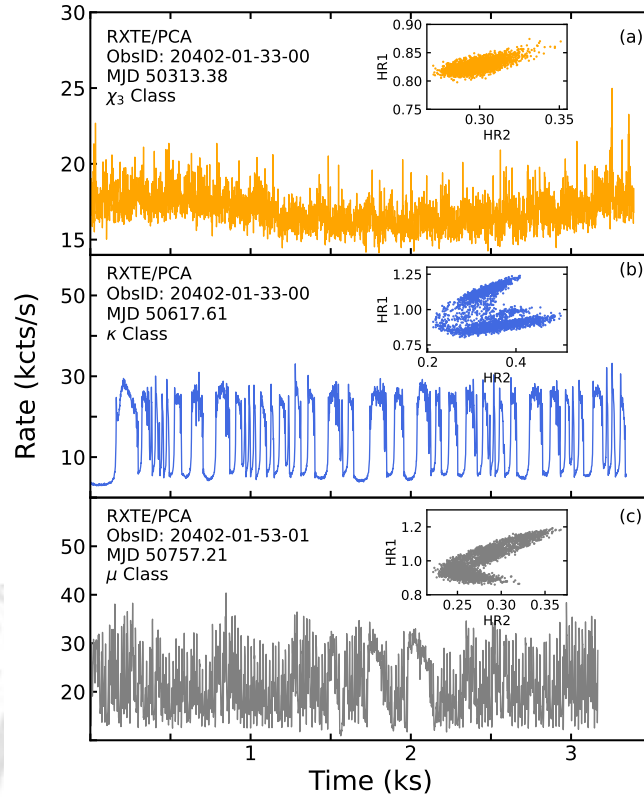


Figure 3.17: *RXTE/PCA* light curves of 1 s time bin of the source GRS 1915 + 105 in 3 – 60 keV energy range corresponding to χ_3 , κ and μ variability classes. The CCDs of the respective classes are presented in the insets of each panel. See the text for details.

parent similarity exists between the dip segments of the canonical κ class and those of the ‘unknown’ variability class observed during AS1, the intrinsic noise amplitude is nearly twice as high in the case of the κ class, indicating different underlying variability processes. Moreover, we also find that the noise amplitudes of the dip segments in AS1 are nearly twice that of the corresponding Poisson noise in these intervals, implying the presence of intrinsic variability during the dip durations beyond random statistical fluctuations. Given the similarity between the small-amplitude spikes observed during the steady interval of the ‘unknown’ class (AS2) and those seen in the χ_3 variability class, we compare the Poisson noise-subtracted intrinsic fractional variability amplitude (F_{var}) for these two cases. For this, we compute F_{var} following [Vaughan et al. \(2003\)](#) for both χ_3 class and AS2 observation. We find that $F_{\text{var}} \sim 7\%$ for χ_3 class, whereas it increases significantly to $\sim 45 - 47\%$ during the AS2 observation. This indicates that the small-amplitude spikes and fluctuations observed in the steady interval of the ‘unknown’ variability class are intrinsically different from the variability characteristics of the χ_3 class.

Further, we find that the distribution of $HR1$ and $HR2$ in the CCD (see Fig. 3.15c) of AS1 observation remains completely different from the canonical χ_3 class but resemble with that of κ and μ class to some extent (see Fig. 3.17). However, the upper and lower branches of the μ class CCD remain asymmetric, whereas a more extended lower branch towards higher $HR2$ values is observed for the AS1 observation.

Furthermore, we compare the characteristics of the present ‘unknown’ class in the context of the canonical states of GRS 1915+105 proposed by [Belloni et al. \(2000\)](#). We

note that, Belloni et al. (2000) identified three basic spectral states while classifying the variability properties of GRS 1915+105. Among these, state C and state B correspond to the quiescent and outburst states, respectively. More specifically, state C is associated with low flux and is harder in nature, typically located towards the higher HR2 region of the CCD. In contrast, state B is characterized by high flux, higher HR1, and lower HR2 values. In addition to these, another state known as state A is observed during transitions between states B and C. In general, state A exhibits low flux but softer spectral colors and is typically located in the lower-left region of the CCD.

It is important to mention that the λ and κ , basic classes of GRS 1915 + 105 (Belloni et al., 2000), exhibit low-flux dips associated with the quiescent state C and repeated high-count episodes corresponding to the outburst state B (Belloni et al., 2000). Typically, the low-count dips of varying durations remain located along the lower branch of the CCD in these two classes. Similarly, we observe that the low flux dips of the ‘unknown’ class during AS1 form the harder branch of the CCD (see inset in Fig. 3.15a) and resemble the quiescent state C of GRS 1915 + 105, as proposed by Belloni et al. (2000). On the other hand, high count spikes generally reside in the higher HR1 region of the CCD, indicating the possible presence of the outburst state B. However, we find the presence of a cluster of points in the CCD corresponding to steady durations characterized by small-amplitude spikes in the light curve of AS1 (see inset in Fig. 3.15a). This region of the CCD, which exhibits softer spectral characteristics and low flux, broadly resembles state A, albeit with a much greater spread. Typically, state A appears for short durations in the λ and κ classes and therefore contributes only marginally to the CCD (Belloni et al., 2000). Nevertheless, in the present case, the irregular and structured variability observed in AS1 and AS2 observations makes it more challenging to confirm the presence of state A. Based on the overall study, we conclude that this ‘unknown’ variability class is distinct from all previously known classes of GRS 1915 + 105, and we identify it as the τ class.

3.3.2 Twin Peak HFQPOs of τ Class

We generate 1 ms resolution light curves with the combined data from both *LAXPC10* and *LAXPC20* in 3 – 60 keV energy range. This allows us to examine the power spectral properties in the wideband frequency range of 0.01 – 500 Hz. Each PDS in rms space is modeled using a **constant** and **Lorentzian** functions. We find that multiple **Lorentzian** components at several frequencies are required to fit the PDS continuum over the entire wideband frequency range. In particular, it is observed that one zero-centroid Lorentzian component (L_{lor}^0), along with additional Lorentzian components at several distinct frequencies, are required to model the red noise continuum. For example, two Lorentzian functions L_{lor}^1 and L_{lor}^2 are required to fit the broad bump-like features present at ~ 0.65 Hz and ~ 7.35 Hz in the power spectra of AS1 (1b) observation. In addition, one additional Lorentzian component (L_{lor}^3) is needed to fit the power spectral break present at ~ 0.25 Hz. It may be noted that the inclusion of each of these additional components (L_{lor}^1 - L_{lor}^3) significantly improves the overall fit with a reduction in the fitted χ^2 by ~ 29 (L_{lor}^1), 157 (L_{lor}^2) and 28 (L_{lor}^3) for degrees of freedom reduced by 3 corresponding to each component. Interestingly, the significance of these broad features are found to be 12.6σ (L_{lor}^1), 10.4σ (L_{lor}^2) and 3.2σ (L_{lor}^3), whereas the quality factor remains < 2 , indicating broad characteristics. Similarly, two broad ($Q\text{-}fac \lesssim 2$) but significant ($\sim 9\sigma$) features at ~ 0.48 Hz and ~ 7.35 Hz are present

for AS2 (2b). However, unlike AS1 (1b), the power spectral break frequency is found to be around ~ 1.2 Hz in AS2 (2b). As before, modeling of these individual features renders a reduction of χ^2 within 50 – 275 for 3 degrees of freedom. Moreover, the above findings suggest that these low-frequency broad bump-like features are perhaps connected to inherent variability properties of the ‘unknown’ class and distinguish it from the other known classes of GRS 1915 + 105.

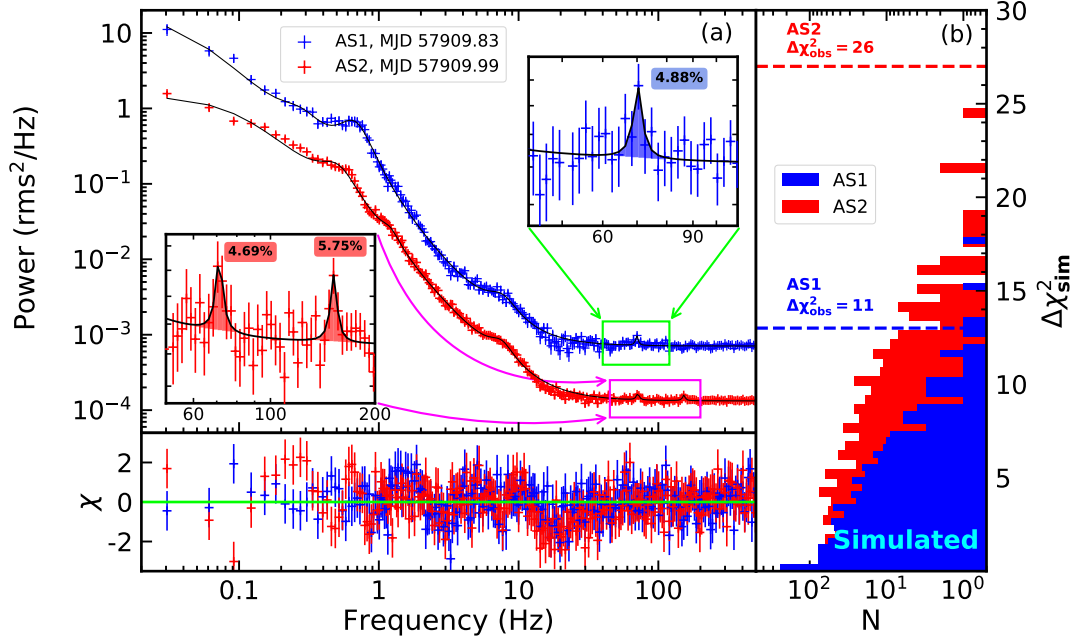


Figure 3.18: *Panel (a)*: Power density spectra of Epoch AS1 and AS2 in the broad-band frequency range (0.01 – 500 Hz). Each PDS is obtained in 3 – 60 keV energy band using *LAXPC10* and *LAXPC20* combined observation. Zoomed view of the detected HFQPO and/or harmonic features are shown in the inset. For clarity purpose, PDS of Epoch AS1 is re-scaled by multiplying factor 5. *Panel (b)*: The distribution of $\Delta\chi^2_{\text{sim}}$ with the number of occurrences (N), obtained from 1000 simulated power spectra. The horizontal dash lines denote the $\Delta\chi^2_{\text{obs}}$ values obtained using observational date for AS1 (blue) and AS2 (red), respectively. See the text and Majumder et al. (2025b) for details.

Table 3.9: Details of the detected HFQPO characteristics along with the fit statistics for Epoch AS1 and AS2. Here, ν_{QPO} , Δ_F , N_{lor} , $Q\text{-fac}$, σ_{QPO} and rms_{QPO} denote the frequency, width, normalization, quality factor, significance and rms amplitude of the detected HFQPO and/or harmonic features. rms_{total} denotes the rms amplitude of the entire PDS. χ^2/dof indicates the reduced chi-square (χ^2_{red}) of the best fitted PDS. $P_{\text{simfittest}}$ represents the *simfittest* probability. See the text and Majumder et al. (2025b) for details.

Epoch	$\chi^2/\text{d.o.f}$	$P_{\text{simfittest}}$ ($\times 10^{-3}$)	ν_{QPO} (Hz)	Δ_F (Hz)	N_{lor} ($\times 10^{-4}$)	$Q\text{-fac}$	σ_{QPO}	rms_{QPO} (%)	rms_{total} (%)
AS1 (1b)	166/228	16	$70.24^{+0.87}_{-0.85}$	$4.01^{+1.18}_{-1.21}$	$3.04^{+1.56}_{-1.39}$	17.52	2.2	4.88 ± 0.97	56.33 ± 10.48
AS2 (2b)	220/224	1	$71.15^{+1.01}_{-1.05}$	$5.33^{+3.32}_{-2.85}$	$2.34^{+1.05}_{-0.79}$	13.35	3	4.69 ± 0.78	57.78 ± 7.06
			$152.30^{+1.55}_{-2.06}$	$7.23^{+4.25}_{-3.88}$	$2.59^{+0.73}_{-0.55}$	21.07	4.7	5.75 ± 0.81	57.78 ± 7.06

Interestingly, we observe that significant residuals are still present near ~ 70 Hz in both observations (segments 1b and 2b, see Table 3.8), which are further modeled using a *Lorentzian* function. The inclusion of additional *Lorentzian* results in a reduction in chi-square (χ^2) of ~ 11 (for AS1) with the degrees of freedom (d.o.f) reduced by 3. Further, we notice the presence of an additional peak at ~ 150 Hz along with ~ 70 Hz

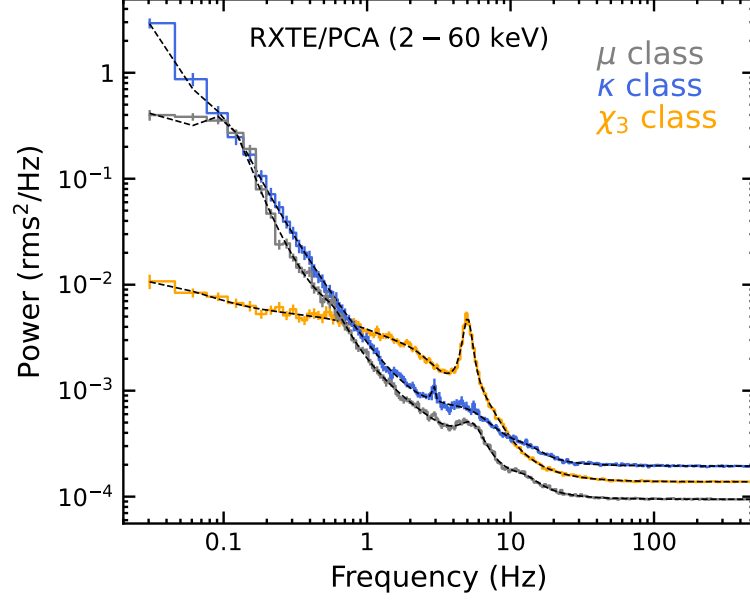


Figure 3.19: The PDS in 2 – 60 keV energy band of χ_3 , κ , and μ classes corresponding to the same observations for which the light curves are presented in Fig. 3.17. See the text for details.

during the Epoch AS2 (segment 2*b*). As before, simultaneous fitting of both these two peaks reduces χ^2 by ~ 26 in AS2. Finally, the best fit of the entire PDS is obtained with $\chi^2/\text{d.o.f}$ of 166/228 (segment 1*b* of AS1) and 220/224 (segment 2*b* of AS2). In Fig. 3.18a, we present the best-fitted PDS of Epoch AS1 and AS2, respectively. It is observed that the overall shape of the PDS remains similar for both observations, including the broad features present around ~ 0.6 Hz and ~ 8 Hz, respectively. The residual variations corresponding to the model-fitted PDS are shown in the bottom panel of Fig. 3.18a.

The power spectral modeling indicates the evidence of a HFQPO feature at $70.24^{+0.87}_{-0.85}$ Hz and $71.15^{+1.01}_{-1.05}$ Hz having significance (quality factor) of 2.2σ (17.52) and 3σ (13.35) in the best fitted PDS of Epoch AS1 (1*b*) and AS2 (2*b*), respectively. In addition, we compute the rms amplitude by taking the square root of the integrated power of the Lorentzian function describing the HFQPO feature and find it to be $(4.88 \pm 0.97)\%$ (AS1) and $(4.69 \pm 0.78)\%$ (AS2). Further, we also notice the presence of a possible harmonic-like feature at $152.30^{+1.55}_{-2.06}$ Hz (Fig. 3.18) along with the fundamental peak at ~ 70 Hz during Epoch AS2. The significance (quality factor) and percentage rms amplitude of the harmonic-like feature are found to be 4.7σ (21.07) and $(5.75 \pm 0.81)\%$, respectively. In addition, the total rms amplitude over the entire PDS of frequency range 0.01 – 500 Hz is found to be $(56.33 \pm 10.48)\%$ and $(57.78 \pm 7.06)\%$ during Epochs AS1 and AS2, respectively. The best-fitted and estimated HFQPO parameters and the fit statistics for both observations are tabulated in Table 3.9.

Next, we perform `simftest` (Lotti et al., 2016, Athulya et al., 2022) available within the XSPEC environment to further investigate the possible detection of the HFQPO and harmonic features. In general, the `simftest` script⁷ simulates synthetic spectra by adding random Poisson noise to the best-fitted model. This approximates the real statistical fluctuations expected in the observational data. Next, the fitting is performed

⁷<https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XspecManual.html>

for the individual simulated spectra, which allows us to determine the significance of a fitted model component. With this, we generate 1000 simulated power spectra and obtain the simulated $\Delta\chi_{\text{sim}}^2$ to compare with the observed $\Delta\chi_{\text{obs}}^2$. Here, $\Delta\chi_{\text{sim}}^2$ and $\Delta\chi_{\text{obs}}^2$ are the change in chi-square statistics with and without fitting the HFQPO and/or harmonic-like feature in the simulated and observed PDS, respectively. The obtained results are depicted in Fig. 3.18b using the histogram. We find that for both AS1 and AS2, $\Delta\chi_{\text{obs}}^2$ resides away from the main simulated distribution of $\Delta\chi_{\text{sim}}^2$. These findings yield a ‘low’ chance probability of ~ 0.001 and 0.016 of getting the features by random statistical fluctuations in AS1 and AS2, respectively. Moreover, based on these statistical analyses and the best-fitted HFQPO parameters (see Table 3.9), we conclude the possible evidence of HFQPO and/or harmonic features in AS1 and AS2 observations, respectively. However, low significance of the observed features (see Table 3.9) possibly implies the feeble nature of the HFQPOs and therefore the results should be interpreted accordingly. It is worth mentioning that the PDS for all the segments of AS1 and AS2, along with the rest of the observations in Table 3.8 are analyzed. However, we find the presence of HFQPOs for the segments 1b and 2b only, and therefore, the results are presented in Fig. 3.18 and Table 3.9 for these observation segments.

Further, we examine the power spectral properties of χ_3 , κ and μ classes using *RXTE/PCA* data and compare with that of the ‘unknown’ variability class observed during AS1 and AS2. The PDS computation is performed following the similar methodology described above and modeled using the combination of **constant** and **Lorentzian** components. In Fig. 3.19, we present the PDS corresponding to χ_3 , κ and μ classes in 2 – 60 keV energy band. We observe that a strong low-frequency QPO is present at ~ 5 Hz in the PDS of χ_3 class, whereas broad bump-like features are visible around ~ 6 Hz in the κ and μ class observations. In addition, a QPO-like feature seems to be present at ~ 3 Hz in the PDS of κ class. Moreover, it is evident that the overall shape of the PDS in μ and κ class including the low-frequency power spectral break near ~ 0.1 Hz and ~ 0.6 Hz along with bump-like features around ~ 6 Hz remain marginal identical to the PDS obtained during AS1 and AS2 (see Fig. 3.18) without the presence of HFQPOs. However, the appearance of a strong QPO feature at ~ 5 Hz along with a flat-topped noise distribution at lower frequencies makes the PDS of χ_3 observation completely distinct from the rest of the classes.

On the Modeling of LFQPO

In this section, we examine the accuracy in modeling the low-frequency (< 20 Hz) domain of the PDS. In doing so, we consider the PDS of the AS1 observation up to 20 Hz for modeling, which is shown in the top panel of Fig. 3.20. The bottom panels of Fig. 3.20 present the variation of model fitted residuals with different model combinations as described below. First, we fit one simple **powerlaw** to model the red noise part of the PDS and obtain a reduced chi-square (χ_{red}^2) of 7 with large variations in the residuals. Next, we include one **Lorentzian** (L_{lor}^1) component at 0.6 Hz to fit the LFQPO-like feature. This yields a worst fit for a $\chi_{\text{red}}^2 = 3.6$ with significant residual variation at 0.2 – 0.3 Hz and 7 – 8 Hz (see Fig. 3.20). Hence, we include two additional **Lorentzian** components (L_{lor}^2 and L_{lor}^3) to model these bump-like features, resulting in a $\chi_{\text{red}}^2 = 0.9$ (see Fig. 3.20). Moreover, we note that excluding either the L_{lor}^2 or L_{lor}^3 component from the fit results in χ_{red}^2 value exceeding 1.3. From this

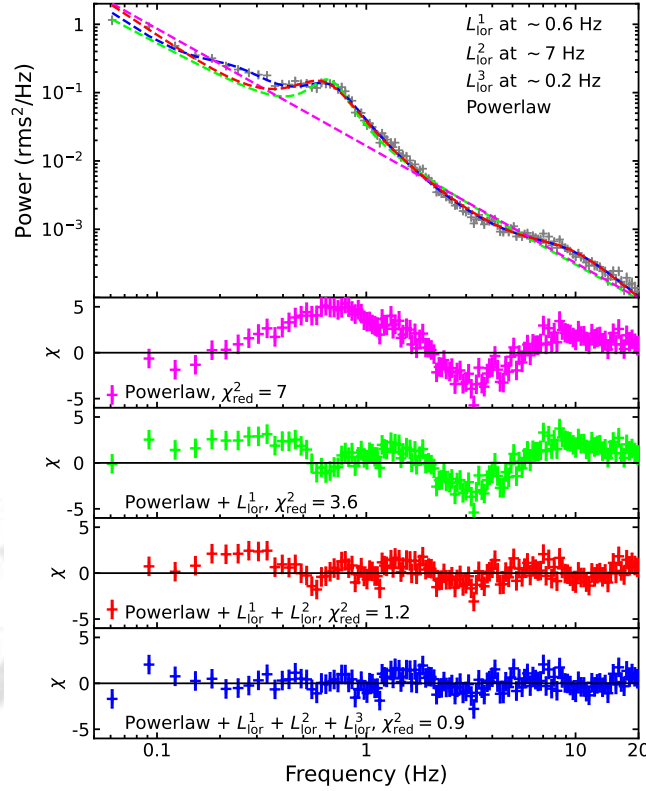


Figure 3.20: *Top panel:* PDS of the AS1 observation up to 20 Hz, highlighting the low-frequency variability properties. Dashed lines in different colors represent the model combinations used in the PDS modeling. *Bottom panels:* Variation of the model-fitted residuals for different model combinations, as indicated in the figure. See text for details.

modeling, we find the significance of the broad LFQPO-like feature at 0.63 Hz to be around 11.2σ . Note that the broadband (0.01 – 500 Hz) PDS modeling resulted in the centroid frequency and significance of this feature as 0.65 Hz and 12.6σ , respectively. This suggests that the characteristic frequency of the LFQPO-like feature and its properties remain independent of the choice of modeling the red noise component. Furthermore, a careful investigation of the model-fitted PDS in Fig. 3.20 indicates that the **powerlaw** dominates in the modeling of the red noise component only below ~ 0.18 Hz. On the other hand, the presence of two broad bump-like features at ~ 0.2 and ~ 7 Hz dominates over **powerlaw** in modeling the overall red noise variation. This further suggests that the red noise in the PDS deviates significantly from a simple **powerlaw** form and needs to be modeled using multiple **Lorentzian** components at distinct frequencies.

Energy Dependent Power Spectra

We intend to study the energy-dependent properties of the possible HFQPO and harmonic features obtained in the preceding section. Accordingly, we generate PDS in 3 – 6 keV, 6 – 15 keV, 15 – 25 keV and 25 – 60 keV energy bands, and present the obtained results for AS2 in Fig. 3.21 (left panel). To ascertain the signature of HFQPO and/or harmonic-like features, we fit **Lorentzian** components at the respective frequencies (Table 3.9) and compute significance (σ_{QPO}) and rms amplitudes ($\text{rms}_{\text{QPO}}\%$). We find that in the 3 – 6 keV energy band, a weak feature of HFQPO at ~ 70 Hz is present with significance $\sim 1.8\sigma$ and $\text{rms}_{\text{QPO}} \sim 4.45\%$. However, the

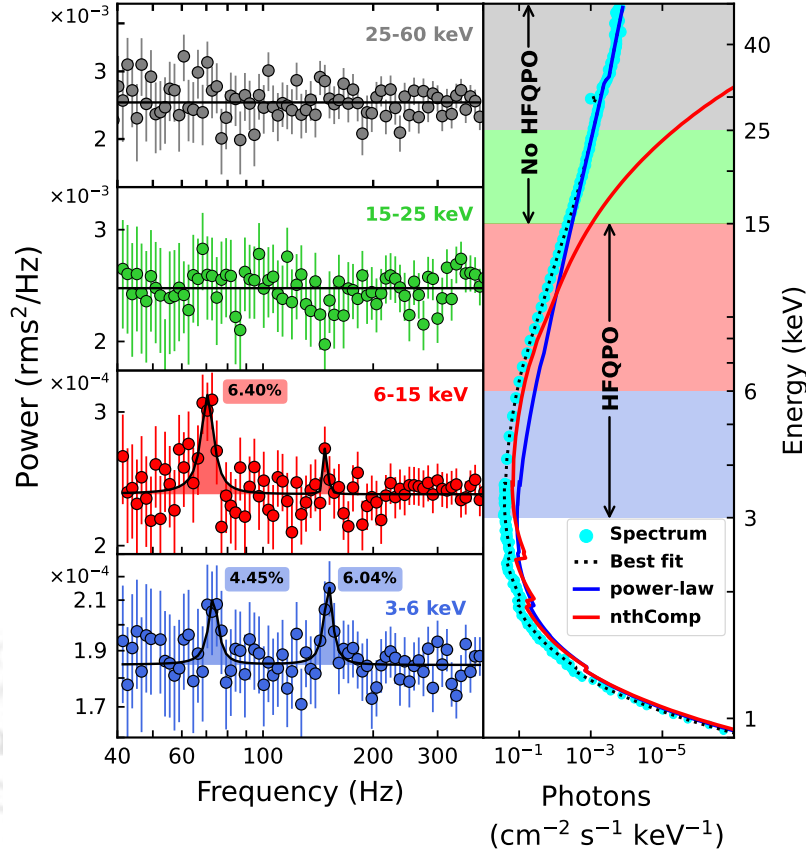


Figure 3.21: *Left panel:* Energy dependent power density spectra of Epoch AS2. In top to bottom panels, the best fitted PDS in different energy ranges are depicted. *Right panel:* Best fitted wideband (0.7 – 50 keV) energy spectrum of combined *SXT* and *LAXPC* observations. The dotted (black) and solid curves (blue/red) represent the best fitted models and spectral components used in the modeling. The shaded regions with different colors represent the energy bands for which the PDS are computed. See the text and Majumder et al. (2025b) for details.

possible harmonic at ~ 150 Hz is seen to be more prominent with a significance of $\sim 4.3\sigma$ and $rms_{QPO} \sim 6.04\%$. On the contrary, in 6–15 keV energy band, the evidence of HFQPO is seen to be more prominent with a significance of $\sim 3.2\sigma$ and $rms_{QPO} \sim 6.43\%$, whereas the harmonic-like feature appears to be insignificant. Moreover, the PDS remains featureless in 15 – 25 keV and 25 – 60 keV energy bands, respectively. In Fig. 3.21 (right panel), we present the best-fitted energy spectrum of the source from combined *SXT* and *LAXPC* data in 0.7 – 50 keV energy band. The model components used in the spectral modeling are indicated in the inset in different colors (*nthcomp* in red and *powerlaw* in blue). We observe that the contribution of the Comptonized component (*nthcomp*) remains significant till ~ 15 keV, where the evidence of HFQPO and/or harmonic features is observed. This suggests that Comptonized emissions are perhaps attributed to these features.

3.3.3 Spectral Features of τ Class

We generate energy spectra of the two selected observations (AS1 and AS2) in the wideband energy range of 0.7 – 50 keV by combining both *SXT* and *LAXPC20* spectra. As before, we adopt the physically motivated model combination, namely $Tbabs \times smedge \times (nthcomp + powerlaw) \times constant$ to fit the spectra of AS1 and AS2

observations. It is found that the above model combination provides the best descrip-

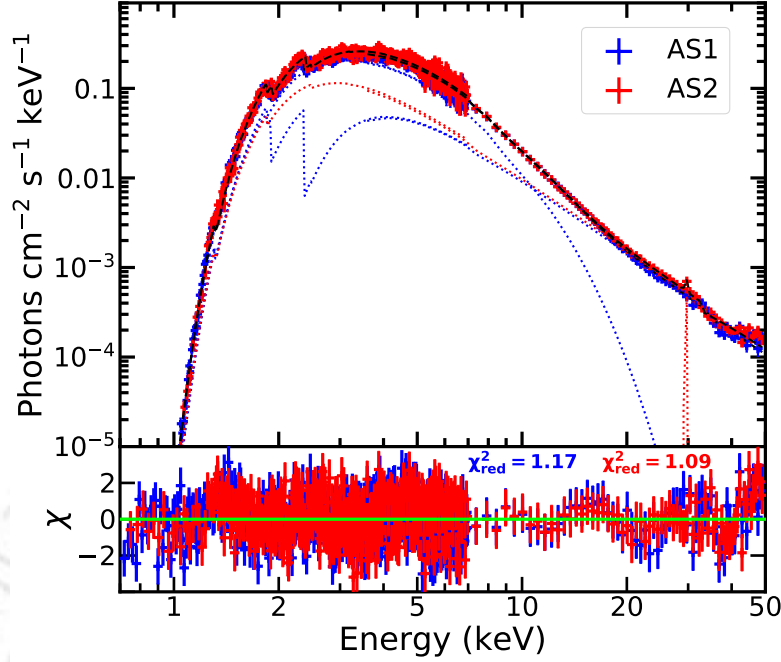


Figure 3.22: Best-fitted unfolded wideband (0.7 – 50 keV) energy spectra of GRS 1915 + 105 during Epochs AS1 and AS2. The spectra are modelled with $Tbabs \times smedge \times (nthcomp + powerlaw) \times constant$. The bottom panel shows the variation of residuals in units of σ . See the text for details.

tion of the observed spectra with a reasonable reduced chi-square value ($\chi^2_{red} = \chi^2/dof$) of 1.17 (AS1) and 1.09 (AS2). We note that a **gaussian** is needed to fit the ‘bump’ present near ~ 30 keV in the *LAXPC* spectra (Aneesha et al., 2024) of AS2. In Fig. 3.22, we present the best-fitted energy spectra of AS1 and AS2 along with residuals using different colors.

The best fitted spectral parameters for observation AS1 (AS2) are obtained as **nthcomp** photon index $\Gamma_{nth} = 1.96^{+0.05}_{-0.02}$ ($1.94^{+0.08}_{-0.06}$), electron temperature $k_B T_e = 1.71^{+0.09}_{-0.04}$ ($1.65^{+0.09}_{-0.07}$) keV and powerlaw photon index $\Gamma_{PL} = 2.78^{+0.04}_{-0.03}$ ($2.75^{+0.03}_{-0.02}$), respectively. Note that the seed photon temperature of **nthcomp** remains unconstrained during the fitting, hence we keep it fixed at 0.2 keV. We estimate the bolometric flux in 1 – 100 keV energy range using the convolution model **cflux**, keeping the model normalization fixed at the best fitted values. The corresponding bolometric luminosity (L_{bol}) is found to be $L_{bol} \sim 0.42 L_{Edd}$ for both observations, where L_{Edd} refers to the Eddington luminosity. This indicates that the source was in the sub-Eddington accretion regime during Epoch AS1 and AS2, respectively. Further, following Zdziarski et al. (1996) and using the model fitted spectral parameters, we compute the optical depth as ~ 13.94 (AS1) and ~ 14.42 (AS2), and Compton y-parameter as ~ 2.61 (AS1) and ~ 2.68 (AS2). This implies the presence of an optically thick Comptonizing corona responsible for the non-thermal emission in the spectra.

As concluded earlier in §3.2.9, we infer that the twin-peak HFQPOs observed in the newly discovered ‘unknown’ class (τ) are also likely associated with the compact corona, which is typically present in GRS 1915 + 105 during the ‘softer’ variability classes.

3.4 Summary

In this Chapter, we present in-depth spectro-temporal investigations of two galactic BH-XRB sources: Swift J1727.8–1613 and GRS 1915+105 using *AstroSat* and *NICER* observations. The key findings of this Chapter are summarized below:

- In the first work of this Chapter, we study the aperiodic temporal variability properties of the BH-XRB source Swift J1727.8 – 1613 during its exceptionally bright outbursting phase. Using combined broadband observations from *AstroSat* and *NICER*, we focus on the detection and characterization of LFQPOs during HIMS of the source. We report the first evidence of evolving type-C LFQPOs in hard X-rays up to ~ 100 keV. The QPO frequency shows a systematic evolution in the range $1.09 - 2.6$ Hz and remains detectable in the $80 - 100$ keV band. Spectral modeling in $0.7 - 40$ keV energy range reveals a dominant thermal Comptonization component (contributing $\sim 88\%$ of the observed flux), along with a weak disk emission signature characterized by an inner disk temperature of $k_B T_{\text{in}} \sim 0.36$ keV. Based on these findings, we conjecture that the observed aperiodic variabilities in hard X-rays of Swift J1727.8 – 1613 are likely driven by the strong Comptonizing corona present during the HIMS.
- In the second part of this Chapter, we investigate the fast spectro-temporal variability signatures of the source GRS 1915 + 105 by studying HFQPOs across distinct variability classes using *AstroSat* data. Specifically, we detect HFQPO features in the δ , κ , ω , and γ classes, with centroid frequencies in the range of $68.14 - 72.32$ Hz. Further, energy-dependent PDS study reveals that the emergent photons in the energy range of $6 - 25$ keV seem to be responsible for generating the HFQPO features. The wideband spectral modeling indicates that in the presence of HFQPO, the thermal Comptonization components dominate in the spectra. Based on the above findings, we conclude that the fast variability produced during the ‘softer’ classes of GRS 1915 + 105 is possibly due to the modulation of the Comptonizing corona that manifests the HFQPO features.
- In the final part of this Chapter, we report the appearance of a newly identified variability class (τ) of GRS 1915 + 105 using archival *AstroSat* data. We find that the presence of aperiodic dips and spike-like features, along with steady intervals in between, in the light curve of the τ class clearly distinguishes it from all previously known variability classes of GRS 1915 + 105. Moreover, we detect evidence of a twin-peak HFQPO feature at ~ 70 Hz and ~ 152 Hz in this newly identified class of the source, which are possibly associated with the Comptonizing corona located in the vicinity of the black hole.

Constraining Accretion-Ejection Geometry of BH-XRBs using Timing and Spectro-Polarimetric Insights

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In Chapter 3, we present a detailed investigation of the fast temporal variability characteristics, including QPOs features, in BH-XRBs across different timescales. Our analysis suggest that these oscillatory features are most likely linked to the modulation of the Comptonizing region that resides in the equatorial plane of the accretion disc close to the black hole. Nevertheless, it is important to note that the precise geometry of the Comptonizing corona in BH-XRBs remains an unresolved issue to date. Several alternative scenarios featuring the models of the sandwich corona ([Haardt and Maraschi, 1993](#), [Stern et al., 1995](#)), radially elongated corona at the truncated inner accretion disc ([Eardley et al., 1975](#), [Chakrabarti and Titarchuk, 1995](#), [Poutanen et al., 1997](#), [Iyer et al., 2015](#)) and vertically extended corona as the base of the jet ([Miyamoto and Kitamoto, 1991](#), [Markoff et al., 2005](#), [Méndez et al., 2022](#), [Zhang et al., 2023](#)) have been proposed over the years. Therefore, the overall geometry of the disc-corona-jet

remains elusive, mostly due to the model degeneracies that complicate the interpretation of the observational data. In this context, X-ray polarimetric information has emerged as a powerful diagnostic tool, offering an additional dimension to the investigation. This essentially provides crucial insights into the accretion geometry of BH-XRBs and helps to break the existing degeneracies.

Thanks to the highly sensitive and sophisticated observation capabilities of *IXPE*, which enables the opportunity to investigate in-depth polarimetric properties of BH-XRBs. So far, *IXPE* has observed twelve BH-XRBs, in search for polarized emission (Krawczynski et al., 2022, Podgorný et al., 2023, Kushwaha et al., 2023, Rawat et al., 2023a,b, Rodriguez Cavero et al., 2023, Veledina et al., 2023, Ratheesh et al., 2024, Jana and Chang, 2024, Steiner et al., 2024, Veledina et al., 2024b,c, Majumder et al., 2024b, Svoboda et al., 2024b, Marra et al., 2024, Ingram et al., 2024, Svoboda et al., 2024a, Podgorný et al., 2024, Mastroserio et al., 2025, Ewing et al., 2025). Despite the significant advancements in X-ray polarimetry, interpreting the observed polarization degree (PD) and polarization angle (PA) within the framework of theoretical models remains a formidable challenge. The classical work by Chandrasekhar (Chandrasekhar, 1960) on semi-infinite electron scattering predicts a low PD of $\sim 2\%$ from the accretion disc of highly inclined systems. However, 4U 1630–47 shows a remarkably higher PD of around 8.3% in its disc-dominated thermal state, deviating substantially from these theoretical expectations (Kushwaha et al., 2023, Ratheesh et al., 2024). Furthermore, PDs of about 4% have been observed in the LHS of Cyg X–1 and Swift J1727.8–1613 (Krawczynski et al., 2022, Ingram et al., 2024), whereas existing models predict only $\sim 1\%$ PD from a wedge-shaped corona in such low-inclined systems (Krawczynski et al., 2022). Therefore, it is evident that the polarimetric findings offer challenges to the existing models, indicating that a deeper understanding of the accretion dynamics and disc-corona-jet geometry in BH-XRBs is yet to be unveiled.

Keeping this in mind, in this Chapter, we explore spectro-polarimetric signatures of various BH-XRBs. While keeping a central focus on X-ray spectro-polarimetry, we also investigate the temporal characteristics of BH-XRBs and attempt to constrain their accretion-ejection geometry through comprehensive timing and spectro-polarimetric analyses.

The content of this Chapter is based on Majumder et al. (2024b) and Majumder et al. (2025d).

4.1 Discovery of X-ray Polarization in LMC X-3

To start with, we carry out the spectro-polarimetric study of the extra-galactic BH-XRB LMC X–3 using its first *IXPE* observation and quasi-simultaneous *NICER* and *NuSTAR* data. *IXPE* first observed LMC X–3 during 7th – 20th July 2023 for a total exposure of about 562 ks. *NICER* monitoring of the source was carried out on 8th July 2023, one day after the start of the *IXPE* observation. On the other hand, *NuSTAR* observed LMC X–3 six times during July 2023, overlapping with the *IXPE* observation period. However, at the time of conducting this study, only one observation on 9th July 2023, with a duration of ~ 28 ks, was publicly available. We utilized all these available observations in our study, along with daily monitoring data of the source from *MAXI/GSC*.

4.1.1 Introduction to LMC X-3

LMC X–3 is a persistent extra-galactic BH-XRB in Large Magellanic Cloud (LMC) at a distance of 48.1 kpc (Orosz et al., 2009), discovered by *UHURU* in 1971. A slowly rotating black hole of spin $0.25^{+0.20}_{-0.29}$ (Steiner et al., 2010, Bhuvana et al., 2021) and mass $6.98 \pm 0.56 M_{\odot}$ (Orosz et al., 2014, Bhuvana et al., 2021) is found to be present at the central core of the system. LMC X–3 is a relatively high inclined system ($\theta_{\text{inc}} \sim 69.24^{\circ} \pm 0.72^{\circ}$) (Orosz et al., 2014). Being a persistent source, it mostly remains in the HSS (Bhuvana et al., 2021) except for a few occasions during which the LHS is also observed (Smale and Boyd, 2012). An exceptionally anomalous low state of peak luminosity $\sim 10^{35} \text{ erg s}^{-1}$ is also observed for a few instances (Torpin et al., 2017). Hence, LMC X–3 remains a favourable candidate to study the polarization properties with *IXPE* due to its dominant soft spectral nature in low-energy X-ray band.

4.1.2 Imprints of Thermal State in Variability Signatures

We study the long-term variability of the source in respective energy bands of different instruments. While doing so, we consider 0.5 day averaged *MAXI/GSC* light curve in 2 – 10 keV energy band (see Fig. 4.1a). The hardness-intensity diagram (HID) with hardness ratio (*HR*) (ratio of count rates in 4 – 10 keV to 2 – 4 keV energy bands) is presented at the top right inset. We observe that during *IXPE* observation the source persistently remains bright with a *MAXI/GSC* mean count rate of $\sim 0.07 \text{ photons cm}^{-2} \text{ s}^{-1}$. In addition, the *MAXI*-HID during the *IXPE* observation (cyan circles) clearly indicates a high/soft nature of the source with a $HR \lesssim 0.5$. Further, we investigate 2000 s binned light curve of *IXPE* combining all the DUs in 2 – 8 keV energy range (see Fig. 4.1b). Interestingly, the variability is observed with a fractional variability (F_{var}) (Vaughan et al., 2003) of $\sim 4.84\%$ and 4.69% in *IXPE* and *MAXI* lightcurves, respectively. However, negligible variability is seen with $F_{\text{var}} \sim 1.98\%$ and 2.58% in *NICER* and *NuSTAR* light curves due to less exposure. Further, we make use of 3 – 20 keV *NuSTAR* data to obtain the power density spectrum (PDS) in 0.001 – 50 Hz frequency range using *MaLTPyNT*¹. The PDS shows no significant variability with rms amplitude of 0.5% in 0.001 – 50 Hz frequency range. This further confirms the high/soft nature of the source during the multi-mission campaign (Remillard and McClintock, 2006).

4.1.3 Measurements of X-ray Polarization

Model-independent Polarimetry

We investigate the polarization properties of LMC X–3 for the first time using the *IXPE* observation conducted for a duration of ~ 562 ks. In general, the polarization measurements are performed using two distinct methods. The first one relies on the model-independent approach based on the analysis of the polarization cube (Kislat et al., 2015) using the dedicated python package *IXPEOBSSIMv31.0.3*² (Baldini et al., 2022). This provides the polarimetric properties by computing the polarization degree (PD) and polarization angle (PA) from the normalized Stokes parameters without any

¹<https://www.matteobachetti.it/maltpynt/>

²<https://ixpeobssim.readthedocs.io/en/latest/>

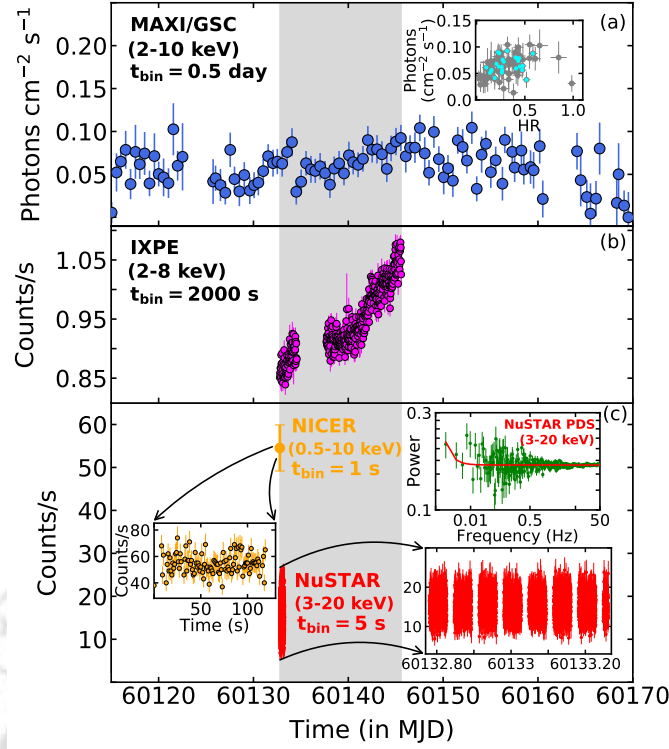


Figure 4.1: Long-term monitoring of LMC X-3 obtained from different instruments in different energy bands. In panel (a), the *MAXI/GSC* lightcurve in 2 – 10 keV energy band of 0.5 day time bin along with the hardness intensity diagram is shown in the top right inset. Panel (b) depicts 2000 s binned *IXPE* average light curve in 2 – 8 keV energy band combining all the DUs. In panel (c), *NICER* (1 s bin) and *NuSTAR* (5 s bin) lightcurves are presented in 0.5 – 10 keV and 3 – 20 keV energy bands, respectively. The PDS obtained from *NuSTAR* data is presented in the top right inset of panel (c). See the text for details.

prior assumption on the emission mechanism. The alternative method depends on the simultaneous modeling of the I, Q, and U Stokes spectra in *XPSEC*. In this approach, the source intensity spectrum (I) is modeled using the appropriate physical components responsible for the emission mechanism and a polarization model accounting for the Q and U spectra (Strohmayer, 2017). Accordingly, we carry out both model-independent and model-dependent analyses to ensure the consistency of the polarimetric measurements.

The model-independent polarization cube analysis is performed using *XPBIN* tool inside the software routine with *PCUBE* algorithm. Following Kushwaha et al. 2023, Majumder et al. 2024b,a, we consider all events from the three DUs of *IXPE* in the analysis. Subsequently, the normalized Q and U Stokes parameters, the polarization degree ($PD = \sqrt{(Q/I)^2 + (U/I)^2}$) and polarization angle ($PA = \frac{1}{2} \tan^{-1}(U/Q)$) are computed in 2 – 8 keV energy band for all observations of the respective sources. Following the guidelines of IAU³ (Contopoulos and Jappel, 1974), we adopt the convention that PA increases counter-clockwise from North to East direction in the sky. We also calculate the minimum detectable polarization at 99% confidence level ($MDP_{99\%}$) and the significance (σ_{pol} in units of σ) for each measurement. It may be noted that an observed $PD > MDP_{99\%}$ indicates a polarization level that would arise from random statistical fluctuations with only 1% chance probability (Kislat et al., 2015).

We find significant detection of polarization in 2 – 8 keV energy band with $PD =$

³<https://aas.org/posts/news/2015/12/iau-calls-consistency-use-polarization-angle>

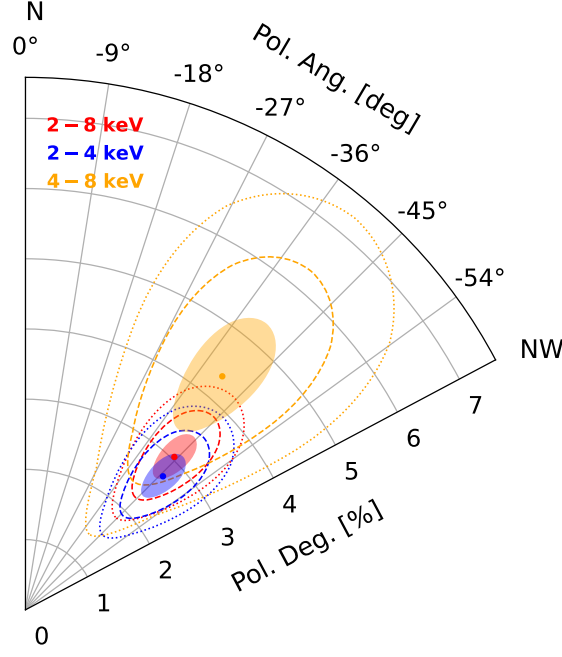


Figure 4.2: Confidence contours of energy-dependent polarization parameters of LMC X-3 obtained with model-independent analysis. Shaded region and regions bounded with dashed and dotted curves represent 1σ , 2σ and 3σ confidence contours. Different energy ranges are marked in different colors. See the text for details.

Table 4.1: Results from model-independent polarimetric study of LMC X-3 in different energy bands. Here, PD, PA, Q/I, U/I, MDP₉₉ and σ_{pol} denote polarization degree, angle of polarization, normalized Q-Stokes parameter, normalized U-Stokes parameter, minimum detectable polarization at 99% confidence level, and detection significance, respectively. See text for details.

Parameters	2 – 4 keV	4 – 8 keV	2 – 8 keV
	(I)	(II)	
PD(%)	2.73 ± 0.40	4.35 ± 0.98	3.04 ± 0.40
PA (°)	-45.85 ± 4.19	-40.13 ± 6.43	-44.24 ± 3.77
Q/I (%)	-0.08 ± 0.40	0.74 ± 0.98	0.08 ± 0.40
U/I (%)	-2.73 ± 0.40	-4.29 ± 0.98	-3.04 ± 0.40
MDP ₉₉ (%)	1.21	2.96	1.21
σ_{pol} (σ)	6.41	3.90	7.20

$3.04 \pm 0.40\%$ ($> 7\sigma$) at $\text{MDP}_{99} = 1.21\%$ alongwith a $\text{PA} = -44.24^\circ \pm 3.77^\circ$ ($> 7\sigma$), measured from north to west in the sky. We further examine the energy-dependent polarization properties in different energy bands, namely (I) 2 – 4 keV and (II) 4 – 8 keV, respectively. The obtained results are tabulated in Table 4.1. We observe that PD increases with energy and reaches to $4.35 \pm 0.98\%$ ($> 3\sigma$) in 4 – 8 keV energy band. We present the polarimetric results obtained from the different energy bands in Fig. 4.2.

Model-dependent Spectro-polarimetry

We carry out the spectro-polarimetric analysis to examine the model-dependent polarization properties of LMC X-3. We simultaneously fit nine Stokes (I, Q and U) spectra obtained from all three DUs of *IXPE* in 2 – 8 keV energy range using *XSPEC*. As a first attempt, we adopt a model combination `const*Tbabs*polconst*(diskbb+nthcomp)` to fit the spectra. Here, `polconst` stands for the constant polarization model with PA_{polconst} and PD_{polconst} as the model parameters. The best fit with $\chi^2_{\text{red}} = 1.12$ yields $PD_{\text{polconst}} = 2.94 \pm 0.61\%$ and $PA_{\text{polconst}} = -44.96^\circ \pm 6.01^\circ$. As PA and PD are seen to vary with energy, we further consider the energy-dependent polarization model `polpow` to fit the spectra. The model uses $PD(E) = A_{\text{norm}} \times E^{-A_{\text{index}}}$ (in fraction) and $PA(E) = \psi_{\text{norm}} \times E^{-\psi_{\text{index}}}$ (in $^\circ$). We fit the Stokes spectra using the model combination

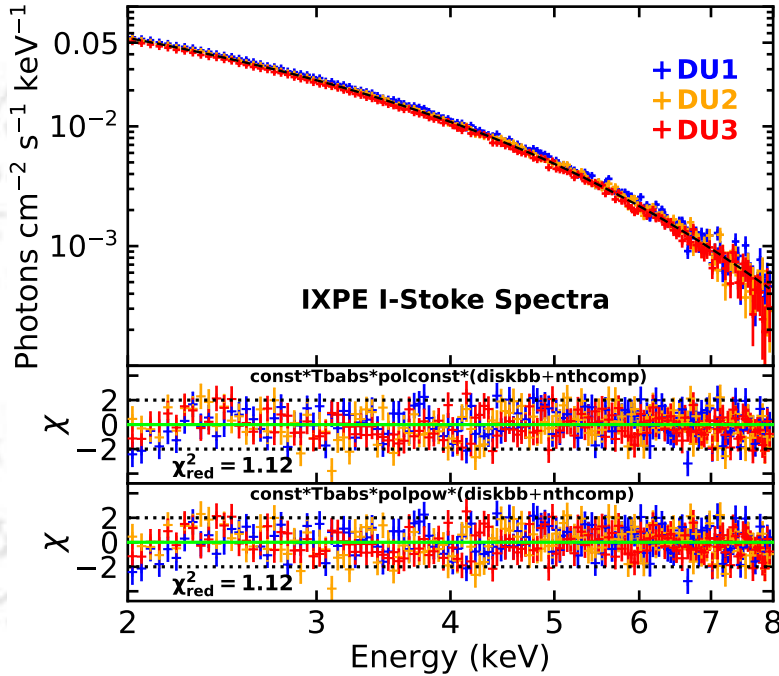


Figure 4.3: *Top*: Best fit I-Stokes spectra of LMC X-3 obtained from model-dependent spectro-polarimetric study in 2 – 8 keV energy band. *Middle-Bottom*: Residuals from different model combinations mentioned in both panels. Blue, orange and red denote results for DU1, DU2 and DU3, respectively. See the text and Majumder et al. (2024b) for details.

`const*Tbabs*polpow*(diskbb+nthcomp)`. While fitting, A_{index} and ψ_{index} are fixed at their best fitted values of -0.82 and 0.24 , respectively as the parameters could not be constrained within 1σ errors. This yields best fit spectra with $\chi^2_{\text{red}} = 1.12$, $A_{\text{norm}} = 0.011 \pm 0.001$ and $\psi_{\text{norm}} = -59.28^\circ \pm 7.82^\circ$, respectively. We integrate the model in 2 – 8 keV energy range with the best fitted parameters and obtain $PD_{\text{polpow}} \sim 4.08 \pm 0.37\%$ and $PA_{\text{polpow}} \sim -41.11^\circ \pm 5.43^\circ$ which differs marginally with the results obtained from model-independent studies (see Table 4.1). All polarization parameters obtained from the spectro-polarimetric study are tabulated in Table 4.2. The best fitted I-Stoke spectra with different models are shown in Fig. 4.3.

Table 4.2: Results from spectro-polarimetric analysis of the *IXPE* Stokes spectra with different models in 2 – 8 keV energy range.

Components	A_{norm}	A_{index}	$\psi_{\text{norm}} (^{\circ})$	ψ_{index}	PD (%)	PA ($^{\circ}$)
polpow	0.011 ± 0.001	$-0.82^{\dagger}$	-59.28 ± 7.82	$0.24^{\dagger}$	4.08 ± 0.37	-41.11 ± 5.43
polconst	—	—	—	—	2.94 ± 0.61	-44.96 ± 6.01

† Frozen parameter as it could not be constrained within 1σ error.

Table 4.3: Best fitted spectral parameters obtained from the modelling of combined *NICER* and *NuSTAR* broad-band (0.5 – 20 keV) energy spectra with various model prescriptions (M1: `const*Tbabs*(diskbb+nthcomp)`; M2: `const*Tbabs*(kerrbb⊗simpl)`; M3: `const*Tbabs*(slimbh⊗simpl)`). Model components and parameters in the table have their usual meanings. All the errors are computed with 90% confidence level. See the text for details.

Model	Model	Different model prescriptions		
Components	Parameters	M1	M2	M3
Tbabs	$n_{\text{H}} (\times 10^{22}) \text{ cm}^{-2}$	$0.04^{\dagger}$	$0.04^{\dagger}$	$0.04^{\dagger}$
diskbb	$k_{\text{B}} T_{\text{in}} \text{ (keV)}$	$1.09^{+0.01}_{-0.01}$	—	—
	N_{diskbb}	$23.11^{+1.06}_{-1.04}$	—	—
	$F_{\text{disc}} (\times 10^{-10}) \text{ erg cm}^{-2} \text{ s}^{-1}$	$6.81^{+0.02}_{-0.02}$	—	—
nthcomp	$k_{\text{B}} T_{\text{e}} \text{ (keV)}$	10^*	—	—
	Γ_{nth}	$2.97^{+0.10}_{-0.13}$	—	—
	$F_{\text{nth}} (\times 10^{-10}) \text{ erg cm}^{-2} \text{ s}^{-1}$	$0.37^{+0.01}_{-0.01}$	—	—
	F-test Probability ($\times 10^{-49}$)	1.83	—	—
kerrbb	a_*	—	$0.295^{+0.008}_{-0.021}$	—
	$M_{\text{BH}} (M_{\odot})$	—	$6.98^{\dagger}$	—
	$\theta_{\text{inc}} \text{ (degree)}$	—	$69.24^{\dagger}$	—
	$\dot{m} (\times 10^{18}) \text{ (g s}^{-1}\text{)}$	—	$4.27^{+0.12}_{-0.13}$	—
	$D \text{ (kpc)}$	—	$48.1^{\dagger}$	—
	f_{h}	—	$1.7^{\dagger}$	—
slimbh	a_*	—	—	$0.273^{+0.011}_{-0.012}$
	$M_{\text{BH}} (M_{\odot})$	—	—	$6.98^{\dagger}$
	$\theta_{\text{inc}} \text{ (degree)}$	—	—	$69.24^{\dagger}$
	$D \text{ (kpc)}$	—	—	$48.1^{\dagger}$
	f_{h}	—	—	$1.7^{\dagger}$
	$L_{\text{disc}} (L_{\text{Edd}})$	—	—	0.27 ± 0.01
	α_{s}	—	—	$0.1^{\dagger}$
simpl	Γ_{simpl}	—	$1.09^{+0.01}_{-0.02}$	$1.09^{+0.01}_{-0.01}$
	$f_{\text{scatt}} \text{ (%)}$	—	$0.83^{+0.11}_{-0.46}$	$0.84^{+0.11}_{-0.45}$
	F-test Probability ($\times 10^{-26}$)	—	1.04	0.11
$\chi^2/\text{d.o.f}$		571/564	620/565	621/564
χ^2_{red}		1.01	1.10	1.10

† Frozen to fiducial values.

*Not constrained within 1σ error; frozen at best fitted values.

4.1.4 Broadband Spectral Modeling and Estimation of BH Spin

We study the broadband spectral properties of the source using quasi-simultaneous observations with *NICER* and *NuSTAR* in the 0.5 – 20 keV energy band. While doing so, we adopt the standard disc model `diskbb` (Makishima et al., 1986) as the source of primary emissions and fit the spectra with the model `const*Tbabs*diskbb`. Here, `Tbabs` (Wilms et al., 2000) takes care of the galactic absorptions and `const` accounts for the cross calibration between different spectra. The obtained fit resulted in a reduced chi-square ($\chi^2_{\text{red}} = \chi^2/d.o.f$) of 1.51 with large residuals above ~ 10 keV, confirming the presence of a high energy tail (see Fig. 4.4).

Next, we consider the thermal Comptonization model `nthcomp` (Zdziarski et al., 1996) in the presence of a multi-temperature disc (as the seed photon distribution) to describe the high energy excess and find a good fit as $\chi^2_{\text{red}} = 1.02$. The inclusion of `nthcomp` component is found significant with F -test⁴ probability of 1.83×10^{-49} . We obtain the best fitted model parameters, such as inner disc temperature $k_B T_{\text{in}} = 1.09^{+0.01}_{-0.01}$ keV and photon index $\Gamma_{\text{nth}} = 2.97^{+0.10}_{-0.13}$. As the electron and seed photon temperatures remain unconstrained, we freeze these parameters at 10 keV and 0.2 keV, respectively. For the same reason, we keep the hydrogen column density fixed at $0.04 \times 10^{22} \text{ cm}^{-2}$ (Yilmaz et al., 2023). With this, we estimate the unabsorbed flux in 0.5 – 20 keV energy range using `cflux` and find that $\sim 96\%$ of the total flux is associated with the disc component. Moreover, the higher disc flux contribution and a steeper photon index ($\Gamma_{\text{nth}} \sim 2.97$) indicate that the source remains in the disc-dominated state. All the model fitted and estimated parameters obtained from the broadband spectral fitting with model prescription `M1:const*Tbabs*(diskbb+nthcomp)` are tabulated in the Table. 4.3.

The broadband energy spectra of LMC X–3 reveal its high/soft nature, and hence, we attempt to estimate the spin of the source using the continuum fitting method in 0.5 – 20 keV energy range. In doing so, we rely on the relativistic accretion disc model `kerrbb` (Li et al., 2005) and following Orosz et al. (2009, 2014), we consider source distance $D = 48.1$ kpc, mass $M_{\text{BH}} = 6.98 M_{\odot}$ and inclination $\theta_{\text{inc}} = 69.24^\circ$ during the fitting. We fix the color factor (f_{h}) to a standard value of 1.7. With this, the spin of the black hole (a_*) and the mass accretion rate ($\dot{m}$) are left as free parameters. In addition, we add `simpl` model (Steiner et al., 2009) to account for the Comptonizing tail above ~ 10 keV. The model `M2:const*Tbabs*(kerrbb⊗simpl)` is found to provide an excellent fit with a χ^2_{red} of 1.10. The resultant fit yields the source spin as $a_* = 0.295^{+0.008}_{-0.021}$ (at 90% confidence) and mass accretion rate as $\dot{m} = 4.27^{+0.12}_{-0.13} \times 10^{18} \text{ g s}^{-1}$. We also find the photon index of `simpl` as $1.09^{+0.01}_{-0.02}$. Further, we employ the slim disc model `slimbb` (Sadowski, 2011) to estimate the source spin, where the viscosity parameter is set as $\alpha_s = 0.1$. The resultant fit renders $\chi^2_{\text{red}} = 1.10$ that provides $a_* = 0.273^{+0.011}_{-0.012}$ (at 90% confidence) and disc luminosity $L_{\text{disc}} = 0.27 \pm 0.01 L_{\text{Edd}}$. Note that in explaining the high energy tail of the spectrum, the addition of `simpl` component is found significant with F -test probability of 1.04×10^{-26} . Interestingly, both models provide consistent spin values that suggest LMC X–3 seems to harbour a weakly rotating black hole at its central core. We present the broadband spectra of LMC X–3 in 0.5 – 20 keV energy range in the top panel of Fig. 4.4 and the fitted residuals obtained from different model combinations are shown in the lower successive panels. All the model fitted and estimated parameters obtained from the broad-

⁴<https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node82.html>

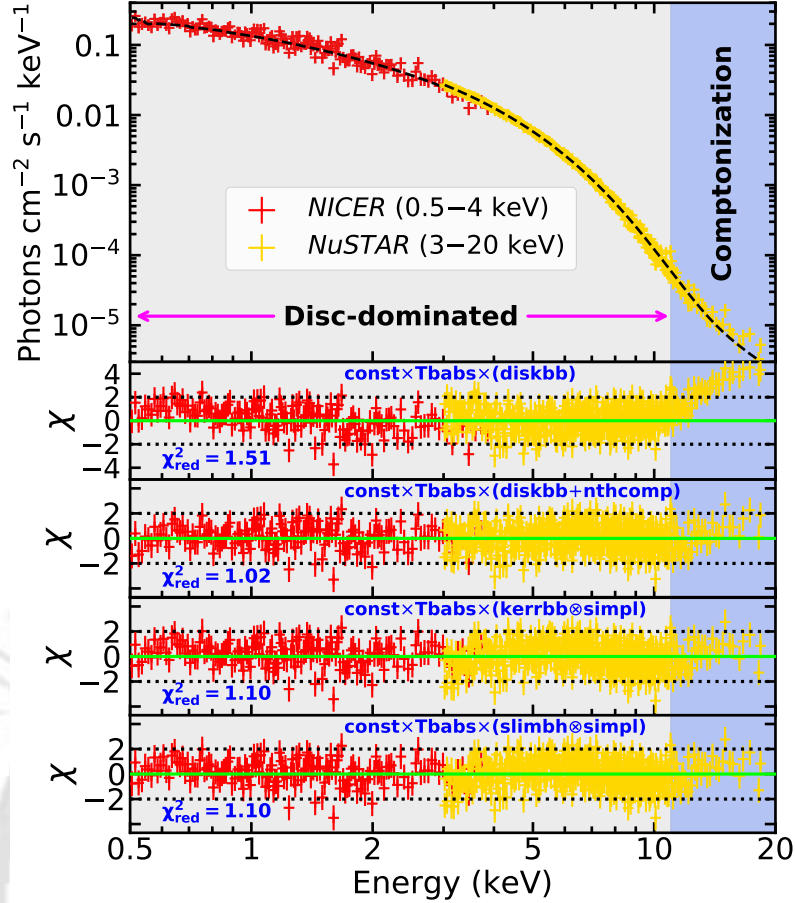


Figure 4.4: *Upper panel:* Best fitted broad-band energy spectrum obtained from the simultaneous *NICER* (0.5 – 4.0 keV) and *NuSTAR* (3–20 keV) observations. *Lower panels:* Variation of the fitted residuals obtained from four different model prescriptions.

band spectral fitting with model prescriptions `M2:const*Tbabs*(kerrbb@simpl)` and `M3:const*Tbabs*(slimbh@simpl)` are shown in Table. 4.3.

4.1.5 Polarization in Thermal State: Physical Insights

The most intriguing results that we find in this study are the detection of significant polarized emission of $PD = 3.04 \pm 0.40\%$ ($> 7\sigma$) with $PA = -44.24^\circ \pm 3.77^\circ$ ($> 7\sigma$). The spectro-polarimetric study from *IXPE* Stokes spectra yields a $PD = 4.08 \pm 0.37\%$ and $PA = -41.11^\circ \pm 5.43^\circ$ that marginally differs from the findings of model-independent studies (see Table 4.1 and Table 4.2). These findings suggest that LMC X–3 is the first ever detected extra-galactic BH-XRB that exhibits X-ray polarization properties. The energy-dependent polarimetric study indicates an increase of PD up to $\sim 4.35 \pm 0.98\%$ in 4 – 8 keV energy band. Similar energy-dependent polarization properties are also reported in several BH-XRBs, including 4U 1630–47 (Kushwaha et al., 2023) and Cyg X–1 (Jana and Chang, 2024). We observe negligible variation of PA over the different energy bands. We report the above findings for the first time for extra-galactic BH-XRBs.

It may be noted that the observed PD ($\sim 3.04\%$) of LMC X–3 is found higher compared to the same obtained in the soft state of Cyg X–1 ($\sim 2.79\%$) (Jana and

Chang, 2024). This possibly happens due to the fact that Cyg X–1 is a low inclination source than the LMC X–3 (Schnittman and Krolik, 2009). Meanwhile, highly polarized (PD $\sim 8.33\%$) emission in the disc-dominated state of 4U 1630+47 is recently reported which seems to be originated from a disc-wind regulated accretion scenario (Ratheesh et al., 2024, Kushwaha et al., 2023). However, no such disc-wind signature is observed from the spectro-polarimetric study of LMC X–3.

We find increasing PDs in the higher energy band as compared to the expected nature from the existing models (Schnittman and Krolik, 2009, Taverna et al., 2020). In reality, the pure electron scattering with high binary inclination of $\gtrsim 70^\circ$ can lead to such high PDs (Chandrasekhar, 1960, Ratheesh et al., 2024). However, the complete ionization of matter assumed in pure electron-scattering theory is unlikely to be achieved in the accretion disc. Alternatively, in a partially-ionized disc atmosphere along with a weak corona, the absorption effect significantly enhances PD up to $\sim 4\%$ for a lower inclination $\lesssim 71^\circ$ and hence, the energy dependent polarization can be explained in a self-similar way (Ratheesh et al., 2024). With this, we infer that the observed PD $\sim 3.04\%$ of LMC X–3 for a disc inclination $\sim 69^\circ$ is possibly resulted from the direct and reflected emissions in a partially-ionized disc atmosphere. Further, the broadband spectral modelling indicates that LMC X–3 seems to be surrounded by a slim disc structure that renders the polarized emission (Ratheesh et al., 2024).

4.2 Towards Unification: Investigation of Timing and Spectro-polarimetric Aspects of Twelve BH-XRBs

In the preceding section, we investigate the spectro-polarimetric properties of the BH-XRB LMC X–3 in the disc-dominated thermal state and found that the measured PD is likely associated with a partially ionized disc atmosphere. However, the polarization properties across diverse spectral states of BH-XRBs are expected to differ significantly from those observed in the canonical soft state. In particular, during the LHS or HIMS, the emission is predominantly governed by the Comptonized corona, and the corresponding polarimetric data can therefore provide crucial insights into the coronal geometry. Motivated by this, we undertake an in-depth timing and spectro-polarimetric analysis of twelve BH-XRBs using quasi-simultaneous archival observations from *IXPE*, *NICER*, *NuSTAR*, and *AstroSat*, covering a broad energy range of 0.5 – 100 keV.

While doing so, we study the evolution of X-ray (soft/hard) and radio flux densities for all sources using multi-mission long-term monitoring data from *MAXI/GSC*, *Swift/BAT*, *RATAN* and *VLITE*. Further, we conduct a comprehensive spectro-temporal study of these sources using *NICER*, *NuSTAR* and *AstroSat* data and confirm the presence of distinct spectral states of the BH-XRBs during the observational campaigns. Using alternative model prescriptions relying on different assumptions on the disc-corona configurations, we attempt to explain the spectral features of the sources and investigate the possibility of having inherent degeneracy among the models. Next, we deduce the polarization properties of the sources using *IXPE* data in the 2 – 8 keV energy range, followed by a detailed spectro-polarimetric correlation study. Subsequently, noticeable positive and negative correlations between polarization degree and spectral parameters serve as powerful diagnostics, offering deeper insights into the complex accretion dynamics and geometry of the BH-XRBs under consideration.

4.2.1 A Quick Walkthrough of the Selected Database

For this work, we analyze all the *IXPE* (Weisskopf et al., 2022) observations of BH-XRBs conducted so far, along with simultaneous/quasi-simultaneous *NICER*, *NuSTAR* and *AstroSat* observations depending on data availability. As of now, *IXPE* observed twelve BH-XRBs, namely Cyg X–1, 4U 1630–47, Cyg X–3, LMC X–1, 4U 1957+115, LMC X–3, Swift J1727.8–1613, Swift J151857.0 – 572147, GX 339 – 4, IGR J17091 – 3624, MAXI J1744 – 294 and GRS 1915 + 105, during its first three and a half years of operational period. The *IXPE*, *NICER* and *NuSTAR* observations used in this work are publicly available in the HEASARC⁵ database and the *AstroSat* data is archived at the ISSDC⁶ website. The quasi-simultaneous multi-mission observations of the sources are separated by at most three days from the *IXPE* Epoch, except LMC X–1 for which the *NuSTAR* observation lies four days after the *IXPE* observation. The sources exhibiting marginal spectro-temporal variability between observations from different missions offer an opportunity for a combined multi-mission study. We mention that *IXPE* monitoring of GRS 1915 + 105 was carried out on 10th May 2025 for about ~ 142 ks. However, the source remained below the detection level with *IXPE*, showing a *MAXI/GSC* flux of ~ 6 mCrab (see Fig. 4.5). Therefore, GRS 1915 + 105 is excluded from the detailed analyses in the following sections. All the observations analyzed in this study are tabulated in Table 4.4 along with the date and ObsID. A brief overview of each of the sources under consideration is presented below, except Swift J1727.8–1613 and LMC X–3, for which the details are presented in Chapter 3 and §4.1.1, respectively. The details of GRS 1915 + 105 are provided in Chapter 3.

4.2.2 Brief Overview of the BH-XRBs of Interest

Cyg X–1

Cyg X-1, the first galactic BH-XRB discovered in 1971 (Webster and Murdin, 1972), continues to be one of the most extensively studied celestial objects. Recent measurements reveal that it hosts a black hole with a mass of $21.2 \pm 2.2 M_{\odot}$ (Miller-Jones et al., 2021), located at a distance of 2.2 ± 0.2 kpc (Miller-Jones et al., 2021), with a supergiant O-type star as its binary companion. Meanwhile, numerous studies confirm the presence of a maximally rotating ‘hole’ having spin greater than 0.99 at the center core of the binary system (Tomsick et al., 2013, Zhao et al., 2021, Kushwaha et al., 2021). Cyg X–1 has remained persistently bright, mostly in the LHS, though it has transitioned to the HSS through short-lived intermediate states over the past few decades (Kushwaha et al., 2021).

4U 1630–47

4U 1630–47 is a recurrent X-ray transient discovered by *Uhuru* (Jones et al., 1976). Since discovery, the source has exhibited more than 20 quasi-period outbursts (Baby et al., 2020, Chatterjee et al., 2022) typically in every 600 – 700 days (Parmar et al., 1995). Since the optical counterpart of the source is still unknown, the dynamical measurement of its mass and distance remains elusive. Several efforts relying on indirect

⁵<https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl>

⁶<https://webapps.issdc.gov.in/astroarchive/archive/Home.jsp>

Table 4.4: Details of the multi-mission observations of the selected sources over different Epochs. In the table, blue shades represent the Epochs for which quasi-simultaneous *IXPE*, *NICER*, and *NuSTAR* observations are available. The gray shades denote the quasi-simultaneous observations with *IXPE* and *NICER* only. The magenta colored shade indicates the Epoch for which only quasi-simultaneous *IXPE* and *NuSTAR* observations are available. The orange colored shade denotes the available *AstroSat* observations close to the *IXPE* Epochs. See the text for details.

Source	Epoch	Instrument	Obs. ID	Start Date	MJD Start	Exposure (ks)	Mean Rate	MAXI/GSC	Swift/BAT	Radio Flux	Spectral
							(cts/s)	Flux (mCrab) (2 – 20 keV)	Flux (mCrab) (15 – 50 keV)	(mJy)	State
Cyg X–1	E1	IXPE	01002901	2022-05-15	59714.64	242	9.82 ± 0.21	401 ± 11	928 ± 34	–	LHS
		NICER	5100320101	2022-05-15	59714.26	8.2	2938 ± 25	–	–	–	–
		NuSTAR	30702017002	2022-05-18	59717.57	16	324 ± 15	–	–	–	–
		AstroSat	A11_080T01_9000005146	2022-05-15	59714.03	47.3	1505 ± 37	–	–	–	–
	E2	IXPE	01250101	2022-06-18	59748.86	86	10.32 ± 0.12	420 ± 14	885 ± 33	–	LHS
		NICER	5100320108	2022-06-20	59750.60	3	3001 ± 25	–	–	–	–
		NuSTAR	90802013002	2022-06-20	59750.50	13	338 ± 14	–	–	–	–
	E3	IXPE	02008201	2023-05-02	60066.96	21	26.93 ± 0.18	888 ± 12	546 ± 21	9.1 ± 0.3 [□]	HSS
	E4	IXPE	02008301	2023-05-09	60073.44	31	33.93 ± 0.23	701 ± 12	613 ± 23	11.7 ± 0.2 [□]	HSS
	E5	IXPE	02008401	2023-05-24	60088.82	25	44.26 ± 0.30	809 ± 20	569 ± 35	2.4 ± 0.2 [□]	HSS
	AstroSat	T05_105T01_9000005662	2023-05-24	60088.79	60.5	1354 ± 36	–	–	–	–	
	E6	IXPE	02008501	2023-06-13	60108.96	29	39.33 ± 0.28	765 ± 27	593 ± 45	8.9 ± 0.2 [□]	HSS
NuSTAR		80902318004	2023-06-14	60109.02	9.8	694 ± 22	–	–	–	HSS	
E7	IXPE	02008601	2023-06-20	60115.04	34	48.09 ± 0.24	803 ± 24	859 ± 46	9.4 ± 0.4 [□]	HSS	
	NICER	6643010104	2023-06-20	60115.97	7.6	23227 ± 201	–	–	–	–	
	NuSTAR	80902318006	2023-06-20	60115.82	10.2	878 ± 26	–	–	–	–	
	E8	IXPE	03002201	2024-04-12	60412.02	55.8	7.28 ± 0.12	333 ± 9	736 ± 31	–	LHS
NICER	7100320104	2024-04-11	60411.10	0.7	1508 ± 18	–	–	–	–		
E9	IXPE	03003101	2024-05-06	60436.37	53.9	7.14 ± 0.11	283 ± 8	919 ± 42	–	LHS	
E10	IXPE	03010001	2024-05-26	60456.04	57.5	7.29 ± 0.12	286 ± 18	747 ± 28	–	LHS	
E11	IXPE	03010101	2024-06-14	60475.65	55.8	5.72 ± 0.09	293 ± 11	725 ± 27	–	LHS	
	NICER	7706010104	2024-06-14	60475.99	6.1	1698 ± 54	–	–	–	–	
E12	IXPE	03002599	2024-10-10	60593.22	110	22.1 ± 2.2	600 ± 13	795 ± 27	–	HSS	
4U 1630–47	E1	IXPE	01250401	2022-08-23	59814.95	459	4.56 ± 0.08	247 ± 8	10 ± 2	–	HSS
		NICER	5501010102	2022-08-23	59814.01	2	479 ± 10	–	–	–	–
		NuSTAR	80802313002	2022-08-25	59816.19	17	348 ± 14	–	–	–	–
	E2	IXPE	02250601	2023-03-10	60013.78	138	10.16 ± 0.12	550 ± 16	246 ± 20	–	SPL
		NICER	6557010101	2023-03-10	60013.76	5	1009 ± 15	–	–	–	–
		NuSTAR	80801327002	2023-03-09	60012.36	12	884 ± 29	–	–	–	–
	AstroSat	A12_056T02_9000005538	2023-03-10	60013.08	29.4	1938 ± 43	–	–	–	–	
Cyg X–3	E1	IXPE	02001899	2022-10-14	59866.04	538	1.33 ± 0.04	106 ± 20	129 ± 26	106 ± 24*	LHS
		NICER	5142010105	2022-10-14	59866.28	5	44.79 ± 3.12	–	–	–	–
		NuSTAR	90802323002	2022-10-13	59865.62	18	197 ± 1	–	–	–	–
	E2	IXPE	02250301	2022-12-25	59938.41	199	4.55 ± 0.09	295 ± 31	144 ± 35	107 ± 36*	HSS
		NuSTAR	90801336002	2022-12-25	59938.33	36	467 ± 2	–	–	–	–
	E3	IXPE	02009101	2023-11-17	60265.83	291	1.43 ± 0.05	131 ± 8	159 ± 13	–	SIMS
		NICER	6692010101	2023-11-17	60265.77	1.9	125 ± 7	–	–	–	–
	E4	IXPE	03250301	2024-06-02	60463.77	50	7.45 ± 0.12	411 ± 16	14 ± 9	–	HSS
LMC X–1	E1	IXPE	02001901	2022-10-19	59871.61	563	0.96 ± 0.03	14 ± 9	13 ± 3	–	HSS
		NICER	5100070101	2022-10-19	59871.79	2.8	193 ± 6	–	–	–	–
		NuSTAR	90801324002	2022-10-24	59876.16	19	15 ± 2	–	–	–	–
4U 1957+115	E1	IXPE	02006601	2023-05-12	60076.10	572	1.09 ± 0.04	19 ± 4	2 ± 1	–	HSS
		NICER	6100400101	2023-05-12	60076.55	0.6	265 ± 8	–	–	–	–
		NuSTAR	30902042002	2023-05-15	60079.33	19	29 ± 4	–	–	–	–
LMC X–3	E1	IXPE	02006599	2023-07-07	60132.77	562	0.97 ± 0.03	16 ± 4	18 ± 3	–	HSS
		NICER	6101010117	2023-07-08	60133.42	0.1	358 ± 23	–	–	–	–
		NuSTAR	30902041002	2023-07-09	60134.51	28	15 ± 3	–	–	–	–
	E2	IXPE	03004899	2024-10-03	60586.51	385	1.62 ± 0.04	40 ± 5	14 ± 9	–	HSS
		NICER	7704010101	2024-10-03	60586.63	2.4	606 ± 11	–	–	–	–
	E3	IXPE	03004901	2024-11-21	60635.94	382	0.42 ± 0.02	8 ± 5	–	–	HSS
		NICER	7704010201	2024-11-23	60637.10	1.7	246 ± 7	–	–	–	–
	E4	IXPE	03005001	2025-01-11	60686.18	389	±	11 ± 4	9 ± 7	–	HSS
NuSTAR		31002032006	2025-01-11	60686.68	35	±	±	–	–	–	

[†]Data are not available in public domain. [□]AMI-LA (15.5 GHz, [Steiner et al. 2024](#)). *RATAN (4.7 GHz, [Veledina et al. 2024b](#)).

Table 4.4: Continued.

Source	Epoch	Instrument	Obs. ID	Start Date	MJD Start	Exposure (ks)	Mean Rate (cts/s)	<i>MAXI/GSC</i> Flux (mCrab) (2 – 20 keV)	<i>Swift/BAT</i> Flux (mCrab) (15 – 50 keV)	Radio Flux (mJy)	Spectral State
Swift J1727.8–1613	E1	IXPE	02250901	2023-09-07	60194.81	19	42.21 ± 0.28	6053 ± 71	4898 ± 173	120 ± 12**	HIMS
		NICER	6203980115	2023-09-08	60195.61	0.2	64955 ± 274	—	—	—	—
		NuSTAR	80902333006	2023-09-07	60194.78	0.7	6536 ± 8	—	—	—	—
		AstroSat	T05_145T01_9000005836	2023-09-08	60195.07	32	541 ± 23	—	—	—	—
	E2	IXPE	02251001	2023-09-16	60203.70	37	41.29 ± 0.25	5058 ± 31	2472 ± 98	144 ± 4.32*	HIMS
		NICER	6203980119	2023-09-13	60200.18	4.9	65392 ± 122	—	—	—	—
		NuSTAR	80902313002	2023-09-16	60203.81	0.6	5478 ± 26	—	—	—	—
	E3	IXPE	02251101	2023-09-27	60214.92	21	36.85 ± 0.22	3395 ± 49	300 ± 10	88 ± 2.64*	HIMS
	E4	IXPE	02251201	2023-10-04	60221.54	17	41.31 ± 0.24	4689 ± 46	206 ± 38	11 ± 0.33*	SIMS
		NICER	6557020401	2023-10-04	60221.18	6.5	66263 ± 62	—	—	—	—
		NuSTAR	80902313008	2023-10-04	60221.54	0.5	4111 ± 4	—	—	—	—
	E5	IXPE	02251301	2023-10-10	60227.47	18	34.62 ± 0.20	3446 ± 38	206 ± 38	35 ± 1.05*	SIMS
		NICER	6203980136	2023-10-09	60226.02	1.9	57789 ± 149	—	—	—	—
		NuSTAR	80902313016	2023-10-10	60227.82	1.1	3196 ± 4	—	—	—	—
	E6	IXPE	03005701	2024-02-11	60351.39	67	8.09 ± 0.13	80 ± 7	21 ± 12	—	HSS
		NICER	7708010101	2024-02-11	60351.39	3.1	6415 ± 37	—	—	—	—
	E7	IXPE	03006001	2024-02-20	60360.07	151	5.59 ± 0.09	67 ± 8	26 ± 22	—	HSS
		NICER	7708010106	2024-02-19	60359.07	0.6	5354 ± 34	—	—	—	—
	E8	IXPE	03005801	2024-04-03	60403.66	202	7.87 ± 0.11	76 ± 11	109 ± 14	—	LHS
		NICER	7708010109	2024-04-03	60403.29	2.5	675 ± 12	—	—	—	—
GX 339 – 4	E1	IXPE	03005101	2024-02-14	60354.93	95	17.44 ± 0.21	—	79 ± 25	—	SIMS
		NICER	7702010112	2024-02-14	60354.98	3.8	5263 ± 34	—	—	—	—
		NuSTAR	91002306002	2024-02-14	60354.70	16	308 ± 13	—	—	—	—
		AstroSat	A05_166T01_9000006070	2024-02-14	60354.31	50.7	629 ± 26	—	—	—	—
	E2	IXPE	03005301	2024-03-08	60377.68	98	7.37 ± 0.11	103 ± 6	12 ± 8	—	HSS
		AstroSat†	A13_028T01_9000006122	2024-03-10	60379.44	—	—	—	—	—	—
Swift J151857.0 – 572147	E1	IXPE	03250201	2024-03-18	60387.15	96	12.18 ± 0.12	422 ± 8	152 ± 17	—	HSS
		NICER	7204220111	2024-03-18	60387.55	4.2	1468 ± 18	—	—	—	—
		NuSTAR	91001311004	2024-03-18	60387.64	9.2	444 ± 17	—	—	—	—
IGR J17091 – 3624	E1	IXPE	04250201	2025-03-07	60741.30	163	0.27 ± 0.02	755 ± 11	82 ± 27	—	LHS
		NuSTAR	81002342008	2025-03-07	60741.58	21	27 ± 15	—	—	—	—
MAXI J1744 – 294	E1	IXPE	04250301	2025-04-05	60770.09	149	0.17 ± 0.11	45 ± 28	—	—	HSS
GRS 1915 + 105	E1	IXPE	04003501	2025-05-10	60805.69	142	—	6 ± 3	—	—	—

†Data are not available in public domain. **RATAN* (4.7 GHz, [Veledina et al. 2023](#), [Ingram et al. 2024](#)); ***E-MERLIN* (5.1 GHz, [Williams-Baldwin et al. 2023](#)).

measurements constrained its mass as $10 \pm 0.1 M_{\odot}$ ([Seifina et al., 2014](#)) and distance as 10 – 11 kpc ([Seifina et al., 2014](#), [Kalemci et al., 2018](#)). The presence of dips in the light curves of the 1996 outburst indicates a high inclination ($i \sim 60 - 70^{\circ}$) of the system ([Tomsick et al., 1998](#), [Seifina et al., 2014](#)). Spectral modeling ([Pahari et al., 2018](#)) and spectro-polarimetric fitting in the high soft state confirm the source’s spin as ~ 0.92 ([Kushwaha et al., 2023](#)). 4U 1630–47 is observed in the HSS in most of its outbursts till date, possibly due to fast transition from LHS to HSS ([Capitanio et al., 2015](#), [Baby et al., 2020](#), [Peng et al., 2024a](#), [Fan et al., 2024](#), [Parra et al., 2025](#)).

Cyg X–3

Cyg X–3 was discovered over five decades ago ([Giacconi et al., 1967](#)) and is a high-mass X-ray binary system hosting a compact object accreting from a Wolf-Rayet donor star ([van Kerkwijk et al., 1992](#)). Despite extensive studies over the years, the nature of the compact object remains uncertain. Recent polarization measurements suggest that it could be a concealed galactic ultra-luminous X-ray source (ULX) surpassing the Eddington limit due to anisotropic emissions ([Veledina et al., 2024b](#)). It is

worth mentioning that Cyg X–3 exhibits exceptional radio activity (Martí et al., 2000, Miller-Jones et al., 2004) which is tightly correlated with the spectral states on several occasions including the detection of innermost jet confined within the X-ray funnel-like structure (Yang et al., 2023). Recent trigonometric parallax measurements from VLBA observations have precisely constrained the source’s distance as $9.67^{+0.53}_{-0.48}$ kpc (Reid and Miller-Jones, 2023).

LMC X–1

LMC X–1 is the first discovered extra-galactic BH-XRB located in the Large Magellanic Cloud (LMC) (Mark et al., 1969) at a well-constrained distance of ~ 48.1 kpc (Pietrzyński et al., 2013). Dynamical measurements have determined the black hole’s mass to be $10.9 \pm 1.4 M_{\odot}$ with a moderate inclination of $36.4^{\circ} \pm 1.9^{\circ}$ (Orosz et al., 2009). Unlike typical X-ray binaries, LMC X–1 consistently remains in the HSS, with thermal emission contributing around 80% of the spectral flux (Steiner et al., 2012, Bhuvana et al., 2021, Jana et al., 2021) and a luminosity of approximately 2×10^{38} erg s^{-1} (Nowak et al., 2001, Bhuvana et al., 2021). The measurements using continuum fitting method in the thermally dominated state constrain LMC X–1 spin as ~ 0.92 (Gou et al., 2009, Bhuvana et al., 2021), indicating the presence of a rapidly rotating black hole.

4U 1957+115

4U 1957+115 is a bright and persistent low-mass X-ray binary, first discovered by the *Uhuru* mission in 1973 (Giacconi et al., 1974). To date, it has consistently been observed in a disc-dominated spectral state, with flux levels varying between 20 and 70 mCrab (Yaqoob et al., 1993, Maitra et al., 2014, Mudambi et al., 2022). Despite decades of observations with various X-ray missions, key system parameters such as distance, inclination, spin, and mass remain highly uncertain. For instance, a high source distance of 20 – 40 kpc and a low inclination ($\sim 13^{\circ}$) have been proposed for a maximum black hole mass of $\sim 6 M_{\odot}$ (Gomez et al., 2015). In contrast, Maitra et al. (2014) reported a high inclination ($\sim 78^{\circ}$) and a distance between 5 – 10 kpc for a black hole mass of less than $10 M_{\odot}$. Nevertheless, several studies suggest the presence of a maximally spinning black hole in 4U 1957+115 (Barillier et al., 2023).

GX 339–4

The transient BH-XRB GX 339 – 4 was discovered by the OSO–7 mission in 1973 (Markert et al., 1973) and typically undergoes outbursts every 2 – 3 years. Since its discovery, it has remained one of the most extensively studied BH-XRBs due to its rich spectro-temporal variability (Méndez and van der Klis, 1997, Corbel et al., 2003, Zdziarski and Gierliński, 2004, Belloni et al., 2005, Nandi et al., 2012, Aneesha et al., 2024). Detailed timing studies across multiple outbursts have identified distinct temporal features, including type-A, type-B, and type-C QPOs, which are closely associated with the canonical spectral states exhibited by the source (Belloni et al., 2005, Nandi et al., 2012, Mondal et al., 2023, Zhang et al., 2024, Aneesha et al., 2024, and references therein). The black hole mass is constrained to be within 8.28 – 11.89 $M_{\odot}$ (Sreehari et al., 2019b), while the source distance is estimated as 8.4 ± 0.9 kpc

(Parker et al., 2016). Recent studies suggest the source inclination angle between $30^\circ - 34^\circ$, though spin measurements remain highly model-dependent, yielding values ranging from negative to moderate positive spins (Zdziarski et al., 2024).

Swift J151857.0—572147

Swift J151857.0 – 572147 is a newly discovered galactic BH-XRB transient, first detected by *Swift*/BAT during its 2024 outburst (Kennea et al., 2024). Follow-up radio observations with ATCA at 5.5 and 9 GHz confirmed the presence of bright radio flares (Carotenuto and Russell, 2024), generally observed for the BH-XRB transients during the transition from hard to soft spectral states. Subsequent observations with NICER and *Insight-HXMT* constrained the source distance, inclination, and spin parameter as ~ 5.8 kpc, $\sim 2.1^\circ$, and ~ 0.84 , respectively (Peng et al., 2024b). Additionally, coherent type-C QPOs were detected with *Insight-HXMT* in the intermediate state of the outburst, which have been linked to the shock instability model of transonic accretion flow around black holes (Chatterjee et al., 2024).

IGR J17091—3624

IGR J17091 – 3624 is a galactic BH-XRB transient system, discovered by *INTEGRAL*/IBIS in 2003 (Kuulkers et al., 2003). The source exhibits periodic outbursts with a quiescent period of typically four years between the successive outbursts (Capitanio et al., 2009, Krimm et al., 2011, Miller et al., 2016, Katoch et al., 2021). Interestingly, IGR J17091 – 3624 exhibits several exotic X-ray variability signatures, including the well-known “heartbeat” class and therefore, often termed as the twin of GRS 1915+105 (Capitanio et al., 2012, Radhika et al., 2018, Katoch et al., 2021, Wang et al., 2024, Shui et al., 2024). Despite multiple outbursts over the last two decades, the mass, inclination, and distance of the source are not well constrained due to the null-detection of its optical counterpart. However, several indirect measurements predict the source parameters. Using reflection spectroscopy, the inclination of the source is estimated as $\sim 30^\circ - 45^\circ$ (Xu et al., 2017, Wang et al., 2018). In addition, spectral modeling suggests a black hole of mass $10 - 12.3 M_\odot$ likely to be present at the center of IGR J17091 – 3624 (Iyer et al., 2015, Radhika et al., 2018). Based on the luminosity estimates, the distance of the source is predicted to lie within $11 - 17$ kpc (Rodriguez et al., 2011).

MAXI J1744—294

MAXI J1744 – 294, located near the galactic center, is the most recently discovered X-ray transient by *MAXI*/GSC on January 2, 2025, at a flux level of ~ 133 mCrab (Kudo et al., 2025). The energy spectra of the source, obtained from follow-up *NuSTAR* observations, are found to be well described with the model comprising a thermal disc component of temperature ~ 0.7 keV, a powerlaw component of photon index ~ 2.3 and iron line profile at ~ 6.6 keV (Mandel et al., 2025). Based on these initial findings, the source is inferred to be a BH-XRB transient observed in the HSS (Mandel et al., 2025). Notably, subsequent *NICER* monitoring of MAXI J1744 – 294 shows an even steeper photon index of ~ 3 (Jaisawal et al., 2025). Assuming a distance of 8 kpc, the luminosity of the source is estimated to be $\sim 1.5 \times 10^{37}$ erg s $^{-1}$ in $2 - 10$ keV energy

range (Mandel et al., 2025). Further, Grollimund et al. (2025) reported the detection of the radio counterpart of the source at ~ 1.3 GHz with *MeerKAT*.

4.2.3 Understanding Temporal Variabilities

Multi-mission Monitoring

We study the variability properties of each source using multi-mission data during the Epochs of *IXPE* observations. In Fig. 4.5, we present the count rate obtained with *MAXI/GSC* (2 – 20 keV) and *Swift/BAT* (15 – 50 keV) monitoring in panels (a) and (b) along with the variation of hardness ratio (*HR*) from *MAXI/GSC* in panel (c), respectively, for all sources under consideration. Note that, flux values associated with the count rates in soft (hard) energy bands with *MAXI/GSC* (*Swift/BAT*) are also mentioned in units of mCrab in the *y*-axis (right side) of the respective panels. Further, radio flux densities obtained from different observational campaigns, such as *RATAN* (Veledina et al., 2024b, Ingram et al., 2024), *E-MERLIN* (Williams-Baldwin et al., 2023), *VLITE* (Peters et al., 2023) and *AMI-LA* (Steiner et al., 2024) near the *IXPE* Epochs, are shown in panel (d) for the respective sources based on their availability. We observe that all sources show marginal variation in both *MAXI/GSC* and *Swift/BAT* count rates over the entire *IXPE* exposure for a given Epoch. Hence, in Fig. 4.5a-c, we present the average values of the respective quantities over the entire *IXPE* exposure of each Epoch.

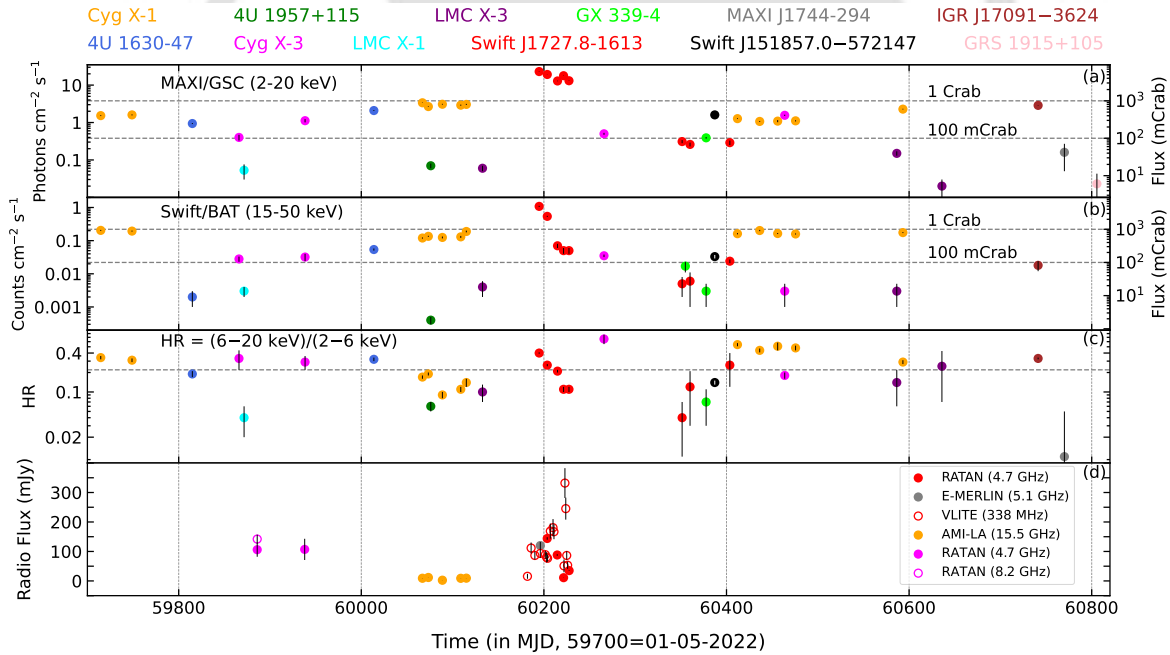


Figure 4.5: Long-term X-ray monitoring of the sources with *MAXI/GSC* (2 – 20 keV), *Swift/BAT* (15 – 50 keV) and the corresponding hardness ratio obtained with *MAXI/GSC* are presented in panel (a), (b) and (c), respectively. Each data point for a given source represents averaged out respective quantity over the exposure of corresponding *IXPE* observation. In panel (d), the variation of radio flux is shown from the quasi-simultaneous radio observations available from various facilities. The 1σ errorbars of the respective quantities are small and remain within the markers for most of the cases. For a given source, the data points plotted with MJD, correspond to the respective Epochs as mentioned in Table 4.4. See the text for details.

Interestingly, for Swift J1727.8 – 1613, we observe that both *MAXI/GSC* and *Swift/BAT* flux decrease as its outburst progresses. The *HR* also sharply decreases

and anti-correlates with the accompanied radio flux density (see Fig. 4.5c-d). The variation of both low and high energy fluxes along with HR in presence of radio ejection suggest that the source evolves through spectral state transitions. In particular, we notice exceptionally bright ($\gtrsim 3$ Crab) intermediate states ($HR \sim 0.1 - 0.5$, E1-E5) followed by relatively faint (~ 30 mCrab) softer states ($HR \sim 0.04 - 0.1$, E6-E7) before the appearance of dimmed (~ 100 mCrab) hard state ($HR \sim 0.3$, E8). Moreover, these variability features resemble the ‘canonical’ state transition as HIMS $\rightarrow$ SIMS $\rightarrow$ HSS $\rightarrow$ LHS (decay), commonly exhibited by BH-XRB transients (see Nandi et al., 2012, for details). Similarly, for Cyg X–1, we observe a marginal increase in the *MAXI/GSC* count rate and a corresponding decrease in the *Swift/BAT* count rate during Epochs E3 to E7. In the subsequent observations (E8 to E11), the *MAXI/GSC* count rate decreases while the *Swift/BAT* count rate rises. In addition, HR shows a significant drop from 0.4 to 0.1 followed by an increase in values exceeding 0.4. This trend possibly indicates the spectral state transitions between LHS (E1-E2, E8-E11) and HSS (E3-E7, E12), respectively (see Table 4.4).

However, only marginal variations are seen in both low- and high-energy count rates for several sources, such as LMC X–1, LMC X–3, 4U 1957 + 115, GX 339 – 4, Swift J151857.0 – 572147 and MAXI J1744 – 294. For all of them, the hardness ratio remains low ($HR \lesssim 0.1$) and these sources are also detected at flux levels below approximately 100 mCrab. These possibly suggest that the sources are likely in softer spectral states. In contrast, Cyg X–3 exhibits a clear sequence of state transitions, evolving from the LHS to the HSS, then to the SIMS, and back to HSS. This evolution is accompanied by moderate changes in count rates and hardness ratio, and is likely associated with strong radio flares (~ 100 mJy) (see Table 4.4, Fig. 4.5, and Veledina et al. 2024b). For 4U 1630 – 47, HSS (Kushwaha et al., 2023) and SPL (Rodriguez Caverio et al., 2023) states are observed with reasonable variations in the count rates and HR . It is worth noting that IGR 17091 – 3624 is observed in the LHS at ~ 1 Crab *MAXI/GSC* flux with $HR \sim 0.4$, very similar to the LHS observations of Cyg X–1. Furthermore, GRS 1915 + 105 is observed with *IXPE* in its current faint and obscured state, with a flux level of ~ 6 mCrab only (see Fig. 4.5). Overall, we observe that the observations in harder spectral states (LHS, HIMS and SPL) and those in relatively softer spectral states (HSS and SIMS) of the sources occupy two distinct regions in the overall HR variation (see Fig. 4.5). Specifically, we notice that $HR \sim 0.22$ separates these two regimes, with $HR > 0.22$ corresponding to harder spectral states and $HR < 0.22$ corresponding to softer spectral states, with some exceptions.

Power Density Spectra

We investigate the power density spectra (PDS) of all sources in different spectral states using *NICER* observations (see Table 4.4) in 0.5 – 10 keV energy range. In addition, PDS properties in hard X-rays (> 10 keV) are also examined using available *NuSTAR* and *AstroSat* observations of the sources. We generate 0.01 s time binned light curves and compute the PDS up to Nyquist frequency of 50 Hz with 1024 newbins per interval using *powspec* inside *HEASOFT V6.34*. The individual power spectra are averaged out to get the resultant PDS in units of rms^2/Hz which is geometrically rebinned in the frequency space with a factor of 1.03 (see Belloni et al., 2002, Belloni et al., 2005, Sreehari et al., 2019a, Majumder et al., 2022). In the upper panels of Fig. 4.6, we present the PDS of the respective sources in different spectral states. We model each

PDS with a combination of `constant` and multiple `Lorentzian` components. Further, we compute the total percentage rms amplitude ($rms_{\text{tot}}\%$) as a measure of variability in 0.1 – 50 Hz and tabulate it in Table 4.5.

Interestingly, we observe that the PDS in several spectral states exhibit distinct variable features. In particular, PDS of Cyg X–1 in the LHS show significant variability with $rms_{\text{tot}}\% \sim 31.1 - 52.4$ (0.5 – 10 keV) and a clear power spectral break at ~ 1.5 Hz with *NICER* observations. Further, power spectral properties in hard X-rays (3 – 80 keV) with quasi-simultaneous *AstroSat* observations exhibit similar break frequencies (~ 1.5 Hz) with $rms_{\text{tot}}\% \sim 37$ in LHS (see Table 4.5 and Fig. 4.6a). We also observe marginal (significant) PDS variability of $rms_{\text{tot}}\% \sim 9.1$ (33) with low (high) energy *NICER* (*AstroSat*) observations of Cyg X–1 in the HSS. Note that similar variability properties including power spectral breaks were also reported by Kushwaha et al. (2021) in LHS and HSS of Cyg X–1.

For Swift J1727.8 – 1613, the presence of type-C QPO feature at ~ 1.4 Hz is observed during HIMS (Epoch 1, hereafter E1) in 0.5 – 100 keV with *NICER*, *NuSTAR* and *AstroSat* quasi-simultaneous observations (see also Nandi et al. 2024, Liao et al. 2024). The evolution of the QPO frequency up to ~ 6.7 Hz is seen with *NICER* in the later Epochs (E2-E5). However, a power distribution, similar to Cyg X–1 (LHS), is observed in the LHS of Swift J1727.8 – 1613 without the presence of power spectral break, whereas marginal variability with $rms_{\text{tot}}\% \sim 1.4$ is noticed during HSS (E6-E7).

The remaining sources (4U 1630 – 47, LMC X–1, LMC X–3, 4U 1957 + 115, Cyg X–3 and Swift J151857.0 – 572147) in SIMS and HSS display weak variability signatures mostly represented by constant noise distribution and occasionally marginal power variation at lower frequencies. Conversely, during the recurrent outburst of GX 339 – 4, a sharp type-B QPO peak at ~ 4.5 Hz ($rms_{\text{QPO}}\% \sim 10.2$) and harmonic feature at ~ 9.5 Hz along with weak broadband noise ($rms_{\text{tot}}\% \sim 15.4$) are observed in SIMS (see Fig. 4.6 and Aneesha et al. 2024). Note that, the QPO features with enhanced $rms_{\text{QPO}}\%$ from 3.76 (0.5 – 10 keV) to 12.6 (3 – 80 keV) are observed with *NICER* and *AstroSat*, respectively. For IGR J17091 – 3624, a sharp type-C QPO at ~ 0.2 Hz ($rms_{\text{QPO}}\% \sim 15$) along with a weak harmonic at ~ 0.4 Hz are observed during the onset phase of the recent outburst (see Fig. 4.6).

Moreover, the overall power spectral properties of the sources, including break frequencies, noise distribution, and the detection of type-C and type-B QPO features, confirm the presence of distinct spectral states during the respective *IXPE* campaigns. These findings further corroborate the results indicating distinct spectral states, obtained from the multi-mission monitoring of the sources.

4.2.4 Examining Wideband Spectral Distribution of BH-XRBs

Spectral Modeling

We investigate the wide-band (0.7–60 keV) spectral characteristics of each source using quasi-simultaneous *NICER* and *NuSTAR* observations. Depending on the availability of spectral coverage from different instruments, the spectra are modeled in different energy ranges (see Table 4.5). For some observations, the spectra at higher energies are seen to be background dominated and/or of large uncertainties. Accordingly, we remove those parts of the spectra and proceed with the modeling. To start with, we adopt the model combination `constant` × `Tbabs` × (`thcomp` ⊗ `diskbb`) (hereafter M1) comprising of a convolution thermal Comptonization component `thcomp` (Zdziarski

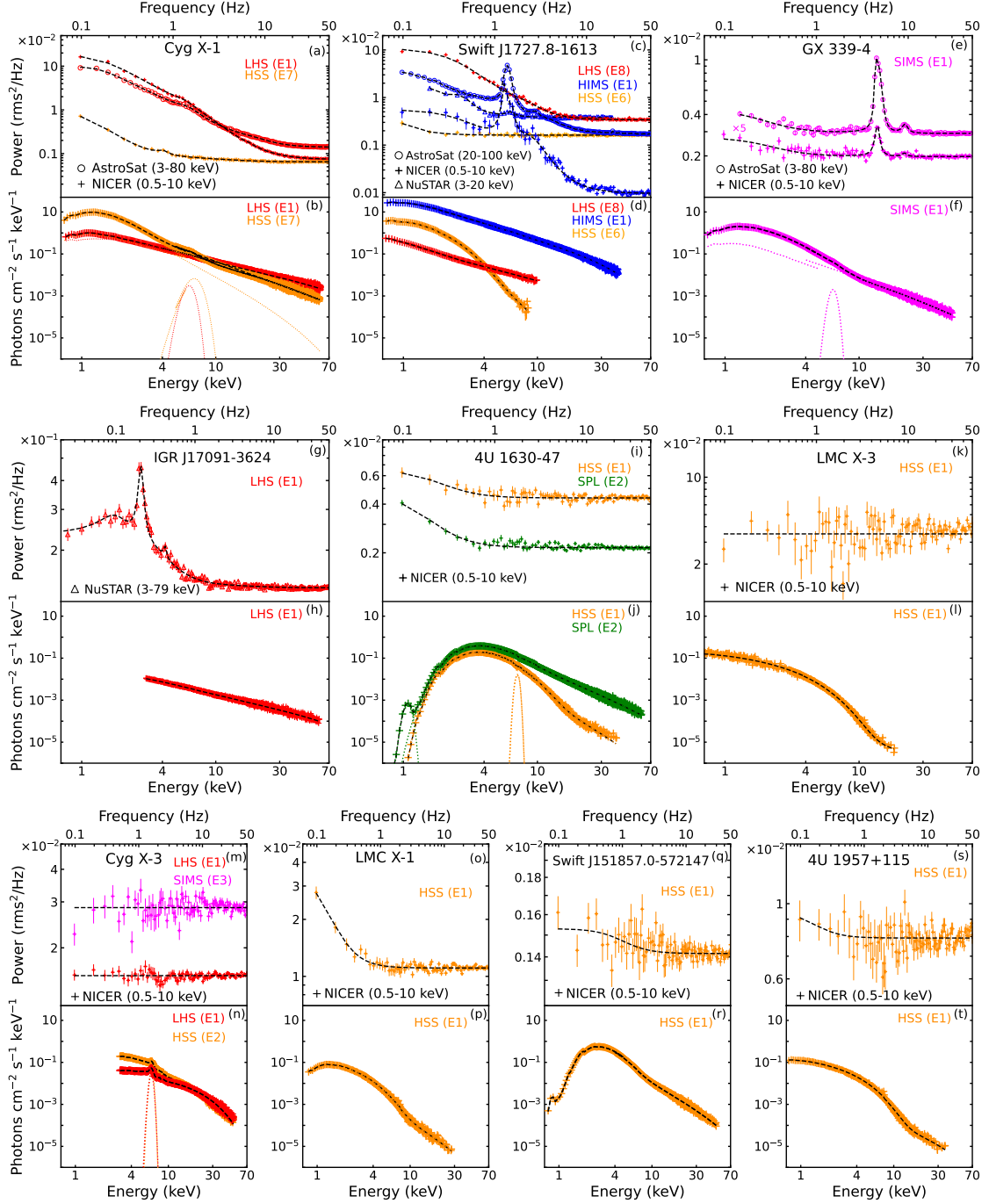


Figure 4.6: Results of temporal (top panel) and spectral (bottom panel) analyses of ten BH-XRBs in different spectral states obtained using quasi-simultaneous *IXPE*, *NICER*, *NuSTAR* and *AstroSat* observations. *Top panels:* PDS obtained from *NICER* (0.5 – 10 keV) and/or *NuSTAR*/*AstroSat* observations in different energy ranges are depicted for the respective sources in various Epochs. The power spectrum of GX 339 – 4 from *NICER* observation is rescaled by a factor of 5. *Bottom panels:* Energy spectra of the sources from *NICER* and/or *NuSTAR* data are shown during the respective Epochs. PDS and energy spectra in LHS, HIMS, SIMS, HSS and SPL states are presented using red, blue, magenta, orange and green colors, respectively. PDS from *NuSTAR* and *AstroSat* data are plotted using circle and triangle, irrespective of the spectral states. See the text and [Majumder et al. \(2025d\)](#) for details.

et al., 2020) along with the standard disc component `diskbb` ([Makishima et al., 1986](#)). Here, `Tbabs` ([Wilms et al., 2000](#)) accounts for the inter-galactic absorption column density and the local absorption to the source. Note that, the component `thcomp` relies on the assumption of spherical geometry of the Comptonizing corona as the source

of hot thermal electrons and up-scatters a fraction of the seed photon distribution of `diskbb` into higher energies. The `constant` is used to adjust the cross-calibration between the spectra of different instruments wherever applicable. With this, the model **M1** is found to provide the best description of the spectra for all sources except a few observations of Cyg X–1 (E6 and E7), Swift J1727.8 – 1613 (E4 and E5) and GX 339 – 1 (E1), which are discussed in the next section. Additionally, we note that a partial covering fraction absorption component `pcfabs` and a Gaussian absorption line `gabs` are required to model the low energy absorption features and the disc-wind regulated absorption line at ~ 7 keV, seen in the spectra of 4U 1630–47 during Epoch-E1. Further, we use `Gaussian` components at ~ 1.8 keV and ~ 2.2 keV (Kushwaha et al., 2023) to account for the instrumental features of *NICER* and at ~ 1 keV for the possible low energy emission line, depending on the strength of the lines in different observations. We also use `Gaussian` line at ~ 6.4 keV in several observations to account for the prominent iron $K\alpha$ line emission. It may be noted that the *NICER* spectra of Cyg X–3 exhibit multiple emission lines at various energies, which restrict us from constraining the parameters of model **M1**. Therefore, we use the *NuSTAR* data only in the spectral study of Cyg X–3. Further, the convolution model `cflux` is used after the `Tbabs` component to estimate the bolometric flux associated with each model component and the entire spectral flux in 1 – 100 keV energy range. Using the estimated distance of each source (see Table 4.5), we compute the bolometric luminosity in units of Eddington luminosity. The best-fitted wide-band spectra (using **M1**) in different energy ranges and spectral states for the respective sources are shown in the bottom panels of Fig. 4.6.

Alternative Spectral Models

We aim to explore the possible alternative disc-corona geometries in explaining the high-energy tail of the observed spectra. To achieve this, we use the `comptt` (Titarchuk, 1994) component as a proxy for `thcomp` in modeling thermal Comptonization. Note that the ‘geometry switch’ selected inside `comptt` model as ‘ ≤ 1 ’ enables a disc-like geometry for the Comptonizing corona. Considering this, we proceed in the spectral fitting of all sources with the model combination `constant×Tbabs×(diskbb + comptt)` (hereafter **M2**). Interestingly, we find that the model **M2** provides a fit equally as good as **M1** for all observations under consideration except a few observations of Cyg X–1 (E6 and E7), Swift J1727.8 – 1613 (E4 and E5) and GX 339 – 4 (E1). This leads to a possible degeneracy between the selected models in describing the observed spectra and the geometry of the Comptonizing region.

It is worth noting that both **M1** and **M2** model combinations fail to provide a satisfactory fit to the observed spectra of Cyg X–1 (E6 and E7), Swift J1727.8 – 1613 (E4 and E5) and GX 339 – 4 in the HSS/SIMS, resulting in a $\chi^2_{\text{red}} \sim 2.7 - 13$ (for **M1**). This is mostly due to the presence of strong reflection features including iron $K\alpha$ line profile at ~ 6.4 keV and reflection hump at ~ 30 keV. To fit these reflection features, we include `relxill` (García et al., 2014) component to model **M1**. Note that, `relxill` assumes an empirical powerlaw to model the emissivity profile of the corona of arbitrary geometry and calculates the primary spectrum considering a `cutoffpl` profile. With this, the model combination `constant×Tbabs×(thcomp⊗diskbb + relxill)` (hereafter **M3**) delineates the spectral data in the HSS/SIMS of Cyg X–1, Swift J1727.8 – 1613 and GX 339–4 with significant improvement in χ^2_{red} in the range $\sim 0.95 - 1.11$. A `Gaussian`

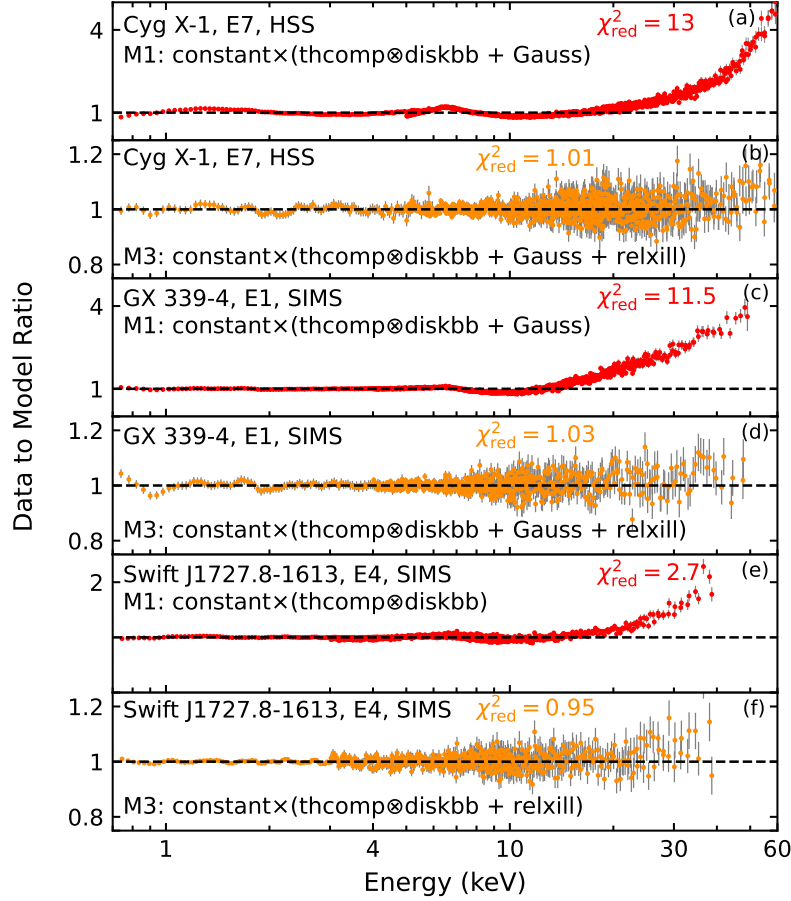


Figure 4.7: Variation of the data to model ratio of the HSS/HIMS spectra of Cyg X–1, GX 339 – 4 and Swift J1727.8 – 1613 fitted with model combination M1 and M3. The improvement in the respective fits by incorporating the reflection model component over M1 is depicted in panels (b), (d) and (f). See the text for details.

at ~ 6.5 keV is also required along with the components of M3 to obtain the best fit for Cyg X–1 and GX 339 – 4 observations. We fix the spin and inclination of the sources to the previously estimated values reported in [Kushwaha et al. \(2021\)](#), [Peng et al. \(2024\)](#), [Mastroserio et al. \(2025\)](#), during the spectral fitting. In Fig. 4.7, we depict the variation of the ratio of data to fitted model (M1 and M3) for these sources, which indicates significant improvement of the respective fits by incorporating the reflection component. We mention that, M3 fails to assert its relevance to the spectra of other sources in different states due to the absence of prominent reflection features.

Spectral Properties

The spectral energy distributions of the individual sources are generally described by the model combination comprising thermal Comptonization, standard disc and occasionally reflection components. Although several models developed based on different coronal geometries are found to describe the observed spectra satisfactorily, we examine the spectral states of the respective sources using model M1 and M3 from the extracted spectral parameters. We present the best-fitted and estimated model parameters for each source in Table 4.5. The variation of the spectral parameters over different observational Epochs indicates the presence of distinct spectral states of the

sources under consideration.

We find that the effects of Comptonization are noticeably high during the LHS of Cyg X-1 with covering fraction $cov_{\text{frac}} \sim 0.61^{+0.04}_{-0.04} - 0.77^{+0.02}_{-0.02}$, where cov_{frac} is the `thcomp` model parameter that measures the fraction of seed photons that are being up-scattered by thermal electrons of the corona. This essentially indicates the Comptonization of up to $\sim 77\%$ of the soft photons in LHS spectra. In addition, a high Comptonized flux contribution of $73 - 80\%$ is also observed in the spectra (see Table 4.5). Indeed, such a high cov_{frac} results in low photon index ($\Gamma_{\text{th}} \lesssim 1.64^{+0.02}_{-0.02}$) as observed during the LHS observations of Cyg X-1. In the HIMS and LHS of Swift J1727.8 - 1613, we find $cov_{\text{frac}} \sim 0.35^{+0.01}_{-0.01} - 0.82^{+0.02}_{-0.02}$ and $\Gamma_{\text{th}} \sim 1.71^{+0.03}_{-0.02} - 2.11^{+0.05}_{-0.04}$ with up to $\sim 64\%$ Comptonized emission. Similarly, LHS of IGR J17091 - 3624 which is dominated by the Comptonized emission ($\sim 87\%$ flux contribution) yields harder ($\Gamma_{\text{th}} \sim 1.62^{+0.02}_{-0.01}$) spectral characteristics. On the other hand, the HSS/SIMS spectra of Cyg X-1 and Swift J1727.8 - 1613 results in low Comptonization with cov_{frac} in the range $0.005^{+0.002}_{-0.002} - 0.38^{+0.04}_{-0.03}$ and thermal disc emission with $39 - 98\%$ flux contribution along with a steeper spectral index ($\Gamma_{\text{th}} \sim 2.32^{+0.06}_{-0.04} - 5.14^{+0.36}_{-0.39}$). Moreover, HSS with $76 - 98\%$ disc contribution are observed for LMC X-1, 4U 1630 - 47, LMC X-3 and 4U 1957 + 115 with negligible Comptonized emission ($cov_{\text{frac}} < 0.1$) as shown in Table 4.5. We find that GX 339 - 4 (Swift J151857.0 - 572147) exhibits intermediate spectral characteristics with $cov_{\text{frac}} \sim 0.34$ (0.21) and $\Gamma_{\text{th}} \sim 2$ (2.5) with $\sim 50\%$ (78%) disc emission during SIMS (HSS).

The reflection spectroscopy of Cyg X-1, Swift J1727.8 - 1613 and GX 339 - 4 with model M3 during the HSS/SIMS results in disc ionization parameter ($\log \xi$) in the range of $3.31^{+0.05}_{-0.05} - 4.29^{+0.14}_{-0.21}$ erg cm s $^{-1}$, iron abundance (A_{fe}) between $\sim 4.61^{+0.36}_{-0.31}$ and $6.35^{+2.08}_{-1.46} A_{\odot}$, and reflection fraction (R_{f}) ranging $\sim 0.59^{+0.05}_{-0.11}$ to $3.16^{+0.35}_{-0.33}$. Here, $A_{\odot}$ represents the solar iron abundance. The best-fitted parameters of the `relxill` component obtained from model M3 are tabulated in Table 4.6, whereas the parameters associated with other spectral components (`diskbb` and `thcomp`) of M3 are presented in Table 4.5 for the respective sources. Notably, a high ionization ($\log \xi \sim 4$) observed in HSS/SIMS generally suggests the reflection of significant coronal emission producing strong reflection signatures. On the other hand, we find that the model component `relxilllp` (Dauser et al., 2013) also delineates the reflection features, assuming the primary source emissivity profile from a lamppost corona. Moreover, another reflection flavor `relxillCp`, in which the spectrum of the coronal emission is computed from the `nthcomp` (Zdziarski et al., 1996) model of spherical geometry, also fits the data for Cyg X-1 (E6 and E7) and Swift J1727.8 - 1613 (E4).

Therefore, it is evident that the reflection spectroscopy also results in degeneracy among several models relying on contemporary coronal geometries. Overall, the wide-band spectro-temporal analysis confirms the presence of distinct spectral states in BH-XRBs, but falls short of resolving the inherent degeneracy among the possible coronal geometries. This again highlights the importance of incorporating X-ray polarimetric observations into the study of BH-XRBs. Subsequently, we explore how polarization measurements of these BH-XRBs can offer deeper insights into this issue.

4.2.5 Decoding Polarization Through Model-Independent Approach

In this section, we conduct an in-depth study of the X-ray polarimetric properties of eleven BH-XRBs observed with *IXPE* across multiple campaigns, employing the

Table 4.5: Results from the wide-band spectral analysis of ten BH-XRBs using *NICER* and *NuSTAR* data, modeled with **M1**: `constant×Tbabs×(thcomp×diskbb)`, unless stated otherwise. Here, n_H , $k_B T_{in}$, $k_B T_e$, Γ_{th} , and cov_{frac} denote the column density, inner disc temperature, electron temperature, photon index, and covering fraction, respectively. F_{disc} , F_{th} , and F_{bol} represent the disc, Comptonized, and total bolometric fluxes, respectively. L_{bol} indicates the bolometric luminosity. rms_{tot} corresponds to the rms amplitude derived from the respective PDS. The energy ranges used for each spectrum and the associated spectral states are also mentioned. See text for details.

Source	Epoch	n_H (10^{22} cm^{-2})	$k_B T_{in}$ (keV)	$k_B T_e$ (keV)	Γ_{th}	cov_{frac}	$\chi^2/d.o.f$	$F_{disc}^{\boxtimes}$ ($10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$)	$F_{th}^{\boxtimes}$ ($10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$)	$F_{bol}^{\boxtimes}$	$L_{bol}^{\boxtimes}$ ($\% L_{Edd}$)	Spectral State	Energy range (keV)	$rms_{tot}^{\dagger}$ (%)
Cyg X-1 ($D = 2.2 \text{ kpc}$)	E1	$0.44^{+0.02}_{-0.02}$	$0.41^{+0.03}_{-0.03}$	$30.35^{+2.87}_{-2.22}$	$1.61^{+0.02}_{-0.01}$	$0.77^{+0.02}_{-0.01}$	1517/1468	0.68	2.45	3.07	1.4	LHS	0.7 – 60	32.5
	E2	$0.34^{+0.02}_{-0.02}$	$0.38^{+0.01}_{-0.01}$	$22.57^{+1.50}_{-1.13}$	$1.61^{+0.01}_{-0.01}$	$0.73^{+0.04}_{-0.03}$	1479/1403	0.74	2.53	3.29	1.5	LHS	0.7 – 60	31
	E6 $^{\boxminus}$	0.51^*	$0.52^{+0.02}_{-0.02}$	10^*	1.01^*	$0.005^{+0.002}_{-0.002}$	2122/1913	1.75	0.22	4.43	2	HSS	3 – 60	–
	E7 $^{\boxminus}$	$0.52^{+0.01}_{-0.01}$	$0.43^{+0.02}_{-0.01}$	10^*	$3.21^{+0.11}_{-0.14}$	$0.31^{+0.03}_{-0.02}$	2185/2167	3.78	0.33	6.18	2.8	HSS	0.7 – 60	9.1
	E8	$0.43^{+0.03}_{-0.03}$	$0.27^{+0.03}_{-0.03}$	20^*	$1.64^{+0.02}_{-0.02}$	$0.65^{+0.06}_{-0.07}$	115/133	0.37	1.15	1.53	0.7	LHS	0.7 – 10	41.5
	E11	$0.39^{+0.02}_{-0.04}$	$0.32^{+0.03}_{-0.04}$	20^*	$1.62^{+0.03}_{-0.03}$	$0.61^{+0.04}_{-0.04}$	152/131	0.39	1.18	1.58	0.7	LHS	0.7 – 10	52.4
4U 1630–47 ($D = 10 \text{ kpc}$)	E1	$6.69^{+0.24}_{-0.30}$	$1.36^{+0.01}_{-0.01}$	20^*	$3.34^{+0.12}_{-0.11}$	$0.052^{+0.008}_{-0.007}$	1134/928	1.56	0.03	1.59	15.1	HSS	0.7 – 40	6.7
	E2	$4.55^{+0.07}_{-0.05}$	$1.46^{+0.02}_{-0.02}$	20^*	$2.47^{+0.05}_{-0.04}$	$0.38^{+0.02}_{-0.01}$	2366/1980	2.76	0.77	3.65	34.7	SPL	0.7 – 60	4.8
Cyg X-3 ($D = 9.7 \text{ kpc}$)	E1	$4.04^{+0.26}_{-0.11}$	$1.21^{+0.02}_{-0.02}$	$6.14^{+0.28}_{-0.34}$	$1.55^{+0.03}_{-0.04}$	$0.83^{+0.02}_{-0.01}$	2921/1842	0.21	0.41	0.64	5.7	LHS	3 – 50	–
	E2	$5.54^{+0.07}_{-0.13}$	$1.01^{+0.01}_{-0.02}$	$7.95^{+0.22}_{-0.14}$	$2.21^{+0.01}_{-0.01}$	$0.63^{+0.01}_{-0.01}$	2709/1903	0.94	0.62	1.58	14.1	HSS	3 – 50	–
LMC X-1 ($D = 48.1 \text{ kpc}$)	E1	$0.50^{+0.01}_{-0.01}$	$0.98^{+0.01}_{-0.01}$	10^*	$2.58^{+0.10}_{-0.09}$	$0.091^{+0.012}_{-0.010}$	744/613	0.065	0.004	0.074	16	HSS	0.8 – 30	10.1
4U 1957+115 ($D = 10 \text{ kpc}$)	E1	$0.08^{+0.01}_{-0.01}$	$1.40^{+0.01}_{-0.01}$	10^*	$1.86^{+0.12}_{-0.10}$	$0.027^{+0.004}_{-0.004}$	728/701	0.092	0.005	0.096	0.9	HSS	0.7 – 40	5

$L_{Edd} = 1.26 \times 10^{39} \text{ erg s}^{-1}$ for $10M_{\odot}$ BH. $\boxtimes$ Calculated in 1 – 100 keV energy range. † Computed in 0.1 – 50 Hz using *NICER* observations in 0.5 – 10 keV energy range. * Frozen values. $^{\boxminus}$ Results are obtained using model M3.

Table 4.5: Continued.

Source	Epoch	η_{H} (10^{22} cm^{-2})	$k_{\text{B}}T_{\text{in}}$ (keV)	$k_{\text{B}}T_{\text{e}}$ (keV)	Γ_{th}	cov_{trac}	$\chi^2/d.o.f$	$F_{\text{disc}}^{\boxtimes}$ ($10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$)	$F_{\text{th}}^{\boxtimes}$	$F_{\text{bol}}^{\boxtimes}$	$L_{\text{bol}}^{\boxtimes}$ ($\%L_{\text{Edd}}$)	Spectral State	Energy range (keV)	$rms_{\text{tot}}^{\dagger}$ (%)
LMC X-3 ($D = 48.1 \text{ kpc}$)	E1	0.04*	$1.10^{+0.01}_{-0.01}$	10^*	$1.78^{+0.45}_{-0.35}$	$0.005^{+0.003}_{-0.002}$	567/543	0.061	0.001	0.062	13.4	HSS	0.7 – 20	–
	E2	0.04*	$1.09^{+0.01}_{-0.01}$	10^*	$2.51^{+0.08}_{-0.07}$	0.3*	153/128	0.11	0.03	0.14	30.8	HSS	1 – 10	–
	E3	0.04*	$0.6^{+0.04}_{-0.03}$	$1.04^{+0.08}_{-0.05}$	$1.72^{+0.11}_{-0.08}$	0.4*	118/117	0.03	0.006	0.035	7.7	HSS	1 – 10	–
	E4	0.04*	$1.07^{+0.01}_{-0.01}$	10^*	$2.05^{+0.05}_{-0.04}$	$0.005^{+0.003}_{-0.003}$	771/706	0.06	0.006	0.07	15.4	HSS	3 – 30	–
Swift J1727.8–1613 ($D = 2.7 \text{ kpc}$)	E1	$0.23^{+0.01}_{-0.01}$	$0.29^{+0.01}_{-0.02}$	$8.44^{+0.16}_{-0.11}$	$1.98^{+0.04}_{-0.02}$	$0.74^{+0.01}_{-0.01}$	1181/931	10.07	15.01	25.24	17.5	HIMS	0.7 – 40	12
	E2	$0.20^{+0.01}_{-0.01}$	$0.43^{+0.02}_{-0.02}$	$9.34^{+0.22}_{-0.23}$	$2.11^{+0.05}_{-0.04}$	$0.82^{+0.02}_{-0.02}$	912/847	11.35	13.58	25.11	17.4	HIMS	0.7 – 40	–
	E4 $\boxtimes$	$0.25^{+0.01}_{-0.01}$	$0.85^{+0.03}_{-0.02}$	10^*	$2.74^{+0.04}_{-0.04}$	$0.38^{+0.04}_{-0.03}$	1373/1447	15.89	3.63	25.04	17.3	SIMS	0.7 – 40	6.1
	E5 $\boxtimes$	$0.29^{+0.02}_{-0.01}$	$0.88^{+0.02}_{-0.02}$	10^*	$2.32^{+0.06}_{-0.04}$	$0.19^{+0.02}_{-0.02}$	1572/1601	10.12	2.09	16.78	11.6	SIMS	0.7 – 60	6.4
	E6	$0.17^{+0.01}_{-0.01}$	$0.48^{+0.01}_{-0.01}$	10^*	$5.14^{+0.36}_{-0.39}$	$0.17^{+0.03}_{-0.03}$	127/132	0.91	0.02	0.93	0.6	HSS	0.7 – 10	1.4
	E7	$0.18^{+0.01}_{-0.01}$	$0.45^{+0.01}_{-0.01}$	10^*	$4.57^{+0.65}_{-0.60}$	$0.13^{+0.09}_{-0.05}$	102/111	0.66	0.01	0.67	0.5	HSS	0.7 – 10	1.3
	E8	0.12*	$0.24^{+0.01}_{-0.01}$	20^*	$1.71^{+0.03}_{-0.02}$	$0.35^{+0.01}_{-0.01}$	126/130	0.08	0.12	0.19	0.1	LHS	0.7 – 10	30.2
	E1 $\boxtimes$	$0.51^{+0.01}_{-0.01}$	$0.60^{+0.02}_{-0.02}$	$0.97^{+0.02}_{-0.01}$	$2.02^{+0.44}_{-0.52}$	$0.34^{+0.08}_{-0.05}$	1603/1538	0.84	0.36	1.71	11.5	SIMS	0.7 – 50	14.2
Swift J151857.0 – 572147 ($D = 5.8 \text{ kpc}$)	E1	$3.83^{+0.02}_{-0.01}$	$0.94^{+0.01}_{-0.01}$	20^*	$2.50^{+0.01}_{-0.01}$	$0.21^{+0.01}_{-0.01}$	1572/1367	2.11	0.34	2.71	8.7	HSS	0.7 – 50	12.6
	E1	1.1*	$0.88^{+0.27}_{-0.38}$	$23.54^{+4.01}_{-2.91}$	$1.62^{+0.02}_{-0.01}$	$0.87^{+0.03}_{-0.03}$	1465/1486	0.02	0.13	0.15	1.7	LHS	3 – 60	24.3
(LHS)														

$L_{\text{Edd}} = 1.26 \times 10^{39} \text{ erg s}^{-1}$ for $10M_{\odot}$ BH. $\boxtimes$ Calculated in 1 – 100 keV energy range. $\dagger$ Computed in 0.1 – 50 Hz using *NICER* observations in 0.5 – 10 keV energy range. * Frozen values. $\boxtimes$ Results are obtained using model M3.

Table 4.6: Best-fitted parameters of the reflection model component `relxill` used in the model combination **M3**: `constant×Tbabs×(thcomp⊗diskbb + relxill)`. The parameters of other components in **M3** are listed in Table 4.5 for the respective Epochs. Here, Γ is the powerlaw index of the source spectrum, A_{Fe} is the iron abundance in solar units, $\log \xi$ is the ionization of the accretion disc, and R_{f} is the reflection fraction parameter. F_{relxill} is the flux associated with the `relxill` model component. The references for the spin and inclination of the sources are mentioned in the footnote. See text for details.

Source	Epoch	Spin (a_*)	Inclination (i) ($^\circ$)	Γ	A_{Fe} ($A_\odot$)	$\log \xi$ (log erg cm s $^{-1}$)	R_{f}	$F_{\text{relxill}}^\square$ (10^{-8} erg cm $^{-2}$ s $^{-1}$)	Spectral State
^a Cyg X–1	E6	0.98*	27*	$2.32^{+0.04}_{-0.06}$	$6.35^{+2.08}_{-1.46}$	$3.86^{+0.09}_{-0.08}$	$0.67^{+0.04}_{-0.04}$	2.33	HSS
	E7	0.98*	27*	$2.04^{+0.01}_{-0.01}$	$4.61^{+0.36}_{-0.31}$	$3.31^{+0.05}_{-0.05}$	$1.11^{+0.03}_{-0.03}$	2.14	HSS
^b GX 339 – 4	E1	0.85*	50*	$2.27^{+0.03}_{-0.03}$	0.5 $^\boxtimes$	$3.92^{+0.12}_{-0.05}$	$3.16^{+0.35}_{-0.33}$	0.54	SIMS
^c Swift J1727.8 – 1613	E4	0.98*	40*	$2.19^{+0.03}_{-0.02}$	5.02 $^\boxtimes$	$4.11^{+0.12}_{-0.13}$	$0.68^{+0.17}_{-0.14}$	5.44	SIMS
	E5	0.98*	40*	$2.48^{+0.02}_{-0.03}$	5.1*	$4.29^{+0.14}_{-0.21}$	$0.59^{+0.05}_{-0.11}$	4.38	SIMS

*Frozen values. $^\boxtimes$ Fixed to the best-fitted values. $^\square$ Calculated in 1 – 100 keV energy range. $A_\odot$ is the solar iron abundance. $r_{\text{g}} = GM/c^2$. ^aKushwaha et al. (2021), ^bMastroserio et al. (2025), ^cPeng et al. (2024).

model-independent techniques outlined earlier. All the calculated polarimetric parameters and the measurement statistics are tabulated in Table 4.7. In Fig. 4.8, we present 3σ confidence contours associated with the measurements of PD and PA for the respective sources in different spectral states. We find a significant degree of polarized emission (PD > MDP₉₉%) in all sources except LMC X–1, Swift J151857.0 – 572147 and MAXI J1744–294. More precisely, we find that PD varies within $1.22 \pm 0.35\%$ – $21.41 \pm 0.41\%$, including all sources in different spectral states within 2 – 8 keV energy band (see Table 4.7). We note that Cyg X–3 shows the maximum degree of polarization, whereas GX 339 – 4 exhibits the lowest PD (> MDP₉₉%) among all sources under consideration. Further, a significant variation of PD is observed over different spectral states of the sources. For example, Cyg X–1 manifests a maximum PD of $\sim 4.8\%$ in the LHS, which decreases to $\sim 1.4\%$ in the HSS (see also Steiner et al. 2024). Interestingly, a similar variation of PD is observed over several spectral states during the outburst phase of Swift J1727.8 – 1613 in which the polarization degree drops down to $\sim 0.4\%$ (HSS) from $\sim 4.7\%$ (HIMS) and again increases to $\sim 3.2\%$ in the LHS (see Table 4.7). Most astonishingly, 4U 1630 – 47 exhibits exceedingly high PD in the HSS ($\sim 8.3\%$) and SPL ($\sim 6.8\%$), respectively (see also Kushwaha et al. 2023, Rodriguez Cavero et al. 2023). Moreover, we find an unprecedentedly high PD of $\sim 9\%$ in the LHS of the recent outburst of IGR J17091 – 3624, which is the maximum reported for any confirmed BH-XRB observed with *IXPE* to date (see also Ewing et al. 2025). In contrast, 4U 1957 + 115 and LMC X–3 are found to show $\sim 1.9\%$ and ~ 2.4 – 3% polarization in the HSS, respectively. It may be noted that, for GX 339 – 4, significant PD ($\sim 1.2\%$, E1) is obtained in 3 – 8 keV energy range (see also Mastroserio et al. 2025), whereas a null-detection is seen considering the entire *IXPE* energy band of 2 – 8 keV. Moreover, we find that the PA of the sources in different spectral states shows marginal variation (see Table 4.7).

Null-detection of X-ray Polarization

It is worth mentioning that we reconfirm the null-detection of polarized emission (PD < MDP₉₉%) for a few sources under consideration. In particular, LMC X–1 remains

Table 4.7: Model-independent polarimetric results obtained using the PCUBE algorithm in the 2 – 8 keV energy band from *IXPE* observations of eleven BH-XRBs. PD and PA represent the polarization degree and angle, respectively. Q/I and U/I are the normalized Stokes parameters. MDP denotes the minimum detectable polarization, and σ_{pol} is the detection significance in units of σ . PDE represents the significance of the energy variation of PD in units of σ . Gray-shaded entries indicate null-detection of polarization. See text for details.

Source	Epoch	Obs. ID	PD (%)	PA (°)	Q/I (%)	U/I (%)	MDP ₉₉ (%)	σ_{pol} (σ)	Spectral State	Remarks (σ)	PDE [‡] Sig. (σ)
Cyg X-1	E1	01002901	3.70 ± 0.19	-20.75 ± 1.50	2.77 ± 0.19	-2.45 ± 0.19	0.59	19	LHS	Detection	2.8
	E2	01250101	3.79 ± 0.32	-25.54 ± 2.39	2.38 ± 0.32	-2.95 ± 0.32	0.96	12	LHS	Detection	< 1
	E3	02008201	2.50 ± 0.40	-19.23 ± 4.63	1.95 ± 0.40	-1.55 ± 0.40	1.22	5.7	HSS	Detection	< 1
	E4	02008301	2.46 ± 0.30	-22.89 ± 3.45	1.71 ± 0.30	-1.76 ± 0.30	0.90	8	HSS	Detection	3
	E5	02008401	2.01 ± 0.29	-25.82 ± 4.11	1.25 ± 0.29	-1.58 ± 0.29	0.88	6.6	HSS	Detection	> 4
	E6	02008501	1.44 ± 0.28	-25.38 ± 5.66	0.91 ± 0.28	-1.12 ± 0.28	0.86	4.5	HSS	Detection	1.2
	E7	02008601	2.07 ± 0.23	-36.37 ± 3.19	0.61 ± 0.23	-1.98 ± 0.23	0.70	9	HSS	Detection	1.1
	E8	03002201	3.75 ± 0.47	-24.22 ± 3.61	2.49 ± 0.47	-2.80 ± 0.47	1.43	7.6	LHS	Detection	1.8
	E9	03003101	3.04 ± 0.48	-18.35 ± 4.54	2.44 ± 0.48	-1.82 ± 0.48	1.46	5.9	LHS	Detection	< 1
	E10	03010001	4.65 ± 0.46	-27.77 ± 2.85	2.63 ± 0.46	-3.83 ± 0.46	1.4	10.1	LHS	Detection	< 1
	E11	03010101	4.76 ± 0.53	-32.64 ± 3.18	1.99 ± 0.53	-4.32 ± 0.53	1.60	9	LHS	Detection	1.5
	E12	03002599	2.79 ± 0.19	-21.97 ± 1.97	2.01 ± 0.19	-1.94 ± 0.19	0.58	14.5	HSS	Detection	> 4
4U 1630-47	E1	01250401	8.34 ± 0.17	17.80 ± 0.60	6.79 ± 0.17	4.86 ± 0.17	0.53	48	HSS	Detection	> 4
	E2	02250601	6.77 ± 0.21	21.36 ± 0.90	4.97 ± 0.21	4.59 ± 0.21	0.65	31.7	SPL	Detection	> 4
Cyg X-3	E1	02001899	20.60 ± 0.31	-89.79 ± 0.43	-20.60 ± 0.31	-0.15 ± 0.31	0.94	66.3	LHS	Detection	> 4
	E2	02250301	10.58 ± 0.28	-87.39 ± 0.75	-10.54 ± 0.28	-0.96 ± 0.28	0.85	38	HSS	Detection	> 4
	E3	02009101	21.41 ± 0.41	-88.09 ± 0.55	-21.36 ± 0.41	-1.43 ± 0.41	1.24	52.7	SIMS	Detection	> 4
	E4	03250301	11.98 ± 0.43	-85.22 ± 1.03	-11.82 ± 0.43	-1.99 ± 0.43	1.31	27.8	HSS	Detection	> 4
LMC X-1	E1	02001901	1.04 ± 0.40	53.97 ± 11.09	-0.32 ± 0.40	0.99 ± 0.40	1.23	1.8	HSS	Null-detection	—

[†]Measurements in 3 – 8 keV. Null-detection in 2 – 8 keV. [‡]Computed considering 6 linear energy bins for all sources except GX 339 – 4, 4U 1957+115 and IGR J17091 – 3624, where 4 linear bins are used.

Table 4.7: Continued.

Source	Epoch	Obs. ID	PD (%)	PA (°)	Q/I (%)	U/I (%)	MDP ₉₉ (%)	σ_{pol} (°)	Spectral State	Remarks (°)	PD _E [⊠] Sig. (°)
4U 1957+115	E1	02006601	1.85 ± 0.37	-42.09 ± 5.75	0.19 ± 0.37	-1.84 ± 0.37	1.13	4.5	HSS	Detection	1.7
	E1	02006599	3.04 ± 0.40	-44.24 ± 3.77	0.08 ± 0.40	-3.04 ± 0.40	1.21	7.2	HSS	Detection	1.8
LMC X-3	E2	03004899	2.39 ± 0.37	-38.43 ± 4.45	0.54 ± 0.37	-2.33 ± 0.37	1.13	6	HSS	Detection	2.3
	E3	03004901	2.19 ± 0.77	-39.42 ± 10.01	0.42 ± 0.77	-2.15 ± 0.77	2.32	2.4	HSS	Null-detection	—
	E4	03005001	2.84 ± 0.52	-47.32 ± 5.24	-0.23 ± 0.52	-2.83 ± 0.52	1.57	5	HSS	Detection	< 1
Swift J1727.8-1613	E1	02250901	4.72 ± 0.28	2.50 ± 1.69	4.71 ± 0.28	0.41 ± 0.28	0.84	17	HIMS	Detection	< 1
	E2	02251001	4.48 ± 0.20	2.28 ± 1.31	4.46 ± 0.20	0.36 ± 0.20	0.62	22	HIMS	Detection	2.8
	E3	02251101	4.39 ± 0.29	0.95 ± 1.87	4.38 ± 0.29	0.15 ± 0.29	0.87	15.3	HIMS	Detection	2.6
	E4	02251201	3.81 ± 0.29	-0.49 ± 2.22	3.81 ± 0.29	-0.07 ± 0.29	0.89	12.8	SIMS	Detection	1.1
	E5	02251301	3.35 ± 0.32	-2.01 ± 2.75	3.34 ± 0.32	-0.23 ± 0.32	0.98	10.4	SIMS	Detection	2.5
	E6	03005701	1.18 ± 0.44	-2.74 ± 10.55	1.18 ± 0.44	-0.11 ± 0.44	1.32	2	HSS	Null-detection	—
	E7	03006001	0.40 ± 0.36	6.05 ± 25.83	0.39 ± 0.36	0.08 ± 0.36	1.08	< 1	HSS	Null-detection	—
	E8	03005801	3.22 ± 0.60	4.18 ± 5.37	3.19 ± 0.60	0.47 ± 0.60	1.83	4.8	LHS	Detection	1.6
GX 339 - 4	E1 [†]	03005101	1.22 ± 0.35	-71.03 ± 8.17	-0.96 ± 0.35	-0.75 ± 0.35	1.05	3.1	SIMS	Detection	3.3
	E2	03005301	0.47 ± 0.36	-25.15 ± 22.07	0.30 ± 0.36	-0.36 ± 0.36	1.09	0.8	HSS	Null-detection	—
Swift J151857.0 - 572147	E1	03250201	0.25 ± 0.26	-22.35 ± 29.98	0.17 ± 0.26	-0.17 ± 0.26	0.78	0.5	HSS	Null-detection	—
	E1	04250201	9 ± 1.41	83.71 ± 4.48	-8.78 ± 1.41	1.96 ± 1.41	4.27	6.1	LHS	Detection	1.2
MAXI J1744 - 294	E1	04250301	0.71 ± 0.42	-15.37 ± 17.21	-0.60 ± 0.42	-0.36 ± 0.42	1.27	1.2	HSS	Null-Detection	—

[†]Measurements in 3 - 8 keV. Null-detection in 2 - 8 keV. [⊠]Computed considering 6 linear energy bins for all sources except GX 339 - 4, 4U 1957+115 and IGR J17091 - 3624, where 4 linear bins are used.

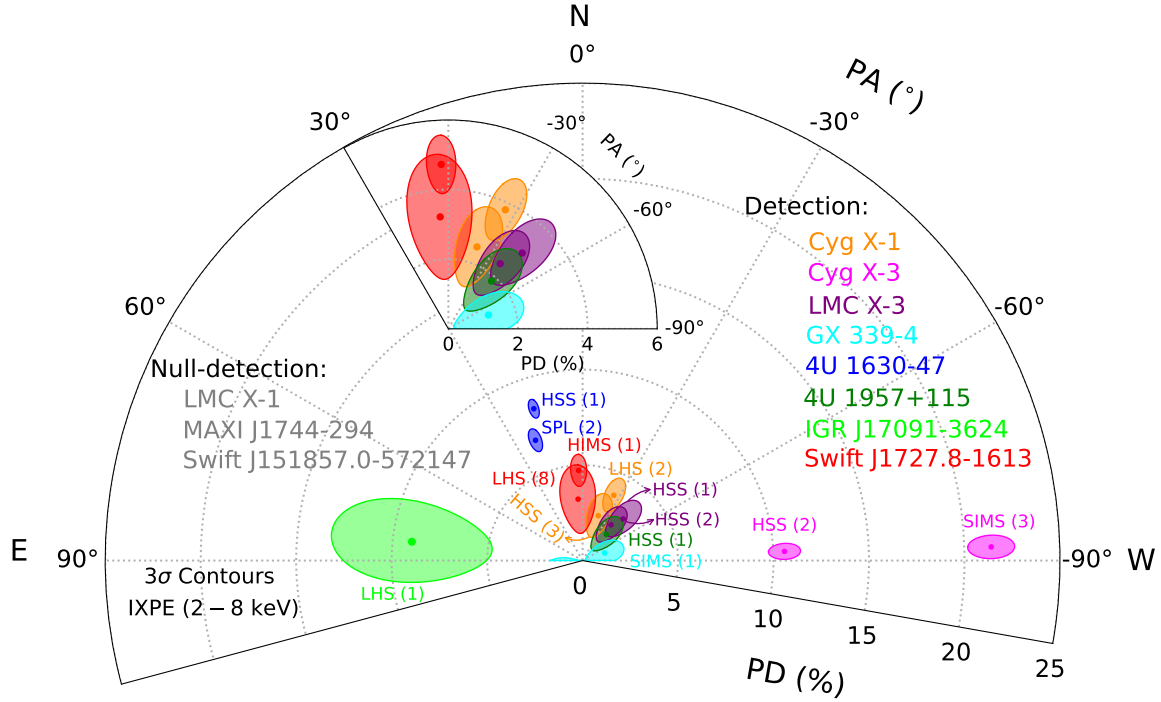


Figure 4.8: Confidence contours (3σ) in the PD-PA plane obtained from the model-independent polarization measurements using 2 – 8 keV *IXPE* data, combining all DUs across various spectral states of the sources. The Epoch of each observation is indicated in parentheses next to the corresponding spectral state. For Swift J151857.0 – 572147, LMC X-1 and MAXI J1744 – 294, null-detection of polarization is observed, whereas all other sources exhibit significant polarization. The inset highlights a zoomed-in region of the PD-PA space for better clarity. See the text and Majumder et al. (2025d) for details.

the first source that fails to manifest significant polarization with *IXPE* (see Table 4.7 and Podgorný et al. 2023). Further, Swift J151857.0 – 572147 exhibits a PD of $\sim 0.25\%$ in 2 – 8 keV which remains significantly low from the corresponding $MDP_{99} \sim 0.78\%$, confirming a null-detection. This finding contradicts the polarization detection with PD $\sim 1.3\%$ as reported by Mondal et al. (2024). This discrepancy possibly arises as the present analysis is carried out using the latest version of the software *IXPEOBSSIM*v31.0.3, fixing the bugs related to the visualization of polarization cubes in the previous releases⁷. We emphasize that our results are consistent with the recent polarization measurements of Swift J151857.0 – 572147 (Ling et al., 2024). Further, the null-detection of polarization is also observed in a few observations of Swift J1727.8 – 1613 (E6, E7), GX 339 – 4 (E2) and LMC X-3 (E3). In addition, for the first time, we report the null-detection of X-ray polarization with PD ($\sim 0.7\%$) $< MDP_{99}(1.3\%)$ in the recently discovered BH-XRB candidate MAXI J1744 – 294 during HSS.

4.2.6 Tracking Polarization Across Photon Energies

We further explore energy-dependent polarization properties of the selected sources that confirm the presence of significant polarized emission in 2 – 8 keV energy range of *IXPE*. For each source except 4U 1957 + 115, IGR J17091 – 3624 and GX 339 – 4, we divide 2 – 8 keV energy range into six linearly spaced energy bins and estimate polar-

⁷https://ixpeobssim.readthedocs.io/en/latest/release_notes.html

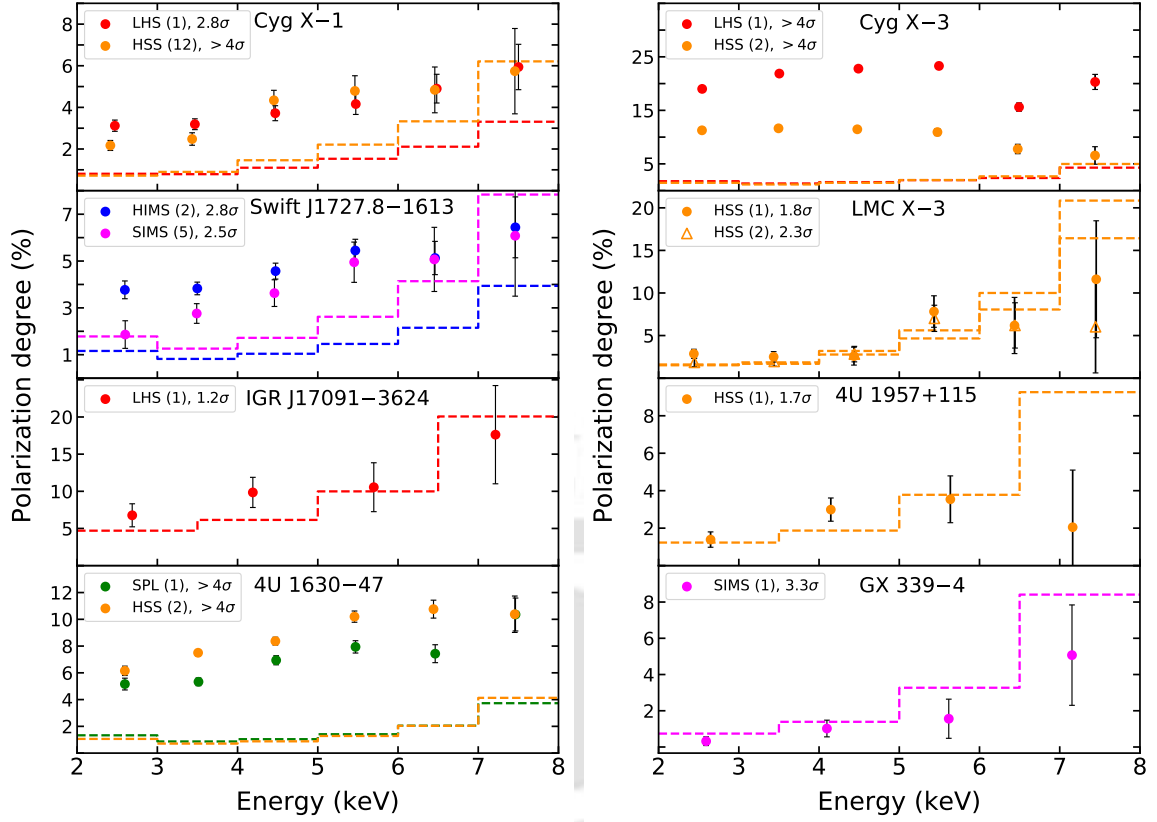


Figure 4.9: Variation of polarization degree (PD) with energy. In each panel, the source name and spectral state (observed during different Epoch) are marked. The histograms in colors represent the minimum detectable polarization at 99% confidence ($MDP_{99\%}$). See the text and Majumder et al. (2025d) for details.

ization using the model-independent approach (see also Svoboda et al. 2024b, Veledina et al. 2023). For 4U 1957 + 115, IGR J17091 – 3624 and GX 339 – 4, only four energy bins are considered for the energy-dependent study to ensure relatively improved photon statistics per energy bin (see also Marra et al. 2024). Further, we estimate the significance of the energy variation of PD over these bins following Krawczynski et al. (2022), Majumder et al. (2024a). In doing so, we consider PD in 2 – 8 keV energy range (see Table 4.7) as the null hypothesis against which the significance of energy variations in PD is computed for each Epoch of a given source. With this, following Majumder et al. (2024a), we calculate the probability of rejecting the null hypothesis using $(N - 1)$ degrees of freedom, taking into account the variation of PD over N energy bins for the respective cases. This essentially indicates the confidence level at which the PD variation is significant over different energy bins. The obtained significance levels of the energy variation of PD are mentioned in Table 4.7 for the respective cases. We observe that this significance varies from $\lesssim 1\sigma$ to $> 4\sigma$ across different Epochs of the sources in various spectral states. In Fig. 4.9, we present the variation of PD with energy over different observational Epochs using filled circles in the respective panels. The histograms in colors represent the $MDP_{99\%}$ associated with the measurements in the selected energy bins for the corresponding Epochs. Note that, for a given source, when multi-Epoch observations are available, we present the results for two Epochs of different spectral states only, except LMC X-3.

Interestingly, we observe that Cyg X-1 and Swift J1727.8-1613 show similar energy variation of PD within $\sim 2 - 6\%$ in different spectral states (LHS, HSS, HIMS

and SIMS). Moreover, for Cyg X–1, the variation in PD with energy remains most significant at a confidence level exceeding 4σ in HSS, whereas it remains 2.8σ for Swift J1727.8 – 1613 in HIMS, when all observational Epochs are considered (see Fig. 4.9). Note that, $PD < MDP_{99\%}$ at higher energy bins in a few Epochs of several sources, indicates a null-detection. Interestingly, unlike Cyg X–1 and Swift J1727.8 – 1613, a weak energy dependency of PD is noticed for IGR 17091 – 3624 in the LHS, for which PD corresponding to two out of four energy bins remain below the $MDP_{99\%}$ (see Fig. 4.9). We find a significant increase in PD with energy up to $\sim 11\%$ in HSS ($> 4\sigma$) and SPL ($> 4\sigma$) state of 4U 1630–47 (see Fig. 4.9). Similarly, distinct variations of PD over several energy bins are observed for Cyg X–3 during LHS ($> 4\sigma$) and SIMS ($> 4\sigma$). LMC X–3 shows constant polarization over the initial three energy bins with a sudden jump in PD up to $\sim 7.8\%$ at ~ 5.4 keV in both Epochs (see Fig. 4.9). Further, we only observe a marginal variation (1.7σ) of PD in 4U 1957+115 up to $\sim 3\%$. Interestingly, significant (3.3σ) energy variation of polarization degree is observed for GX 339 – 4. Although, $PD < MDP_{99\%}$ is obtained in all four energy bins (see Fig. 4.9). Overall, we state that a significant ($> 3\sigma$) variation of polarization degree with energy is observed only for Cyg X–1, 4U 1630–47 and Cyg X–3, whereas a moderate (2σ to 3σ) variation is seen for Swift J1727.8–1613 and LMC X–3. It is worth mentioning that the energy variation of PA for all sources under consideration remains statistically insignificant ($< 2\sigma$). However, we note that PA drops from -30° to -60° at ~ 6 keV in 4U 1957+115, which is marginally significant at 1.6σ confidence level.

4.2.7 Polarimetric Information From Emission Spectra

We explore the model-dependent spectro-polarimetric properties of the sources from the simultaneous fitting of the I, Q and U Stokes spectra of *IXPE* in 2 – 8 keV energy range. Due to the calibration issues (Krawczynski et al., 2022, Veledina et al., 2024b, Steiner et al., 2024), only DU1 data is considered for the spectro-polarimetric study of Cyg X–1, Cyg X–3 and Swift J1727.8–1613, whereas data combining all the DUs are used for the remaining sources. For simplicity, we first adopt the model combination M4: `Tbabs×polconst×(diskbb + powerlaw)` for the spectro-polarimetric fitting. Here, `polconst` represents a constant polarization model, where the degree and angle of polarization are treated as the model parameters. The best-fit results yield χ^2_{red} ranging from 0.91 – 1.79 across all selected sources, with PD varying between ~ 1.16 – 13.06% and PA spanning from -89.13° to 85.15° . Note that the spectro-polarimetric modeling of Swift J1727.8 – 1613 does not constrain the hydrogen column density, likely due to low-energy threshold of *IXPE* (~ 2 keV; see Veledina et al., 2023, Ingram et al., 2024).

Next, we investigate the energy-dependent polarization properties using model-dependent approach for all the sources that demonstrate the signature of X-ray polarization. In doing so, we replace the `polconst` component with the energy-dependent polarization model `polpow`⁸. Empirically, `polpow` assumes a powerlaw variation in the polarization parameters of the form $PD(E) = A_{\text{norm}} \times E^{-A_{\text{index}}}$ (in fraction) and $PA(E) = \psi_{\text{norm}} \times E^{-\psi_{\text{index}}}$ (in $^\circ$) while modeling the Q and U Stokes spectra. We find that the best-fitted ψ_{index} remains consistent with zero within its 1σ errors and hence, we freeze it to zero during the spectral fitting of all observations. Accordingly,

⁸<https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node218.html>

Table 4.8: Results from the spectro-polarimetric modeling of *IXPE* Stokes spectra across different observation Epochs of the sources in 2 – 8 keV energy band. The parameters, with their standard definitions, are obtained from the constant polarization model (polconst) and the energy-dependent polarization model (polpow). See text for details.

Source	Epoch	A_{norm}	A_{index}	ψ_{norm} ($^{\circ}$)	χ^2_{red} (polpow)	PD _{polpow} (%)	PA _{polpow} ($^{\circ}$)	PD _{polconst} (%)	PA _{polconst} ($^{\circ}$)	χ^2_{red} (polconst)
Cyg X-1 ^a	E1	$0.020^{+0.008}_{-0.006}$	-0.43 ± 0.25	-19.83 ± 2.22	1.01	3.93 ± 0.95	-19.83 ± 2.22	3.40 ± 0.26	-19.73 ± 2.24	0.91
	E2	—	—	—	—	—	—	3.41 ± 0.44	-25.13 ± 3.73	1.09
	E3	—	—	—	—	—	—	2.24 ± 0.61	-11.87 ± 7.95	1.15
	E4	$0.008^{+0.005}_{-0.004}$	-0.90 ± 0.56	-17.74 ± 5.45	1.13	3.39 ± 0.40	-17.74 ± 5.45	2.29 ± 0.45	-18.33 ± 5.68	1.13
	E5	$0.003^{+0.003}_{-0.002}$	-1.57 ± 0.57	-8.63 ± 6.16	1.10	3.95 ± 0.31	-8.63 ± 6.16	1.91 ± 0.47	-9.48 ± 7.18	1.10
	E6	0.003 ± 0.002	-1.52 ± 0.68	-16.26 ± 5.74	1.12	3.63 ± 0.47	-16.26 ± 5.74	2.06 ± 0.45	-16.64 ± 6.27	1.13
	E7	0.009 ± 0.005	-0.80 ± 0.47	-25.03 ± 4.56	1.11	3.23 ± 0.99	-25.03 ± 4.56	2.19 ± 0.37	-25.77 ± 4.69	1.11
	E8 ^b	—	—	—	—	—	—	3.04 ± 0.66	-27.09 ± 6.24	1.07
	E9 ^b	—	—	—	—	—	—	3.35 ± 0.67	-25.73 ± 5.79	1.25
	E10 ^b	—	—	—	—	—	—	5.83 ± 0.64	-32.72 ± 3.15	0.96
	E11 ^b	—	—	—	—	—	—	4 ± 0.7	-34.98 ± 5.27	1.05
	E12	$0.009^{+0.005}_{-0.004}$	$-0.9^{+0.4}_{-0.4}$	-24.1 ± 3.26	1.03	3.38 ± 0.48	-24.1 ± 3.26	2.52 ± 0.48	-23.03 ± 3.34	1.05
4U 1630-47	E1 ^c	0.028 ± 0.003	-0.75 ± 0.07	17.90 ± 0.52	1.28	9.25 ± 0.02	17.90 ± 0.52	7.89 ± 0.14	17.94 ± 0.53	1.36
	E2	0.022 ± 0.004	-0.74 ± 0.11	21.45 ± 0.77	1.13	8.02 ± 0.02	21.45 ± 0.77	6.27 ± 0.17	21.30 ± 0.78	1.17

^aOnly *IXPE* spectra of DU1 is fitted. ^{*}Not constrained. ^bdiskbb is not required. ^cpowerlaw is not required. ^dSpectral fitting performed within 3 – 8 keV range.

Table 4.8: Continued.

Source	Epoch	A_{norm}	A_{index}	ψ_{norm} ($^{\circ}$)	χ^2_{red} (polpow)	PD_{polpow} (%)	PA_{polpow} ($^{\circ}$)	PD_{polconst} (%)	PA_{polconst} ($^{\circ}$)	χ^2_{red} (polconst)
Cyg X-3 ^a	E1 ^c	0.028 ± 0.004	-0.73 ± 0.09	-88.92 ± 0.93	1.46	8.89 ± 0.11	-88.92 ± 0.93	7.09 ± 0.24	-89.13 ± 0.95	1.79
	E2 ^c	0.018 ± 0.002	-0.58 ± 0.11	-88.48 ± 0.97	1.31	4.43 ± 0.16	-88.48 ± 0.97	3.58 ± 0.21	-88.58 ± 1.01	1.36
	E3 ^c	0.024 ± 0.005	-0.87 ± 0.12	-86.98 ± 3.45	1.32	9.75 ± 0.21	-86.98 ± 3.45	7.33 ± 0.31	-87.84 ± 1.19	1.63
	E4 ^c	0.11 ± 0.03	-0.17 ± 0.11	-86.35 ± 1.34	1.31	14.33 ± 0.44	-86.35 ± 1.34	13.06 ± 1.01	-86.29 ± 2.19	1.31
4U 1957+115	E1	—	—	—	—	—	—	1.83 ± 0.33	-43.73 ± 5.19	1.09
LMC X-3	E1	$0.011^{+0.007}_{-0.006}$	-0.82 ± 0.5	-44.29 ± 3.59	1.12	4.08 ± 0.26	-44.29 ± 3.59	2.94 ± 0.37	-44.94 ± 3.63	1.12
	E2	$0.003^{+0.002}_{-0.001}$	-1.67 ± 0.51	-40.47 ± 4.02	1.07	4.71 ± 0.58	-40.47 ± 4.02	2.24 ± 0.56	-38.21 ± 7.17	1.08
	E4	—	—	—	—	—	—	2.85 ± 0.83	-44.18 ± 8.08	1.03
Swift J1727.8-1613 ^a	E1	$0.022^{+0.015}_{-0.009}$	-0.42 ± 0.36	2.21 ± 2.74	1.08	4.26 ± 0.21	2.21 ± 2.74	3.94 ± 0.38	2.02 ± 2.75	1.08
	E2	$0.018^{+0.008}_{-0.006}$	-0.55 ± 0.26	1.53 ± 2.08	1.38	4.29 ± 0.85	1.53 ± 2.08	3.85 ± 0.28	1.41 ± 2.10	1.39
	E3	$0.021^{+0.018}_{-0.010}$	-0.37 ± 0.23	-3.55 ± 3.24	1.04	3.75 ± 0.88	-3.55 ± 3.24	3.53 ± 0.39	-3.63 ± 3.25	1.04
	E4	$0.007^{+0.005}_{-0.004}$	-1.08 ± 0.54	-1.21 ± 3.76	1.05	4.00 ± 0.36	-1.21 ± 3.76	3.11 ± 0.41	*	1.06
	E5	$0.004^{+0.003}_{-0.002}$	-1.49 ± 0.54	-7.21 ± 4.11	0.97	4.59 ± 0.41	-7.21 ± 4.11	2.94 ± 0.45	-8.38 ± 4.44	0.98
	E8	$0.006^{+0.005}_{-0.003}$	-1.28 ± 0.47	0.76 ± 4.21	0.97	4.81 ± 0.17	0.76 ± 4.21	3.22 ± 0.51	2.68 ± 4.54	0.97
GX 339-4 ^d	E1	—	—	—	—	—	—	1.16 ± 0.31	-72.52 ± 7.78	1.03
IGR J17091-3624 ^b	E1	$0.025^{+0.016}_{-0.013}$	-0.89 ± 0.43	85.11 ± 3.88	1.04	10.41 ± 0.51	85.11 ± 3.88	8.24 ± 1.16	85.15 ± 4.03	1.05

^aOnly *IXPE* spectra of DU1 is fitted. ^{*}Not constrained. ^bdiskbb is not required. ^cpowerlaw is not required. ^dSpectral fitting performed within 3 – 8 keV range.

we obtain the best spectral fit for all sources with $\chi^2_{\text{red}} \sim 0.97 - 1.46$. Furthermore, integrating $\text{PD}(E)$ in 2 – 8 keV energy range using the best-fitted model parameters (A_{index} and A_{norm}), we obtain PD as 3.23 – 14.33%. Moreover, with ψ_{index} frozen to zero, the polarization angles are obtained as the best-fitted ψ_{norm} values that vary from -88.92° to 85.11° . Note that, in a few observations of Cyg X–1, 4U 1957+115 and GX 339 – 4 (see Table 4.8), the data is unable to constrain the parameters of **polpow** component even at 1σ level, and hence, we refrain from the modeling with **polpow** for these observations. In Table 4.8, we present the best-fitted model parameters obtained from the spectro-polarimetric study of all sources. We find that the model-dependent polarimetric results are in agreement with the findings of the model-independent study except Cyg X–3, confirming the robustness of the polarization measurements for the individual sources. However, for Cyg X–3, we obtain significantly low PD compared to the results of the model-independent study, likely due to multiple low-energy unpolarized emission lines including strong iron complex around ~ 6.4 keV (see Veledina et al. 2024b), dominating the Stokes spectra.

4.3 Investigating Spectro-Polarimetric Correlation

We examine the spectro-polarimetric correlation properties for each source based on the results obtained from wide-band spectral modeling using model M1 and the polarimetric measurements. Specifically, we explore the correlation between the observed PD obtained from model-independent study, and best-fitted spectral parameters, namely the ratio of disc to Comptonized spectral flux (F_{ratio}) in 1 – 100 keV energy range, and the covering fraction (cov_{frac}) obtained from the **thcomp** model. In Fig. 4.10, we present the variation of PD with F_{ratio} (see Table 4.5) using different markers, where the covering fraction (cov_{frac} , in percent) is represented by the colors of respective markers. The color bar on the right indicates the range of cov_{frac} . The spectral state and the corresponding Epoch (in parentheses) for each observation are marked in the figure.

We observe an apparent anti-correlation between PD and F_{ratio} , and a correlation between PD and cov_{frac} for the sources under consideration. However, 4U 1630–47, Cyg X–3, and IGR J17091 – 3624 deviate significantly from this trend in the PD– F_{ratio} plane (see Fig. 4.10) and therefore, these sources are excluded from the present correlation study. To ascertain the firmness of the apparent correlations, we compute the Pearson correlation coefficient (ρ) based on the variations in spectro-polarimetric parameters. Excluding the aforementioned outliers, we find $\rho = 0.7$ for the PD– cov_{frac} correlation and $\rho = -0.5$ for the PD– F_{ratio} anti-correlation. Furthermore, excluding Epoch E1 of LMC X–3, which appears as a marginal outlier in the PD– F_{ratio} plane, along with 4U 1630–47, Cyg X–3 and IGR J17091 – 3624 as before, the correlations become relatively stronger yielding $\rho = 0.8$ and $\rho = -0.6$ for PD– cov_{frac} and PD– F_{ratio} , respectively.

Furthermore, we find a strong correlation (anti-correlation) between PD and cov_{frac} (F_{ratio}) with $\rho \sim 0.9$ (-0.9) for Swift J1727.8 – 1613. In particular, a sharp drop in PD is noticed from $\sim 4.7\%$ (HIMS) to $\sim 0.4\%$ (HSS) (see also Svoboda et al. 2024a) during which F_{ratio} increases from ~ 0.7 to ~ 66 and cov_{frac} noticeably reduces down to 13% from a maximum value of 82%. A similar trend is observed for Cyg X–1 with $\rho = 0.9$ (-0.9) for the respective positive (negative) correlations between

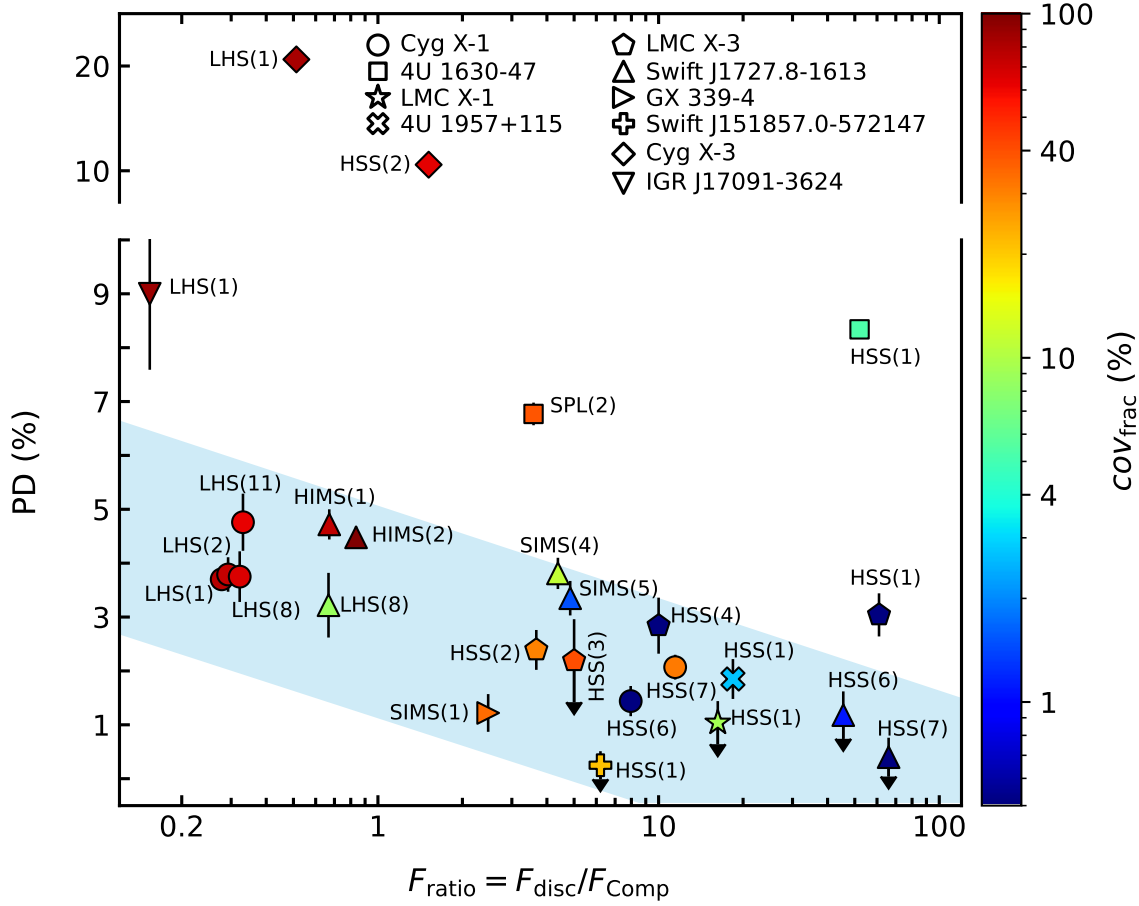


Figure 4.10: Variation of PD (2 – 8 keV), obtained from model-independent analysis, as a function of the disc to Comptonized flux ratio (F_{ratio}) derived in 1 – 100 keV energy range from wide-band spectral modelling. The color bar represents the covering fraction (cov_{frac}) obtained from the `thcomp` model, while each data point is labeled with the corresponding spectral state and observational Epoch. Data points within the shaded region (light blue) are used to compute the Pearson correlation coefficient. Downward arrows indicate null-detections of polarization for the respective sources. See the text and Majumder et al. (2025d) for details.

PD and cov_{frac} (F_{ratio}). As before, a low (high) $F_{\text{ratio}} \sim 0.3$ (11.5) and high (low) $\text{cov}_{\text{frac}} \sim 61 - 77\%$ (0.5 – 31%) are observed in the LHS (HSS) of Cyg X–1 with PD $\sim 3.7 - 4.8\%$ (1.4 – 2.1%) (see Fig. 4.10). Moreover, we also find a similar behavior in the LHS of IGR J17091 – 3624, for which a very high PD ($\sim 9\%$) is seen with $\text{cov}_{\text{frac}} \sim 87\%$ and $F_{\text{ratio}} \sim 0.2$. These findings suggest that a significant contribution in the polarization degree comes from the Comptonized emission for Swift J1727.8 – 1613, Cyg X–1 and IGR J17091 – 3624 in the HIMS and/or LHS. Furthermore, we notice a low polarization degree (PD $\lesssim 2\%$) for all the sources except 4U 1630–47 and LMC X–3 in the HSS/SIMS with $F_{\text{ratio}} \gtrsim 2$ and $\text{cov}_{\text{frac}} \lesssim 30\%$. Interestingly, 4U 1630–47 being the source of extreme soft nature ($F_{\text{ratio}} \sim 52$, $\text{cov}_{\text{frac}} \sim 5\%$) manifests a high polarization degree of $\sim 8.3\%$ in the HSS, whereas it reduces to 6.8% in the SPL state with $F_{\text{ratio}} \sim 3.6$ and $\text{cov}_{\text{frac}} \sim 38\%$. We observe that 4U 1957 + 115 (GX 339 – 4) shows PD $\sim 1.2\%$ (1.9%) with $\text{cov}_{\text{frac}} \sim 2.7\%$ (34%) and $F_{\text{ratio}} \sim 18$ (2.4) in the HSS (SIMS). Moreover, LMC X–3 exhibits moderate polarization with PD in the range of 2.4 – 3% for $F_{\text{ratio}} \gtrsim 4$ and $\text{cov}_{\text{frac}} \sim 0.5\%$ during the HSS.

In this study, we present a comprehensive spectro-polarimetric investigation of eleven BH-XRBs using quasi-simultaneous observations from *IXPE*, *NICER*, *AstroSat*

and *NuSTAR*. *IXPE* data are analyzed to examine the polarization properties in 2 – 8 keV energy range, while combined *NICER*, *AstroSat* and *NuSTAR* observations provide insights into the spectro-temporal behavior across the wide energy range (0.5 – 100 keV). Subsequently, the spectro-polarimetric findings are used to investigate the accretion-ejection dynamics and geometry surrounding the sources.

Spectro-temporal studies using *NICER*, *NuSTAR* and *AstroSat* observations in 0.5 – 100 keV energy range impart distinct variability properties in various spectral states of the sources. The obtained results are in line with the spectro-temporal characteristics generally seen in the respective spectral states of BH-XRBs (Belloni et al., 2005, Remillard and McClintock, 2006, Nandi et al., 2012, Sreehari et al., 2019a, Méndez et al., 2022, Aneesha et al., 2024, Shui et al., 2024, Li et al., 2025). These findings reinforce the presence of distinct spectral states as observed during the multi-mission campaigns of the sources.

In particular, we observe a high fractional variability amplitude $rms_{\text{tot}}\% \sim 30 - 52$ in the PDS of LHS, whereas significantly low variability with $rms_{\text{tot}}\% \sim 6 - 14$ are seen in the intermediate states (HIMS and SIMS) of the sources (see Table 4.5). Negligible power distribution at lower frequencies results in marginal variability ($rms_{\text{tot}}\% \sim 1 - 10$) for the sources in the HSS (see Table 4.5 and Fig. 4.6). In addition, we find the presence of a strong type-C QPO feature at ~ 1.4 Hz (E1), which evolves to ~ 6.7 Hz (E2-E5), during the HIMS and SIMS of Swift J1727.8–1613 over a wide energy range of 0.5 – 100 keV with *NICER*, *NuSTAR* and *AstroSat* observations (see Fig. 4.6). The origin of this QPO is attributed to a strong Comptonizing corona surrounding the central source (Chakrabarti and Titarchuk, 1995, Chakrabarti et al., 2008, Nandi et al., 2024); however, based on the correlation between the evolution of QPO frequency and quasi-simultaneous radio jet ejections, Liao et al. (2024) suggest a jet-like, vertically elongated corona for Swift J1727.8 – 1613. A similar type-C QPO at ~ 0.2 Hz is detected in LHS of IGR J17091 – 3624 (see Fig. 4.6). Moreover, we also observe a type-B QPO in the disc-dominated SIMS of GX 339 – 4 in the 0.5 – 80 keV energy range from *NICER* and *AstroSat* data. Similar type-B QPOs have been observed during 2024 and earlier outbursts of GX 339 – 4, indicating the presence of a compact corona located very close to the black hole, accompanied by dominant disc emission (Nandi et al., 2012, Aneesha et al., 2024).

Admittedly, the wide-band energy spectral analysis (0.7 – 60 keV) reveals distinct spectral states of each source. The observed spectra of all sources are well described by a standard accretion disc component (`diskbb`) combined with thermal Comptonization of soft photons by a spherical corona (`thcomp`) (see Table 4.5 and Fig. 4.6). The spectral properties exhibit a strong correlation with the spectral states of the sources. In particular, during LHS and HIMS, the spectra are dominated by Comptonized emission, contributing $\sim 64 - 87\%$ of the total flux, accompanied by a high covering fraction ($cov_{\text{frac}} \sim 61 - 87$). In contrast, the HSS and SIMS are characterized by a prominent disc component, contributing up to 39–98% with marginal Comptonization effects ($cov_{\text{frac}} \sim 0.5 - 38\%$) across all sources. We observe the present findings to be broadly consistent with the previously reported results for the respective sources. For example, Svoboda et al. 2024a found a steeper $\Gamma_{\text{th}} \sim 4.9$ and low $cov_{\text{frac}} \sim 20\%$ in the HSS of Swift J1727.8 – 1613, which agrees well with our findings of $\Gamma_{\text{th}} \sim 4.6 - 5.1$ and $cov_{\text{frac}} \sim 17\%$. In addition, the LHS results for Cyg X–1 (E1) are consistent with those of Krawczynski et al. (2022), except for their measurement of a high electron temperature, which is likely because of the differences in spectral energy coverage

and/or the choice of model components.

We also notice that the Comptonization model with a disc-like coronal geometry (`comptt`) yields a comparable fit to the observed spectra, similar to the spherical corona model (`thcomp`). This evidently indicates the degeneracy in determining the corona geometry. Furthermore, strong reflection signatures detected in the soft state observations (HSS and SIMS) of Cyg X-1, Swift J1727.8-1613, and GX 339-4 allow the detailed investigation of alternative coronal geometries using various reflection models. We also observe that the reflected emission, either from a lamppost corona, modeled with `relxillp`, or from a spherical corona as described in `relxillCp`, can be reproduced satisfactorily considering a highly ionized accretion disc ($\log \xi \sim 4$). All these findings highlight the inherent degeneracy among different disc-corona geometry models in explaining the observed spectral characteristics.

4.4 Models of X-ray Polarization: Interpretations and Limitations

X-ray polarization measurements with *IXPE* reveal significant polarized emission across several spectral states of the sources in 2 – 8 keV energy range, except for LMC X-1 (see also Podgorný et al. 2023), Swift J151857.0-57214 (see also Ling et al. 2024) and MAXI J1744-294. We find that Cyg X-1 exhibits PD within 3 – 4.8% in LHS, which decreases to 1.4 – 2.5% in HSS. A similar noticeable reduction in the PD from 4.7% (HIMS) to 0.4% (HSS) is also observed for the exceptionally bright transient Swift J1727.8-1613. The most recent *IXPE* observation of this source confirms the recovery of PD $\sim 3.2\%$ in the faint LHS. We mention that these results are in agreement with the previously reported polarimetric findings of Cyg X-1 (Krawczynski et al., 2022, Jana and Chang, 2024, Steiner et al., 2024) and Swift J1727.8-1613 (Veledina et al., 2023, Ingram et al., 2024, Svoboda et al., 2024a, Podgorný et al., 2024).

Intriguingly, an exceptionally high PD of $\sim 8.3\%$ is observed in the HSS of 4U 1630-47, which drops to $\sim 6.8\%$ during the SPL state exhibiting strong ($> 4\sigma$) energy dependency (see Table 4.7 and Fig. 4.9; also Kushwaha et al. 2023, Rodriguez Cavero et al. 2023, Rawat et al. 2023b,a, Ratheesh et al. 2024). In contrast, low PD values are observed in several sources: LMC X-3 ($\sim 2.4 - 3\%$), 4U 1957+115 ($\sim 1.9\%$) and GX 339-4 ($\sim 1.2\%$), being consistent with the previous measurements (Majumder et al., 2024b, Svoboda et al., 2024b, Garg et al., 2024, Marra et al., 2024, Mastroserio et al., 2025). In the present work, we report polarization detections analyzing the most recent *IXPE* observations of Cyg X-3 (PD $\sim 21.4\%$, SIMS), LMC X-3 (PD $\sim 2.4\%$, HSS) and IGR J17091-3624 (PD $\sim 9\%$, LHS), apart from the earlier measurements of these sources. In addition, for the first time to the best of our knowledge, we report the null-detection of X-ray polarization in LMC X-3 (E3) and a newly discovered BH-XRB candidate MAXI J1744-294.

Meanwhile, several models have been proposed to account for the observed polarization in BH-XRBs. For instance, remarkably high PD ($\sim 8.3\%$) of 4U 1630-47 is attributed to the emission from a partially ionized thin/slim accretion disc viewed at inclination $i \gtrsim 60^\circ$ (Ratheesh et al., 2024). A similar explanation is also suggested for LMC X-3 in the HSS that exhibits PD $\sim 3\%$ at $i \sim 70^\circ$ (Majumder et al., 2024b, Svoboda et al., 2024b). Further, scattering of photons in strong disc winds of different opening angles ($\alpha_w \sim 30^\circ - 40^\circ$) has also been suggested as another possible

mechanism to explain high PD values of 4U 1630–47 (Kushwaha et al., 2023, Rawat et al., 2023b, Nitindala et al., 2025). However, Tomaru et al. (2024) demonstrated that electron scattering in an optically thin wind produces polarization in a direction opposite to that obtained from the intrinsic emission from an optically thick disc. As a result, the wind component is expected to depolarize the total emission, including the intrinsic disc emission. Therefore, the presence of a disc-wind from the optically thick disc alone appears insufficient to account for the observed high polarization degree in 4U 1630–47. On the other hand, in high-spin black hole systems, strong relativistic effects cause intense gravitational lensing that bends emitted photons back onto the disc. This enhances the reflection features and significantly affects the observed polarization (Schnittman and Krolik, 2009). Such an effect appears consistent with the polarimetric observations (PD $\sim 1.2 - 2.5\%$) in the soft state as reported for rapidly spinning systems like Cyg X–1 ($a_* > 0.998$) and 4U 1957 + 115 ($a_* \sim 0.988$) (Marra et al., 2024, Steiner et al., 2024).

Furthermore, it has been suggested that $\sim 4\%$ (Cyg X–1, LHS) and $\sim 9\%$ (IGR J17091 – 3624, LHS) polarization can be obtained from a wedge-shaped corona with mildly relativistic outflowing plasma model of Beloborodov (1998) having inclination in the range $30^\circ \lesssim i \lesssim 60^\circ$ (Poutanen et al., 2023, Ewing et al., 2025). A similar model of bulk Comptonization involving a mildly relativistic outflow predicts an even higher polarization degree up to $\lesssim 10\%$ (Dexter and Begelman, 2024). Notably, observed $\sim 4.7\%$ PD at $i \sim 40^\circ$ in HIMS of Swift J1727.8 – 1613 also seems to be consistent with the predictions from a wedge-shaped corona with outflowing plasma velocity $\lesssim 0.2c$ (Poutanen et al., 2023). However, QPOs are detected in Swift J1727.8 – 1613 (0.5 – 100 keV) and IGR J17091 – 3624 (3 – 79 keV) during observations simultaneous with *IXPE*, although their physical origin remains unclear within the framework of the outflowing corona geometry. On the other hand, Kumar (2024) predicted PD $\sim 0.5 - 4\%$ assuming a simple static spherical corona for $30^\circ \lesssim i \lesssim 60^\circ$. This appears broadly consistent with the low PD of $\sim 1.2\%$ observed at $i \sim 30^\circ$ in the SIMS of GX 339 – 4.

All the above interpretations of the polarimetric findings point toward a persistent degeneracy in understanding the different accretion-ejection dynamics. More precisely, predictions regarding the disc-corona-jet geometry become even more challenging when the simultaneous origin of temporal features (QPOs), spectral distributions and polarization (PD) is considered. This emphasizes the need for a unified framework of accretion-ejection processes in BH-XRBs that can consistently explain both timing and spectro-polarimetric observations.

4.5 Constraints on the Accretion-Ejection Geometry in BH-XRBs

Following the discussion of model degeneracies and the need for a unified model framework, we next explore physically motivated accretion-ejection geometries capable of explaining the commonly observed spectro-temporal features, while also offering a promising basis for interpreting the spectro-polarimetric signatures in BH-XRBs. Towards this, a plausible disc-corona-jet configuration based on the two-component accretion flow model (Chakrabarti and Titarchuk, 1995) is illustrated in Fig. 4.11 and discussed in detail below.

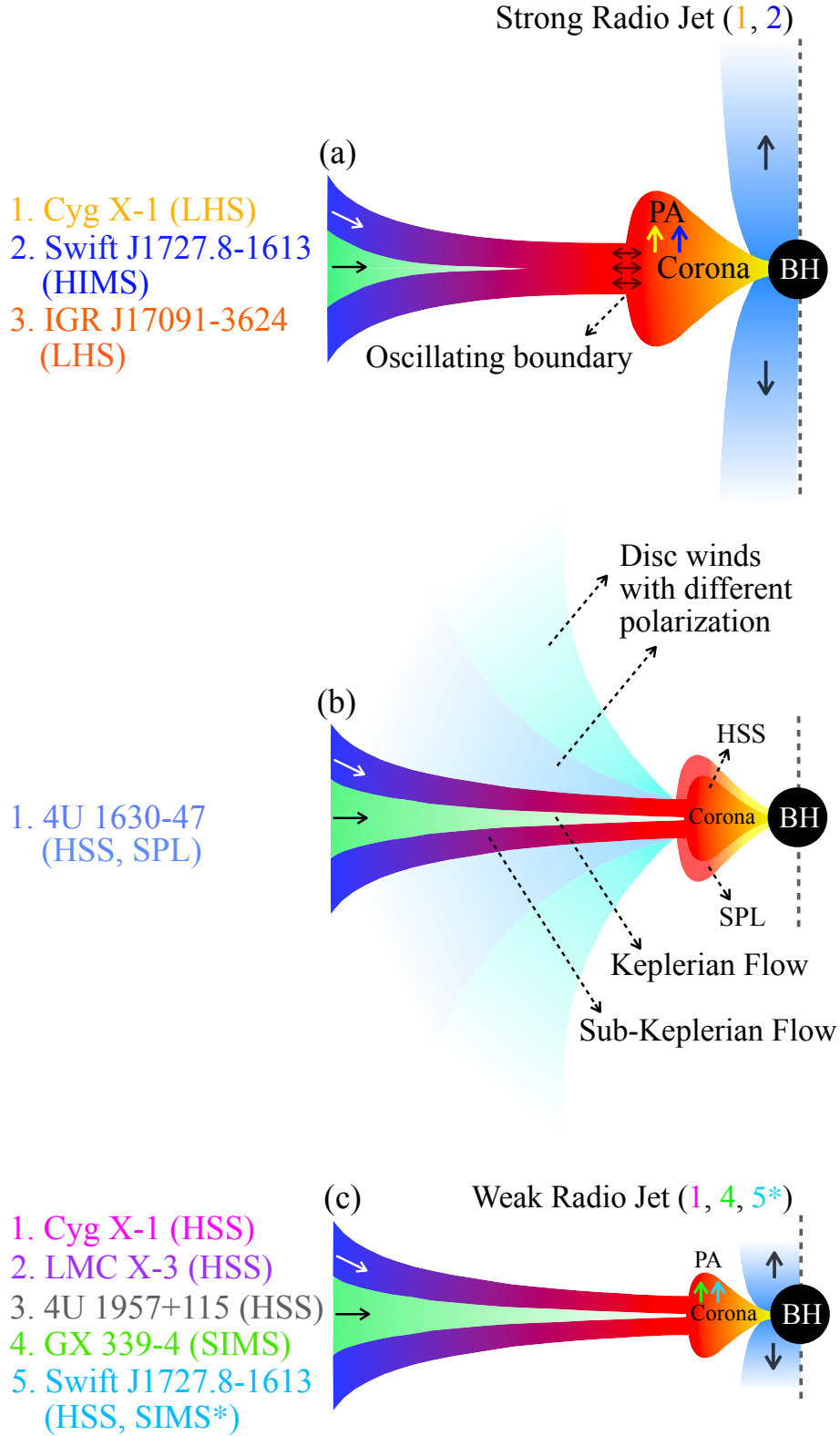


Figure 4.11: Schematic representation of the possible disc-corona-jet configurations for seven BH-XRB sources based on the framework of two-component accretion flow scenario. The Keplerian and sub-Keplerian components, as indicated in panel (b), are also present in the other two configurations. Colored vertical arrows in the corona regions of panels (a) and (c) indicate the direction of polarization angle for the respective sources. In panels (a) and (c), the jet configuration applies only to the sources in distinct spectral states, which are marked by their respective serial numbers. See the text for details.

The spectro-polarimetric correlation study (see Fig. 4.10) suggests that the polarization signatures ($PD \sim 3 - 9\%$) in the LHS/HIMS of Cyg X-1, Swift J1727.8 - 1613 and IGR J17091 - 3624 are primarily governed by the dominant Comptonization process characterized by $F_{\text{ratio}} < 1$ and $cov_{\text{frac}} \sim 35 - 87\%$. Interestingly, the radio jet position angle of Cyg X-1 and Swift J1727.8 - 1613 roughly aligns along the observed PA throughout the respective *IXPE* campaigns (Miller-Jones et al., 2021, Wood et al., 2024). This suggests that PA is possibly oriented perpendicular to the disc-corona geometry. Further, it may be noted that PA resulting from multiple Compton upscatterings generally tends to align along the minor axis of the corona (Ingram et al., 2024). These pieces of evidence suggest a disc-corona configuration comprising a radial corona located close to the black hole, along with a truncated accretion disc at larger radius during LHS/HIMS (see Fig. 4.11a) of Swift J1727.8 - 1613 and Cyg X-1. The above configuration potentially explains the QPOs in Swift J1727.8 - 1613 (see Fig. 4.6c) in terms of the oscillating boundary of the Comptonizing region (see Fig. 4.11a and Molteni et al. 1996, Nandi et al. 2024). It is worth mentioning that the coronal geometry in IGR J17091 - 3624 remains inconclusive from the polarimetric results due to the unresolved position angle of the radio jet. Although the presence of QPO in the LHS of IGR J17091 - 3624 (see Fig. 4.6g) perhaps indicates a similar disc-corona configuration presented in Fig. 4.11a. However, the absence of QPO in Cyg X-1 implies that either the coronal boundary fails to satisfy the necessary resonance condition for modulation, or the oscillation is too subtle to be detected as predicted by Majumder et al. (2025a).

For 4U 1630 - 47, an absorption feature around ~ 7 keV is observed, suggesting the presence of strong disc winds in the HSS ($F_{\text{ratio}} \sim 52$ and $cov_{\text{frac}} \sim 5\%$) spectra. Accordingly, a disc-dominated accretion configuration along with a weak corona, accompanied by strong disc winds with varying opening angles (see also Nitindala et al. 2025), is likely favored for this source (see Fig. 4.11b). However, a relatively strong corona ($cov_{\text{frac}} \sim 38\%$) may be present in the SPL state as compared to the HSS (see Fig. 4.11b).

For GX 339 - 4, a low PD ($\sim 1.2\%$) is observed within 3 - 8 keV energy range during SIMS ($cov_{\text{frac}} \sim 34\%$ and $F_{\text{ratio}} \sim 2.4$), while null-detection of PD is seen in the HSS (Table 4.7). This possibly associates the polarization signature of the source with Comptonized emission. We notice $PD < MDP_{99\%}$ in the entire *IXPE* energy range of 2 - 8 keV during SIMS, which possibly resulted from the depolarization of the overall radiation by unpolarized and/or oppositely polarized (as compared to corona) disc emission (Ingram et al., 2024) at lower energies (2 - 3 keV). The polarization angle of GX 339 - 4 aligns with the direction of the discrete radio jet knot (Mastroserio et al., 2025). These findings predict the GX 339 - 4 configuration comprising a radially extended weak compact corona coexisting with a strong disc ($F_{\text{ratio}} \sim 2.4$, $\Gamma_{\text{th}} \sim 2$), as illustrated in Fig. 4.11c. Moreover, a type-B QPO (see Fig. 4.6e) observed in this source could be explained from this configuration using an analogous argument presented above for Fig. 4.11a (see also Nandi et al. 2012, Aneesha et al. 2024).

Furthermore, we conjecture that a similar disc-corona configuration (see Fig. 4.11c) is also preferred in the disc-dominated HSS/SIMS of other sources (LMC X-3, 4U 1957+115, Cyg X-1 and Swift J1727.8 - 1613) with major contributions from thermal disc and/or various general relativistic effects (Majumder et al., 2024b, Svoboda et al., 2024b, Marra et al., 2024, Steiner et al., 2024, Svoboda et al., 2024a) in the observed PD (1.4 - 3%). It is noteworthy that although the presence of a radial corona is

avored for 4U 1630 – 47, LMC X–3, and 4U 1957 + 115 in Fig. 4.11, the coronal geometry remains uncertain due to the lack of resolved radio jet orientation for these sources. Moreover, high PD (up to $\sim 21\%$) dominated by reflected emission in Cyg X–3 appears inconsistent with the disc-corona configurations presented in Fig. 4.11. It has been suggested that a disc-corona geometry featuring an optically thick funnel in the innermost region of the accretion disc, which obscures most of the primary emission, is favored for Cyg X–3 (Veledina et al., 2024b,c). Finally, we mention that, although the two-component accretion flow configuration aligns with the disc-corona geometry inferred from polarimetric studies for most of the BH-XRBs, a detailed radiative transfer computation is needed within this framework for the predictions on X-ray polarization.

4.6 Summary

In this Chapter, we perform a detailed timing and spectro-polarimetric study of eleven BH-XRBs using quasi-simultaneous *IXPE*, *NICER*, *NuSTAR* and *AstroSat* observations. Our analyses provide valuable insights into the accretion-ejection dynamics and the geometry of BH-XRBs under consideration. The key findings from our study along with their implications are summarized below.

- The combined spectro-temporal results in the wide-band energy range (0.5 – 100 keV) reveal the presence of distinct canonical spectral states of BH-XRBs, which are closely connected to the temporal characteristics and emission mechanism of the sources. The timing and spectral features result in degeneracy among the different viable disc-corona geometries of the sources.
- The detection of X-ray polarization is reconfirmed in eight out of twelve BH-XRBs observed with *IXPE*, with moderate to strong energy dependence of PD and with energy-independent PA. Out of these, we report the first detection of X-ray polarization for LMC X–3 and IGR J17091–3624, and non-detection of polarization in MAXI J1744–294. A comprehensive spectro-polarimetric correlation study reveals significant positive (negative) correlations between PD and $cov_{\text{frac}}(F_{\text{ratio}})$, indicating contributions from various X-ray emission components (disc and corona) of BH-XRBs to the observed polarization.
- Timing and spectro-polarimetric results, combined with the known radio-jet position angles of the sources, suggest that a two-component accretion disc-corona dynamics may be plausible for Swift J1727.8–1613, Cyg X–1, GX 339–4, and IGR J17091–3624. In this framework, a radially extended strong corona is likely to be present at the inner part of a truncated accretion disc during harder states, while a comparatively weaker corona persists in softer states.
- For 4U 1630–47, LMC X–3, and 4U 1957+115, a thermally dominated accretion disc with a weak corona seems to be preferred. However, the coronal geometry still remains ambiguous due to the minimal contribution of Comptonized emission in the *IXPE* band and the lack of complementary radio observations. Additionally, our study also supports the presence of disc winds in 4U 1630–47. We also note that the disc-corona geometry outlined in this work bears limitations to explain the observed features of Cyg X–3, for which an alternative

configuration involving an optically thick inner funnel has been proposed ([Veldina et al., 2024b,c](#)). In addition, for LMC X-1, MAXI J1744-294, and Swift J151857.0-572147, the polarimetric data fail to provide insights into the accretion disc-corona dynamics and geometry, showing a non-detection of X-ray polarization.





Probing Accretion Dynamics of Extragalactic Black Hole ULXs

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As discussed in §1.3.4, BH-ULXs are a subset of X-ray binaries with black hole accretor candidates that exhibit very high ($> 10^{39}$ erg s⁻¹) luminosities, typically exceeding the Eddington limit for a $10M_{\odot}$ black hole. Given that the optical counterparts of most BH-ULXs remain unresolved (Kaaret et al., 2017), our present understanding of the secondary companion star in these binary systems remains limited. These limitations hinder reliable dynamical mass measurements of the central accretor. Additionally, due to the lack of observational constraints, binary system parameters such as inclination and spin of the accreting black hole remain largely unconstrained. These persistent challenges make them one of the long-standing puzzles in X-ray astronomy, while also enabling as a promising field of research.

Thanks to the rich X-ray spectro-temporal variability properties exhibited by BH-ULXs, which are believed to be powerful diagnostic tools for probing the accretion dynamics of these systems, much like those observed for BH-XRBs in Chapter 3 and 4. For example, the study of short-term variability, including mHz QPOs observed in BH-XRBs, is often used to predict the accretion dynamics and the nature of the accretor

(Das et al., 2021). It may be noted that the characteristics of mHz QPOs resemble those with the Type-C LFQPOs frequently observed in BH-XRBs (Belloni et al., 2005, Nandi et al., 2012, Sreehari et al., 2019a, and references therein). Several studies indicate that the mass of BH-ULXs can be determined from the appropriate scale factor corresponding to the QPO frequencies observed in BH-XRBs and BH-ULXs, and eventually favors the existence of IMBH (Dewangan et al., 2006, Strohmayer and Mushotzky, 2009, Pasham and Strohmayer, 2012, Feng and Kaaret, 2010, Agrawal and Nandi, 2015b). Further, using *RXTE* observations of M82 X–1, Pasham et al. (2014) discovered a pair of coherent QPO frequencies ~ 3.32 Hz and ~ 5.07 Hz with the harmonic ratio 3 : 2. These QPOs can be interpreted as analogous to the HFQPO often seen in several BH-XRBs (Belloni et al., 2012, Sreehari et al., 2020, Majumder et al., 2022) and consequently, a $\sim 428M_{\odot}$ black hole is expected to be present at the core of M82 X–1 (Pasham et al., 2014, 2015, Kaaret et al., 2017).

On the other hand, ULX spectra exhibit a soft excess at low energies (< 2 keV) and a characteristic turnover around ~ 10 keV (Feng and Soria, 2011), features that remain distinctly different from those of typical BH-XRB spectra. To delineate the ULX spectra, often two disc blackbody-like components with different temperatures are generally used (Stobbart et al., 2006, Poutanen et al., 2007, Kara et al., 2020). Moreover, it has been suggested that the hotter component originates from the inner accretion flow by means of the inverse Comptonization of the soft photons by the swarm of hot electrons present in the corona (Roberts, 2007, Middleton et al., 2015, Mukherjee et al., 2015, Jithesh et al., 2017). On the contrary, the emission of the soft component may emerge from the optically thick outflow originated within the spherization radius (Shakura and Sunyaev, 1973, Poutanen et al., 2007). Note that the presence of strong winds has also been reported for BH-ULXs (see Pinto et al. 2017 and references therein).

Needless to mention, despite several piecewise studies, there remains a significant lack in understanding the origin of major spectro-temporal variabilities within a single physically motivated framework of accretion dynamics in BH-ULXs. Considering this, we revisit the *XMM-Newton* data archive and select several BH-ULX candidates to perform a comprehensive study of their accretion dynamics. Furthermore, we attempt to constrain the spin and mass of some of the sources and predict their possible system inclinations.

The content of this Chapter is based on Majumder et al. (2023) and Majumder et al. (2025a).

5.1 Details of Selected BH-ULXs and Archival Observations

In this work, we consider nine BH-ULXs, namely NGC 1313 X–1, NGC 5408 X–1, NGC 6946 X–1, IC 342 X–1, M82 X–1, NGC 55 ULX1, NGC 4395 ULX1, NGC 5204 X–1 and NGC 4190 ULX1, having decade-long observations with *XMM-Newton*. The sources are primarily selected based on the publicly available *XMM-Newton* observations spanning over about a decade and the previous predictions of having black hole accretors at the central core of these objects. Further, out of these nine sources, five sources (NGC 1313 X–1, NGC 5408 X–1, NGC 6946 X–1, M82 X–1, and IC 342 X–1) are selected based on their previous reports on the detection of mHz QPO fea-

Table 5.1: Observation details of the five ULXs observed with *XMM-Newton*. In the table, source names, ObsID, Epoch, date of observation, along with MJD and exposure time are mentioned. The count rate in 0.3 – 10 keV energy range of the *EPIC-PN* detector, along with fractional variability (F_{var}) in percentage, are also tabulated. See text for details.

Source	ObsID	Epoch [⊗]	Date	MJD	Effective Exposure (ks)	Rate (cts/s) (0.3 – 10 keV)	(F_{var}) [⊠] (%)
NGC 1313 X-1	0106860101 [†]	XMM1	2000-10-17	51834.14	10.6	0.85 ± 0.08	3.63 ± 1.16
	0205230601 [†]	XMM2	2005-02-07	53408.48	8.2	1.01 ± 0.10	3.30 ± 1.43
	0405090101	XMM3	2006-10-15	54023.98	38.0	0.85 ± 0.08	3.48 ± 2.27
	0693850501	XMM4	2012-12-16	56277.67	32.4	1.03 ± 0.08	3.36 ± 1.79
	0693851201	XMM5	2012-12-22	56283.66	63.7	1.08 ± 0.05	1.54 ± 0.15
	0742590301 [†]	XMM6	2014-07-05	56843.97	60.0	1.81 ± 0.11	4.17 ± 1.04
	0742490101 [†]	XMM7	2015-03-30	57111.19	63.8	0.86 ± 0.09	2.43 ± 0.47
	0803990101 [†]	XMM8	2017-06-14	57918.89	132.2	1.70 ± 0.11	27.28 ± 0.26
	0803990301 [†]	XMM9	2017-08-31	57996.68	33.8	0.93 ± 0.08	2.75 ± 2.57
	0803990601 [†]	XMM10	2017-12-09	58096.46	33.6	1.73 ± 0.11	2.84 ± 1.29
NGC 5408 X-1	0112290501 [†]	XMM1	2001-07-31	52121.54	3.0	1.53 ± 0.11	7.63 ± 0.19
	0112291001 [†]	XMM2	2002-07-29	52484.35	6.0	1.19 ± 0.12	12.09 ± 0.35
	0112291201 [†]	XMM3	2003-01-27	52667.01	2.8	0.95 ± 0.08	16.23 ± 0.12
	0302900101	XMM4	2006-01-13	53748.77	81.2	1.08 ± 0.05	9.12 ± 1.01
	0500750101	XMM5	2008-01-13	54478.79	34.1	0.99 ± 0.05	12.35 ± 0.53
	0653380201	XMM6	2010-07-17	55394.13	77.3	1.22 ± 0.06	7.29 ± 1.11
	0653380301	XMM7	2010-07-19	55396.13	89.4	1.20 ± 0.06	6.12 ± 1.39
	0653380401	XMM8	2011-01-26	55587.67	80.5	1.14 ± 0.06	6.87 ± 1.31
	0653380501	XMM9	2011-01-28	55589.65	46.5	1.08 ± 0.05	7.45 ± 0.94
	0723130301	XMM10	2014-02-11	56699.02	18.7	0.99 ± 0.02	10.33 ± 0.46
	0723130401	XMM11	2014-02-13	56701.02	33.1	1.08 ± 0.08	11.02 ± 0.52
NGC 6946 X-1	0200670301	XMM1	2004-06-13	53169.78	9.7	0.39 ± 0.05	14.61 ± 0.65
	0500730201	XMM2	2007-11-02	54406.91	31.6	0.37 ± 0.06	21.92 ± 0.91
	0500730101	XMM3	2007-11-08	54412.94	18.5	0.38 ± 0.06	26.96 ± 0.74
	0691570101	XMM4	2012-10-21	56221.74	56.8	0.44 ± 0.06	7.35 ± 2.59
	0870830101 [†]	XMM5	2020-07-08	59038.93	12.6	0.42 ± 0.08	24.52 ± 2.26
	0870830201 [†]	XMM6	2020-12-15	59198.32	16.1	0.37 ± 0.11	7.10 ± 1.22
	0870830301 [†]	XMM7	2021-04-04	59308.22	10.7	0.38 ± 0.06	13.30 ± 0.89
	0870830401 [†]	XMM8	2021-05-25	59359.89	12.5	0.34 ± 0.05	23.82 ± 0.55
M82 X-1	0112290201	XMM1	2001-05-06	52035.38	15.2	4.17 ± 0.18	2.99 ± 0.37
	0206080101	XMM2	2004-04-21	53116.90	29.0	3.17 ± 0.16	1.42 ± 0.48
	0560590101 [†]	XMM3	2008-10-03	54742.88	19.2	8.01 ± 0.27	8.87 ± 0.16
	0560590301 [†]	XMM4	2009-04-29	54950.36	15.2	4.91 ± 0.20	2.51 ± 0.40
	0657800101	XMM5	2011-03-18	55638.69	9.2	3.24 ± 0.22	8.77 ± 0.87
	0657801901	XMM6	2011-04-29	55680.55	3.9	3.05 ± 0.15	3.03 ± 0.26
	0657802101	XMM7	2011-09-24	55828.21	10.5	3.19 ± 0.16	3.10 ± 0.41
IC 342 X-1	0093640901 [†]	XMM1	2001-02-11	51951.06	5.4	0.47 ± 0.06	3.44 ± 1.89
	0206890101 [†]	XMM2	2004-02-20	53055.31	6.6	0.98 ± 0.09	2.45 ± 1.49
	0206890201 [†]	XMM3	2004-08-17	53234.82	19.6	0.55 ± 0.07	6.42 ± 1.64
	0693850601	XMM4	2012-08-11	56150.83	36.0	0.52 ± 0.06	3.85 ± 3.58
	0693851301 [†]	XMM5	2012-08-17	56156.84	37.4	0.66 ± 0.07	2.27 ± 4.39

[†]Non-detection of QPO.

[⊠]Fractional variability, calculated from the background subtracted *EPIC-PN* light curves in 0.3 – 10 keV energy range.

[⊗]XMM*i* stands for XMM-Newton, where *i* can run from 1 to 11 based on the observations.

Table 5.2: Details of the *XMM-Newton* observations analyzed in this work of the four selected BH-ULXs. In the table, all the symbols have their usual meanings. Here, count rate (Rate) and F_{var} are not estimated for the observations affected by high particle background flares and the corresponding columns are filled with ‘—’ symbol. Similarly, rms_{total} is not estimated when PDS is modeled only with a **constant** component and for such cases, the respective column is filled using ‘—’. See the text for details.

Source	ObsID	Epoch	Date	MJD	Effective Exposure (ks)	Rate (cts s ⁻¹) (0.3 – 10 keV)	F_{var} (%)	rms_{total} (%)
NGC 55 ULX1	0028740201	XMM1	2001-11-14	52227.63	30.4	1.80 ± 0.23	16.39 ± 1.84	24.11 ± 2.88
	0028740101	XMM2	2001-11-15	52228.05	26.1	1.94 ± 0.33	21.09 ± 2.38	22.61 ± 0.92
	0655050101	XMM3	2010-05-24	55340.32	113.7	0.91 ± 0.16	10.16 ± 6.15	50.29 ± 1.47
	0824570101	XMM4	2018-11-17	58439.62	108.9	0.66 ± 0.14	5.98 ± 2.23	45.36 ± 1.73
	0852610101	XMM5	2019-11-27	58814.87	4.7	1.69 ± 0.23	10.02 ± 1.32	—
	0852610201	XMM6	2019-12-27	58844.52	4.8	1.72 ± 0.24	9.80 ± 1.44	—
	0852610301	XMM7	2020-05-11	58980.93	5.8	0.70 ± 0.15	9.34 ± 3.94	—
	0852610401	XMM8	2020-05-19	58988.40	4.8	1.66 ± 0.34	12.22 ± 3.14	—
	0864810101	XMM9	2020-05-24	58993.92	117.7	0.92 ± 0.16	16.42 ± 6.29	45.79 ± 3.16
	0883960101	XMM10	2021-12-12	59560.31	130	1.14 ± 0.11	5.65 ± 2.75	48.21 ± 13.77
NGC 4395 ULX1	0112521901	XMM1	2002-05-31	52425.03	13.9	0.27 ± 0.09	9.03 ± 3.18	—
	0112522001	XMM2	2002-06-12	52437.76	17.1	—	—	—
	0112522701	XMM3	2003-01-03	52642.93	6.7	0.29 ± 0.09	11.23 ± 8.24	—
	0142830101	XMM4	2003-11-30	52973.14	103.4	0.33 ± 0.11	4.11 ± 1.19	44.22 ± 5.18
	0744010101	XMM5	2014-12-28	57019.42	53.5	—	—	—
	0744010201	XMM6	2014-12-30	57021.42	53	—	—	—
	0824610101	XMM7	2018-12-13	58465.26	112.8	0.40 ± 0.12	16.83 ± 6.87	25.65 ± 3.32
	0824610201	XMM8	2018-12-19	58471.24	113.6	0.47 ± 0.11	81.17 ± 4.59	41.55 ± 2.13
	0824610301	XMM9	2018-12-31	58483.22	110.5	0.38 ± 0.27	93.85 ± 57.71	45.18 ± 6.28
	0824610401	XMM10	2019-01-02	58485.21	105.9	0.76 ± 0.16	25.67 ± 6.64	36.54 ± 5.64
	0913600101	XMM11	2022-12-10	59923.34	33	0.31 ± 0.07	12.74 ± 4.36	37.78 ± 12.22
	0913600501	XMM12	2022-12-14	59927.98	30	0.31 ± 0.16	10.65 ± 5.24	35.58 ± 6.53
	0913600601	XMM13	2022-12-19	59932.32	38.8	0.22 ± 0.07	15.57 ± 5.38	39.04 ± 12.93
	0913600701	XMM14	2022-12-22	59935.65	28	0.26 ± 0.06	7 ± 4	40.38 ± 17.66
	0913600801	XMM15	2022-12-26	59939.86	28	0.24 ± 0.08	8.14 ± 1.58	32.23 ± 7.93
	0913600901	XMM16	2022-12-30	59943.59	28	—	—	—
	0932391701	XMM17	2024-06-01	60462.76	43	0.26 ± 0.05	8.28 ± 4.07	39.57 ± 7.02
	0932391801	XMM18	2024-06-02	60463.69	36	—	—	—
NGC 5204 X-1	0142770101	XMM1	2003-01-06	52645.05	16.9	0.66 ± 0.13	4.90 ± 1.38	—
	0142770301	XMM2	2003-04-25	52754.57	$\lesssim 1$	—	—	—
	0150650301	XMM3	2003-05-01	52760.18	2.9	1.11 ± 0.17	4.16 ± 3.13	28.41 ± 1.62
	0405690101	XMM4	2006-11-15	54054.85	1.9	1.37 ± 0.19	~ 0.42	—
	0405690201	XMM5	2006-11-19	54058.84	35.7	1.13 ± 0.18	5.11 ± 1.23	36.45 ± 7.38
	0405690501	XMM6	2006-11-25	54064.82	15.9	0.83 ± 0.14	5.25 ± 1.42	46.96 ± 3.73
	0693851401	XMM7	2013-04-21	56403.21	15	0.66 ± 0.13	7.64 ± 6.57	—
	0693850701	XMM8	2013-04-29	56411.19	11.3	0.70 ± 0.13	5.01 ± 1.22	—
	0741960101	XMM9	2014-06-27	56835.95	21.3	0.64 ± 0.13	2.04 ± 1.12	—
	0921360101	XMM10	2023-05-18	60082.92	123	0.77 ± 0.15	2.74 ± 1.12	43.51 ± 7.88
	0921360201	XMM11	2023-11-10	60258.43	122	0.95 ± 0.21	4.82 ± 1.78	32.44 ± 8.72
NGC 4190 ULX1	0654650101	XMM1	2010-06-06	55353.51	21.1	—	—	—
	0654650201	XMM2	2010-06-08	55355.47	9.8	1.05 ± 0.17	4.29 ± 1.82	—
	0654650301	XMM3	2010-11-25	55525.06	5.8	1.77 ± 0.25	6.53 ± 1.12	—

tures. It is worth mentioning that M82 X–1 is kept aside from the spectral study of the present work, irrespective of having multiple observations, because of the significant contamination from nearby objects in the *XMM-Newton* aperture (see [Majumder et al. 2023](#) and references therein). However, we consider the *XMM-Newton* of the source for the temporal study. Moreover, a preliminary analysis of the variability properties of the BH-ULX candidate NGC 247 ULX1 suggests that the source exhibits a dipping behavior in its light curves (see [Alston et al. 2021](#) also), accompanied by supersoft characteristics, which remain distinct from those of other sources. Therefore, we exclude

NGC 247 ULX1 in this study. Note that the four remaining sources of our sample of nine BH-ULXs, namely NGC 55 ULX1, NGC 4395 ULX1, NGC 5204 X–1, and NGC 4190 ULX1, have been relatively less studied and serve as ideal targets for detailed analysis. The details of all the observations considered in this work are tabulated in Table 5.1 and 5.2. Below, we present the brief characteristics of the individual sources selected for this work.

NGC 1313 X–1

NGC 1313 X–1 is one of the three bright ULXs located in the nearby ($d \sim 4.25$ Mpc) barred spiral galaxy NGC 1313 (Tully et al., 2016). The source luminosity is observed as $\sim 10^{40}$ erg s $^{-1}$. The source belongs to the hard-ultraluminous spectral state and exhibits significant spectral variability (Pintore and Zampieri, 2012). It is suggested that the source is powered by the super-Eddington accretion onto a stellar-mass black hole (Gladstone et al., 2009, Bachetti et al., 2013). On the contrary, the sub-Eddington accretion onto IMBH of mass $2524 - 6811 M_{\odot}$ is also believed to be an alternative possibility (Huang, 2019). The spin (a_k) of the source is reported as $0.960 - 0.998$ (Caballero-García and Fabian, 2010), indicating maximally rotating BH-ULXs.

NGC 5408 X–1

NGC 5408 X–1 is a nearby ULX source at a distance of 4.8 Mpc, located at ~ 20 arcsec off from the center of the host galaxy NGC 5408 (Luangtip et al., 2021). The observed peak luminosity is found as $\sim 10^{40}$ erg s $^{-1}$. The source is a good candidate for the timing studies as it exhibits variabilities on different time scales ranging from few tens of seconds to few months (Strohmayer, 2009, Heil and Vaughan, 2010, De Marco et al., 2013, Hernández-García et al., 2015). Employing the scaling law of QPO frequency as well as the dynamical mass measurement, the mass of the central source is obtained within IMBH regime (Strohmayer and Mushotzky, 2009, De Marco et al., 2013, Cseh et al., 2013, Luangtip et al., 2021). Using reflection spectroscopy, Caballero-García and Fabian (2010) reported the spin of the source as $0.70^{+0.12}_{-0.05}$.

NGC 6946 X–1

NGC 6946 X–1 is one of the four ULXs in the spiral galaxy NGC 6946 at a distance of 7.72 Mpc (Anand et al., 2018). This source is found to be one of the most variable ULXs that demonstrates short term variabilities with fractional rms amplitude reaching up to $\sim 60\%$ (Rao et al., 2010). In addition, the existence of soft lag at the lower frequencies and hard lag at relatively higher frequencies are reported (Hernández-García et al., 2015). Upon scaling the mHz QPO frequency detected for this source with the low frequency QPOs (LFQPOs) of the galactic BH-XRBs, the mass of NGC 6946 X–1 is revealed as $(1 - 4) \times 10^3 M_{\odot}$ (Rao et al., 2010). It is noteworthy to mention that the spin of the central source in NGC 6946 X–1 remains inconclusive till date.

M82 X–1

The “cigar galaxy” commonly known as M82 resides at a distance of 3.63 Mpc (Middleton et al., 2015) and hosts two well-known ULX sources M82 X–1 and X–2 separated

by only 5 arcsec (Brightman et al., 2020) in the sky plane. M82 X–1, being the most luminous ULX of the host galaxy with peak luminosity reaching up to $\sim 10^{41}$ erg s $^{-1}$, remains one of the most promising IMBH candidate over the years. The mass of M82 X–1 is predicted as $300 - 810M_{\odot}$ from the mass-luminosity correlation (Feng and Kaaret, 2010), although Pasham et al. (2014) inferred its mass as $\sim 400M_{\odot}$ from the scaling relation of 3 : 2 twin-peaked QPO frequency. Further, Stuchlík and Kološ (2015) reported the ranges of mass and spin of the source as $140M_{\odot} < M_{\text{BH}} < 660M_{\odot}$ and $0.05 < a_k < 0.6$, respectively.

IC 342 X–1

IC 342 is a nearby spiral galaxy at a distance ~ 3.61 Mpc (Middleton et al., 2015) and it contains two ULXs, namely IC 342 X–1 and X–2. The source IC 342 X–1 is one of the most studied ULX sources since its discovery by *Einstein* IPC observations (Fabbiano and Trinchieri, 1987). Subsequently, *ROSAT* (Bregman et al., 1993, Roberts and Warwick, 2000) and *ASCA* observations (Kubota et al., 2001) also confirmed its ultra-luminous state with maximum observed luminosity $\gtrsim 10^{39}$ erg s $^{-1}$. The spectral state transitions, namely from the disc-dominated state to the power-law dominated state, are first observed in IC 342 X–1 (Kubota et al., 2001). Several studies from observational and theoretical fronts predict the mass of IC 342 X–1 in the range of $20 - 1783 M_{\odot}$ (Agrawal and Nandi, 2015b, Das et al., 2021). Moreover, the spinning nature of the source still remains inconclusive.

NGC 55 ULX1

NGC 55 ULX1 is the brightest ULX in the spiral galaxy NGC 55 at a distance of 1.94 Mpc¹ with a peak luminosity of $\sim 4 \times 10^{39}$ erg s $^{-1}$. Interestingly, in most of the previous studies, the source was found in the SUL state with disc-dominated spectra (Jithesh, 2022, Barra et al., 2022).

NGC 4395 ULX1

NGC 4395 ULX1 is one of the ULXs located in the NGC 4395 galaxy at a distance of 4.76 Mpc with luminosity $\sim 3 \times 10^{39}$ erg s $^{-1}$ (Ghosh et al., 2022). Detailed spectral study with *XMM-Newton* and *Chandra* observations rules out the possibility of having an SUL state by confirming its steep power-law tail (Earnshaw and Roberts, 2017).

NGC 5204 X–1

The source NGC 5204 X–1 is located ~ 15 arcsec away from the centre of the host galaxy NGC 5204 at a distance of 4.8 Mpc. The evidence of significant outflows resulting in several emission features is observed in NGC 5204 X–1 with *XMM-Newton* (Kosec et al., 2018).

¹<https://ned.ipac.caltech.edu>

NGC 4190 ULX1

The low surface brightness galaxy NGC 4190 located at a distance of 3 Mpc contains NGC 4190 ULX1, a bright ULXs of luminosity $\sim (3 - 10) \times 10^{39} \text{ erg s}^{-1}$ (Ghosh and Rana, 2021). The mass of the source is predicted to be in the range of $10 - 30 M_{\odot}$, indicating the presence of a stellar-mass black hole in the system (Ghosh and Rana, 2021). Recently, a super-Eddington slim disc scenario is also suggested for NGC 4190 ULX1 (Earnshaw et al., 2024).

5.2 Probing Temporal Variability Across Various Timescales

5.2.1 Tracking Short-term Variability

We study the short-term variability properties of all the sources considered in this work. While doing this, we first generate background-subtracted 200 s binned *EPIC-PN* light curves in 0.3–10 keV energy range. Next, to deduce the variability properties of the sources, we calculate the fractional rms variability amplitude, $F_{\text{var}} = \frac{\sqrt{S^2 - \sigma_{\text{err}}^2}}{\bar{x}}$ following Vaughan et al. (2003), Bhuvana et al. (2021). Here, $\bar{x}$, S^2 and σ_{err}^2 are the mean count rate, variance, and associated error of the light curve. We find that the sources exhibit distinct variability properties with F_{var} varying in a wide range of 1.42–93.85% including all the sources and NGC 4395 ULX1 remains the most variable source (see Table 5.1 and 5.2).

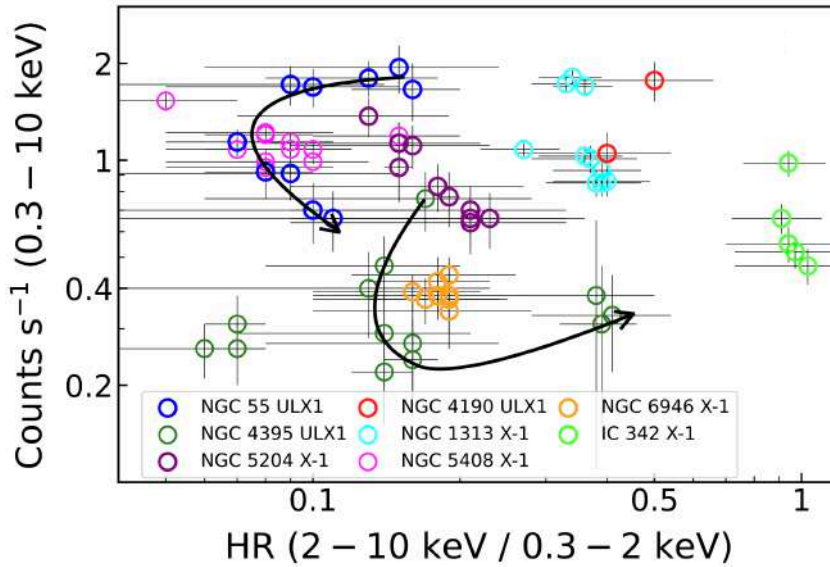


Figure 5.1: Hardness-intensity diagram (HID) of eight BH-ULXs. The variation of *EPIC-PN* background subtracted count rate in 0.3–10 keV energy range with the hardness ratio is shown for each source. The black curved arrows represent the ‘C-shaped’ patterns observed in the HID of NGC 55 ULX1 and NGC 4395 ULX1, respectively. See text for details.

Further, we generate the hardness-intensity diagram (HID) by defining the hardness ratio as $HR = C_1/C_2$ with C_1 and C_2 being the background subtracted count rates in 2–10 keV and 0.3–2 keV energy ranges, respectively. In Fig. 5.1, the HID of the respective sources are presented using different colored open circles. We observe that

each source shows a distinct pattern in the HID. In particular, NGC 55 ULX1 and NGC 5408 X–1 roughly show $HR \lesssim 0.15$ and IC 342 X–1 exhibit a relatively harder nature with $HR \sim 1$, whereas the rest of the sources remain confined within $0.15 \lesssim HR \lesssim 0.6$ in the HID. We observe that the HIDs of NGC 55 ULX1 and NGC 4395 ULX1 differ from the other sources, as they coarsely exhibit a ‘C-shaped’ pattern (see Fig. 5.1). Out of this, three of the most recent observations of NGC 4395 ULX1 show fainter characteristics at higher energies ($\gtrsim 2$ keV) and remain as outliers ($HR \sim 0.07$) from the ‘C-shaped’ pattern in the HID. Note that the intensity of these two sources varies significantly with HR , whereas the remaining sources do not show such variations. On the other hand, an apparent negative correlation is observed between HR and the count rate of NGC 5204 X–1, NGC 1313 X–1, and IC 342 X–1, respectively.

5.2.2 mHz QPOs: Distinct Characteristics of BH-ULXs

To study the mHz QPO properties of BH-ULXs, we first generate power density spectra (PDS) for all the observations of NGC 1313 X–1, NGC 5408 X–1, NGC 6946 X–1, IC 342 X–1 and M82 X–1 using the *EPIC-PN* data in 0.3 – 10 keV energy range. The `ftools` task `powspec`² available in *HEASOFT* V6.29.1³ is used to obtain the PDS. Background-subtracted light curves of 0.5 s time resolution are used to generate the PDS with a Nyquist frequency of 1 Hz. In general, the light curves are divided into shorter segments of equal duration to generate an individual power spectrum. All the power spectra are further averaged in a single frame to obtain the resultant PDS. We notice that the number of newbins per interval (in `powspec`), which determines the duration of the light curve segments, plays an important role in order to maximize the signal-to-noise ratio in the power spectra. In particular, we observe that the specific choice of the number of newbins per interval results the prominent feature of individual QPOs, provided the minimum frequency in the PDS is chosen as roughly one-tenth to one-thirtieth of the observed QPO frequency. A similar method is adopted in [Atapin et al. \(2019\)](#) to obtain the power density spectra of the sources under consideration. We choose a specific number of newbins per interval (see Table. 5.3) to construct the individual PDS, which is further averaged in a single frame to obtain the resultant PDS for the significant detection of QPO features. A constant binning factor of 1.04 is used to rebin the final PDS in the frequency space. Note that the number of newbins per interval plays an important role in order to maximize the signal-to-noise ratio in the power spectra to detect the prominent QPO features. The number of newbins per interval is presented in Table 5.3.

Each PDS expressed in Leahy normalization ([Leahy et al., 1983](#)) represents a Poisson noise of power level ~ 2 with flat-topped noise (FTN) at the low frequency along with QPO features. Following [Caballero-García et al. \(2013\)](#), we adopt the model combination comprising of a `constant` (for the Poisson noise power), a zero-centroid `Lorentzian` (for the low-frequency FTN) and an additional `Lorentzian` profile (for the QPO feature) to obtain the best fit power spectra. Each `Lorentzian` is characterized by three parameters, namely centroid (LC), width (LW), and normalization (LN) (see [Sreehari et al., 2020](#), [Majumder et al., 2022](#), and references therein). The model fitted PDS of the six sources are depicted in the respective panels of Fig. 5.2. In the top panel, we display the power spectrum of NGC 5408 X–1 (ObsID–0653380201),

²<https://heasarc.gsfc.nasa.gov/xanadu/xronos/examples/powspec.html>

³<https://heasarc.gsfc.nasa.gov/xanadu/xspec/>

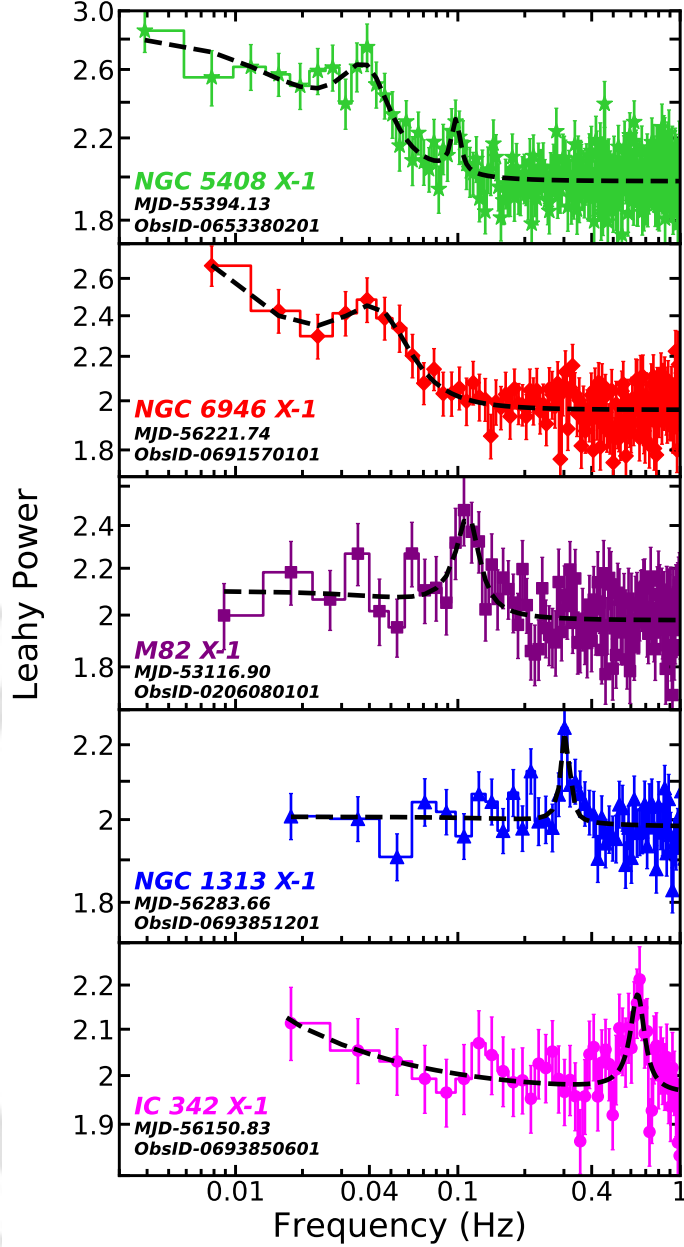


Figure 5.2: Leahy normalized PDS obtained from *EPIC-PN* data of the BH-ULXs: NGC 1313 X-1, NGC 5408 X-1, NGC 6946 X-1, IC 342 X-1 and M82 X-1. In each panel, the observed highest QPO frequency in 0.3 – 10 keV energy range for a given source is presented along with source name and observation details. Each PDS is modelled with the combination of Lorentzians and a constant. See text for details.

where the Poisson noise level and the FTN are fitted with a constant and a zero centroid Lorentzian component. Next, we include one Lorentzian at ~ 40 mHz to fit the excess positive residuals near this frequency. The fit is obtained with a χ^2_{red} of $219/250 = 0.88$, although significant positive residuals still remain around ~ 100 mHz. To address this, another Lorentzian is added to the composite model at around ~ 100 mHz. The resultant fit is obtained with a $\chi^2_{\text{red}} = 0.85$. We follow the above methodology to fit all the remaining PDS corresponding to each source and find that the requirement of the number of model components generally vary with observations. It is perceived that the FTN in the PDS can be well-fitted using the zero-centroid Lorentzian of all the sources except IC 342 X-1. A power-law profile with index ~ 0.73 provides a better fit of the low-frequency FTN component of IC 342 X-1.

Table 5.3: Details of the QPO characteristics obtained from the best fitted power density spectra of six BH-ULXs in 0.3–10 keV energy range. Here, ν_{QPO} , ΔF , Q - fac and σ_{QPO} denote the centroid frequency, width, quality factor and significance of the QPO features. $rms_{\text{QPO}}\%$ and $rms_{\text{total}}\%$ denote the percentage rms amplitudes of the QPOs and the entire PDS, respectively. All the errors are computed with 68% confidence level. See text for details.

Source	ObsID	MJD	ν_{QPO} (mHz)	ΔF (mHz)	Q - fac $\boxtimes$	σ_{QPO} (σ)	rms_{QPO} (%)	rms_{total} (%)	χ^2/dof	No. of Newbins per Interval
NGC 1313 X-1	0405090101	54023.98	$82.14^{+1.35}_{-1.58}$	$9.12^{+4.64}_{-6.77}$	9.01	3.34	8.17 ± 0.49	22.59 ± 1.27	107/122	256
	0693850501	56277.67	$304.60^{+4.21}_{-4.99}$	$33.34^{+11.12}_{-11.05}$	9.14	4.67	11.29 ± 0.59	18.74 ± 1.54	16/36	512
			$667.31^{+37.60}_{-47.19}$	$68.63^{+33.14}_{-22.58}$	9.72	1.62	7.04 ± 0.18	18.74 ± 1.54	16/36	512
	0693851201	56283.66	$305.04^{+6.22}_{-3.58}$	$37.25^{+15.23}_{-10.18}$	8.18	2.76	11.46 ± 0.72	15.69 ± 0.95	51/50	256
NGC 5408 X-1	0302900101	53748.77	$18.51^{+1.06}_{-1.14}$	$15.66^{+2.83}_{-2.43}$	1.18	9.41	15.37 ± 1.24	27.17 ± 10.84	542/506	1024
	0500750101	54478.79	$9.02^{+0.67}_{-0.71}$	$2.56^{+2.45}_{-2.08}$	3.52	2.41	7.81 ± 2.62	28.97 ± 12.90	1225/1018	2048
	0653380201	55394.13	$38.13^{+0.28}_{-0.50}$	$25.07^{+1.41}_{-1.19}$	1.52	4.02	12.27 ± 1.19	31.40 ± 3.47	210/247	512
			$97.94^{+2.76}_{-2.72}$	$10.79^{+0.74}_{-0.48}$	9.08	2.73	6.16 ± 0.48	31.40 ± 3.47	210/247	512
	0653380301	55396.13	$39.14^{+0.27}_{-0.23}$	$6.54^{+0.62}_{-0.50}$	6.08	1.94	4.89 ± 0.50	23.54 ± 2.46	76/58	256
	0653380501	55589.65	$17.99^{+1.58}_{-1.93}$	$14.31^{+4.41}_{-3.81}$	1.26	5.40	14.34 ± 1.81	28.33 ± 8.09	505/506	1024
	0723130301	56699.02	$11.09^{+0.91}_{-1.04}$	$6.68^{+3.36}_{-2.74}$	1.66	3.51	13.92 ± 4.23	34.90 ± 9.10	33/40	256
			$44.22^{+1.84}_{-1.12}$	$3.87^{+3.05}_{-2.79}$	11.44	2.38	7.41 ± 1.41	34.90 ± 9.10	33/40	256
	0723130401	56701.02	$13.08^{+0.74}_{-0.85}$	$7.39^{+3.44}_{-2.47}$	1.77	4.48	14.42 ± 3.98	32.10 ± 11.65	566/506	1024

$\boxtimes Q \lesssim 2$ indicates ‘QPO like’ broad features (see also Majumder et al. 2023).

Table 5.3: Continued.

Source	ObsID	MJD	ν_{QPO} (mHz)	Δ_F (mHz)	$Q\text{-}fac^{\boxtimes}$	σ_{QPO} (σ)	rm_{SQPO} (%)	rm_{Stotal} (%)	χ^2/dof	No. of Newbins per Interval
NGC 6946 X-1	0200670301	53169.78	$38.71^{+5.61}_{-2.53}$	$9.67^{+6.22}_{-5.84}$	4.00	2.04	29.05 ± 0.51	48.98 ± 6.01	149/122	512
	0500730201	54406.91	$9.23^{+0.81}_{-0.92}$	$5.85^{+2.43}_{-2.02}$	1.59	3.79	20.60 ± 2.06	44.18 ± 12.32	1168/1018	2048
	0500730101	54412.94	$8.44^{+0.43}_{-0.35}$	$1.91^{+1.19}_{-1.12}$	4.40	2.90	13.41 ± 2.13	38.35 ± 8.58	62/74	1024
	0691570101	56221.74	$41.72^{+5.04}_{-5.69}$	$41.12^{+12.52}_{-13.09}$	1.01	4.32	23.47 ± 0.61	41.13 ± 2.74	133/122	256
	0112290201	52035.38	$55.85^{+1.44}_{-2.01}$	$6.44^{+5.89}_{-3.45}$	8.67	2.37	11.54 ± 4.33	32.68 ± 10.30	637/506	2048
M82 X-1	0206080101	53116.90	$110.81^{+5.03}_{-4.26}$	$31.82^{+19.72}_{-13.47}$	3.48	3.61	12.13 ± 2.18	20.21 ± 4.06	80/105	512
	0657800101	55638.69	$45.55^{+1.61}_{-2.19}$	$5.85^{+4.41}_{-2.73}$	7.78	2.21	21.88 ± 7.75	68.48 ± 12.84	635/504	2048
	0657801901	55680.55	$47.63^{+5.47}_{-3.22}$	$17.13^{+6.32}_{-5.28}$	2.78	2.94	32.95 ± 11.18	64.62 ± 24.32	362/250	512
	0657802101	55828.21	$35.74^{+2.53}_{-2.44}$	$11.48^{+5.05}_{-3.73}$	3.12	3.33	28.30 ± 10.64	42.74 ± 14.28	53/58	1024
	0693850601	56150.83	$643.40^{+15.30}_{-23.89}$	$112.20^{+59.69}_{-46.52}$	5.73	3.75	25.82 ± 0.46	48.30 ± 13.74	32/51	256
IC 342 X-1	0028740101	52228.05	$20.43^{+1.26}_{-1.67}$	$3.06^{+0.38}_{-0.44}$	6.68	2.81	6.63 ± 0.31	36.12 ± 2.15	156/122	512

$\boxtimes Q \lesssim 2$ indicates ‘QPO like’ broad features (see also Majumder et al. 2023).

The best fit PDS of NGC 5408 X-1 (ObsID-0653380201) confirms simultaneous detection of two QPOs at $\nu_{\text{QPO}} \sim 38.13^{+0.28}_{-0.50}$ mHz and $\sim 97.94^{+2.76}_{-2.72}$ mHz, respectively. The significance (σ_{QPO}) of the detected QPOs are obtained as 4.02σ and 2.73σ . The percentage rms amplitudes of ~ 38.13 mHz and ~ 97.94 mHz QPOs are estimated (Sreehari et al., 2020, Majumder et al., 2022, and references therein) as 12.27 ± 1.19 percent and 6.16 ± 0.48 percent, respectively. Further, we calculate the rms amplitudes of the entire PDS in $0.001 - 1$ Hz frequency range, which is obtained as 31.40 ± 3.47 percent. Following the above approach, we find the presence of QPO features in twenty one observations for all BH-ULXs and two of them exhibit twin peak QPO features (for NGC 1313 X-1 and NGC 5408 X-1, the $\nu_{\text{QPO}} \sim 667$ mHz and ~ 98 mHz) that appear simultaneously in the PDS. The model fitted parameters and the estimated parameters of the QPO features are presented in Table 5.3.

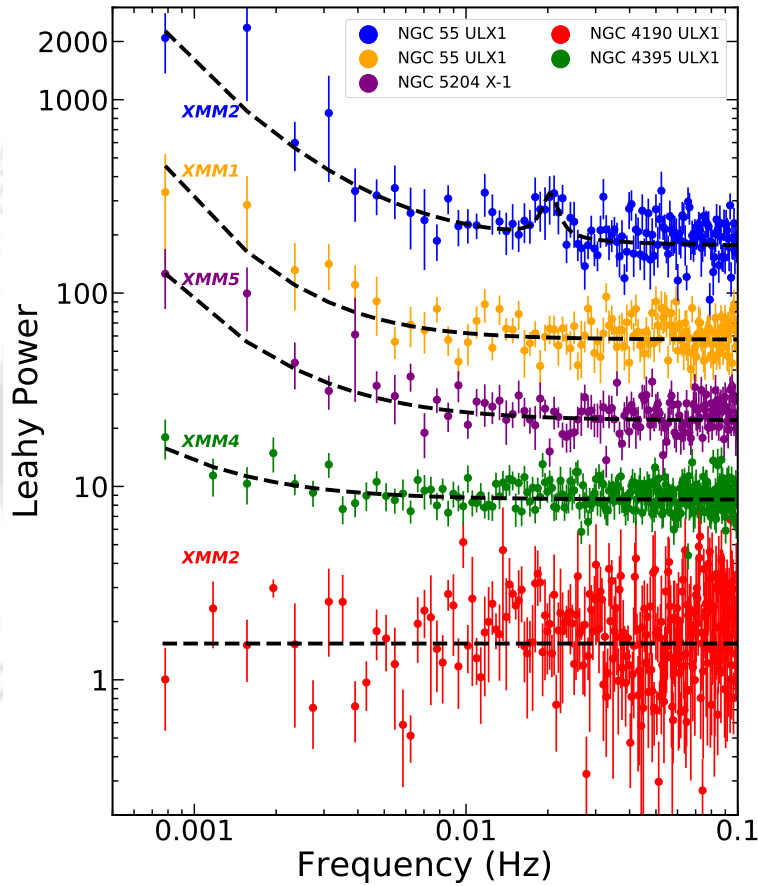


Figure 5.3: The PDS of NGC 55 ULX1, NGC 5204 X-1, NGC 4395 ULX1 and NGC 4190 ULX1 are depicted with different colors in respective Epochs. Each PDS is fitted with the combination of **constant**, **powerlaw**, and **Lorentzian** components as needed. The powers corresponding to the first four PDS presented from top to bottom are rescaled with the constant multiplicative factors of 100, 32, 12, and 4.5, respectively, for better clarity. See text for details.

Following a similar approach described above, we investigate the PDS of the observations for the remaining four sources (NGC 55 ULX1, NGC 5204 X-1, NGC 4395 ULX1, and NGC 4190 ULX1) using *EPIC-PN* data in $0.3 - 10$ keV energy range. The PDS of these sources shows a constant Poisson noise power within $1.64 - 1.96$ and a power-law distribution towards the low-frequency, which are modeled with a **constant** and **power-law** components, respectively. However, no significant variability is seen for a few observations of the sources (see Table 5.2), and a **constant** component is

found to be sufficient to fit the PDS. In Fig. 5.3, we depict the PDS of the sources in different colors for respective Epochs. Further, we estimate the total percentage rms amplitude of the PDS in the 0.001 – 0.1 Hz frequency range for the individual sources and find it to vary within 22.61 – 50.29%. Interestingly, out of these four sources, we find the presence of a QPO-like feature at $\nu_{\text{QPO}} = 20.43^{+1.26}_{-1.67}$ mHz with $\sigma_{\text{QPO}} \sim 2.8\sigma$, $\text{rms}_{\text{QPO}} \sim 6.63\%$ and $Q\text{-}fac \sim 6.68$ in NGC 55 ULX1 (see Fig. 5.3).

5.3 Analysis of Spectral Distribution in BH-ULXs

We generate *XMM-Newton* energy spectra for all the observations in 0.3 – 10 keV energy range. XSPEC of HEASOFT V6.29.1 is used to model the energy spectrum. While spectral fitting, we follow the standard procedure to extract the background spectrum file, instrument response file (rmf) and ancillary response file (arf). Each spectrum is grouped with 25 counts per spectral bin using `specgroup` tool of SAS V19.1.0. We fit *EPIC-PN* and *EPIC-MOS* spectra simultaneously to improve the counting statistics. The cross-calibration between different instruments is taken care by including a `constant` component in the spectral fitting (Pintore et al., 2014). For NGC 5408 X–1, we include a plasma component (APEC in XSPEC) of temperature ~ 0.9 keV to adjust the low energy residuals (see Pintore et al., 2014). Following Earnshaw et al. (2019), we include a `gaussian` at ~ 1 keV to fit the NGC 6946 X–1 spectra. We do not include M82 X–1 in the spectral study as the effect of contamination due to the close proximity (within 5 arcsec) of M82 X–2 can not be ruled out (Brightman et al., 2016b).

5.3.1 Modeling of Spectra: Phenomenological to Physical Insights

To start with, we first perform the spectral modeling of the BH-ULXs showing QPO features, namely NGC 1313 X–1, NGC 5408 X–1, NGC 6946 X–1 and IC 342 X–1. We initially model the energy spectra of *XMM-Newton* in 0.3 – 10 keV energy range using the phenomenological model combination `TBabs × (diskbb + diskbb)`. Here, `TBabs` (Wilms et al., 2000) accounts for the galactic absorption and two `diskbb` models (Makishima et al., 1986) correspond to the standard accretion disc components. We notice that the above model combinations are inadequate (*e.g.*, $\chi^2_{\text{red}} = 1.41$ for NGC 1313 X–1, ObsID-0693851201) in explaining the high energy tail of the spectra beyond ~ 7 keV. Hence, a `simpl` (Steiner et al., 2009) model that delineates the fractional scattering of the seed photons into a powerlaw distribution is included in the spectral fitting. Such a model combination (hereafter M1) `TBabs × (diskbb + simpl × diskbb)` is seen to describe the spectral shape of the BH-ULXs satisfactorily. For example, we obtain best spectral fit for NGC 1313 X–1 (ObsID-0693851201) with $\chi^2_{\text{red}} = 1.19$ that resulted relatively hotter disc temperature ($k_B T_{\text{in}}^{\text{hard}} = 2.08^{+0.46}_{-0.35}$ keV, softer disc temperature ($k_B T_{\text{in}}^{\text{soft}} = 0.23^{+0.02}_{-0.02}$ keV, photon index ($\Gamma_{\text{simpl}} = 1.83^{+0.16}_{-0.09}$, seed photon scattered fraction ($f_{\text{scatt}} = 20.67^{+1.75}_{-0.92}\%$ and column density ($n_{\text{H}} = 0.27^{+0.02}_{-0.02} \times 10^{22}$ atoms cm^{-2}). Accordingly, we employ model M1 to fit the spectra of four BH-ULXs and obtain a statistically acceptable fit. However, we mention that for a few observations, `simpl` model is not required, mostly due to the lack of good quality data at high energies (see Table 5.4). The model fitted parameters and estimated parameters are presented in Table 5.4.

Table 5.4: Details of the best fitted model parameters of combined *EPIC-PN* and *EPIC-MOS* spectra in 0.3 – 10 keV energy range with the model $\text{TBabs} \times (\text{diskbb} + \text{simpl} \times \text{diskbb})$ for four ULXs as mentioned in Table 5.1. In the table, n_H is the hydrogen column density, $k_B T_{\text{in}}^{\text{soft}}$ is the temperature of the soft disc component in keV, $k_B T_{\text{in}}^{\text{hard}}$ is the temperature of relatively hotter disc component in keV. Γ_{simpl} and f_{scatt} is the power-index and Comptonized seed photon fraction of the *simpl* component, respectively. $\chi^2/d.o.f$ and P_{null} refer the reduced χ^2 and null hypothesis probability values. $F_{\text{disc}}^{\text{soft}}$ and $F_{\text{disc}}^{\text{hard}}$ are the flux values in $\text{erg cm}^{-2} \text{s}^{-1}$ associated with hotter and softer *diskbb* component, respectively. F_{bol} and L_{bol} are the bolometric flux and luminosity, respectively. All the errors are computed with 90 per cent confidence level. See text for details.

Source	ObsID	MJD	n_{H}	Model fitted parameters					Estimated parameters					
				$k_{\mathrm{B}}T_{\mathrm{in}}^{\mathrm{soft}}$	$k_{\mathrm{B}}T_{\mathrm{in}}^{\mathrm{hard}}$	Γ_{simpl}	f_{scatt}	$\chi^2/d.o.f$	$P_{\mathrm{null}}^{\boxtimes}$	$F_{\mathrm{disc}}^{\mathrm{soft}}$	$F_{\mathrm{disc}}^{\mathrm{hard}}$	F_{bol}	L_{bol}	
			$(10^{22} \text{ cm}^{-2})$	(keV)	(keV)		(%)			$(0.3 - 10 \text{ keV})$	$(10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1})$	$(0.1 - 100 \text{ keV})$	$(10^{40} \text{ erg s}^{-1})$	
NGC 1313 X-1 (D = 4.25 Mpc ^c)	0106860101 [†]	51834.14	0.21 ^{+0.03} _{-0.03}	0.30 ^{+0.04} _{-0.03}	2.35 ^{+0.25} _{-0.21}	—	—	131/131	0.47	1.50 ^{+0.06} _{-0.06}	2.32 ^{+0.09} _{-0.09}	4.50 ^{+0.09} _{-0.09}	0.97 ± 0.01	
	0205230601 [†]	53408.48	0.40 ^{+0.02} _{-0.02}	0.19 ^{+0.01} _{-0.03}	0.76 ^{+0.03} _{-0.16}	1.09 ^{+0.15} _{-0.01}	60.30 ^{+1.86} _{-1.84}	217/205	0.27	5.01 ^{+0.19} _{-0.19}	3.32 ^{+0.13} _{-0.13}	12.69 ^{+0.32} _{-0.32}	2.74 ± 0.07	
	0405090101	54023.98	0.30 ^{+0.02} _{-0.01}	0.21 ^{+0.01} _{-0.01}	2.07 ^{+0.22} _{-0.17}	1.76 ^{+0.08} _{-0.07}	14.20 ^{+1.29} _{-1.25}	502/445	0.03	2.36 ^{+0.02} _{-0.02}	0.92 ^{+0.01} _{-0.01}	6.63 ^{+0.04} _{-0.04}	1.43 ± 0.01	
	0693850501	56277.67	0.27 ^{+0.03} _{-0.02}	0.24 ^{+0.02} _{-0.04}	2.38 ^{+0.71} _{-0.44}	1.85 ^{+0.15} _{-0.14}	19.70 ^{+1.23} _{-1.82}	489/439	0.05	2.53 ^{+0.03} _{-0.03}	1.00 ^{+0.03} _{-0.03}	7.03 ^{+0.08} _{-0.08}	1.52 ± 0.02	
	0693851201	56283.66	0.27 ^{+0.02} _{-0.02}	0.23 ^{+0.02} _{-0.02}	2.08 ^{+0.46} _{-0.35}	1.83 ^{+0.16} _{-0.09}	20.67 ^{+1.75} _{-0.92}	518/454	0.03	2.57 ^{+0.03} _{-0.03}	0.82 ^{+0.04} _{-0.04}	7.20 ^{+0.05} _{-0.05}	1.56 ± 0.01	
	0742590301 [†]	56843.97	0.29 ^{+0.01} _{-0.01}	0.24 ^{+0.01} _{-0.01}	0.75 ^{+0.03} _{-0.01}	2.53 ^{+0.02} _{-0.02}	60.64 ^{+3.18} _{-2.55}	572/433	0.01	3.41 ^{+0.05} _{-0.05}	3.50 ^{+0.03} _{-0.03}	11.09 ^{+0.05} _{-0.05}	2.40 ± 0.01	
	0742490101 [†]	57111.19	0.27 ^{+0.01} _{-0.01}	0.25 ^{+0.02} _{-0.03}	1.09 ^{+0.06} _{-0.05}	1.38 ^{+0.13} _{-0.11}	53.63 ^{+4.89} _{-2.82}	360/266	0.01	1.81 ^{+0.03} _{-0.03}	1.92 ^{+0.03} _{-0.03}	5.91 ^{+0.05} _{-0.05}	1.28 ± 0.01	
	0803990101 [†]	57918.89	0.29 ^{+0.01} _{-0.01}	0.26 ^{+0.01} _{-0.01}	1.07 ^{+0.03} _{-0.02}	1.18 ^{+0.06} _{-0.05}	33.82 ^{+3.80} _{-2.54}	682/486	0.01	3.35 ^{+0.02} _{-0.02}	4.95 ^{+0.03} _{-0.03}	10.87 ^{+0.05} _{-0.05}	2.35 ± 0.01	
	0803990301 [†]	57996.68	0.29 ^{+0.01} _{-0.02}	0.23 ^{+0.01} _{-0.01}	1.30 ^{+0.09} _{-0.02}	1.35 ^{+0.08} _{-0.07}	44.47 ^{+4.33} _{-3.12}	478/422	0.03	2.46 ^{+0.04} _{-0.04}	2.48 ^{+0.04} _{-0.04}	7.18 ^{+0.09} _{-0.08}	1.55 ± 0.02	
	0803990601 [†]	58096.46	0.27 ^{+0.01} _{-0.01}	0.29 ^{+0.01} _{-0.01}	1.09 ^{+0.01} _{-0.01}	1.09 ^{+0.05} _{-0.02}	34.52 ^{+0.73} _{-0.70}	614/455	0.01	3.14 ^{+0.04} _{-0.04}	5.39 ^{+0.06} _{-0.06}	9.86 ^{+0.08} _{-0.08}	2.13 ± 0.02	
	NGC 5408 X-1	0112290501 [†]	52121.54	0.11 [*]	0.18 ^{+0.01} _{-0.01}	0.82 ^{+0.09} _{-0.08}	—	—	128/130	0.53	3.24 ^{+0.13} _{-0.13}	0.86 ^{+0.05} _{-0.05}	5.28 ^{+0.24} _{-0.24}	1.46 ± 0.06
	(D = 4.8 Mpc ^c)	0112291001 [†]	52484.35	0.12 ^{+0.04} _{-0.03}	0.19 ^{+0.02} _{-0.02}	0.88 ^{+0.42} _{-0.19}	—	—	125/136	0.74	2.12 ^{+0.02} _{-0.02}	0.89 ^{+0.06} _{-0.06}	4.27 ^{+0.12} _{-0.12}	1.18 ± 0.03
	0112291201 [†]	52667.01	0.13 ^{+0.06} _{-0.05}	0.19 ^{+0.03} _{-0.03}	1.08 ^{+0.22} _{-0.15}	—	—	92/97	0.62	2.01 ^{+0.11} _{-0.11}	0.77 ^{+0.05} _{-0.05}	3.11 ^{+0.15} _{-0.15}	0.86 ± 0.04	
	0302900101	53748.77	0.11 ^{+0.01} _{-0.01}	0.16 ^{+0.01} _{-0.01}	0.76 ^{+0.06} _{-0.04}	2.35 ^{+0.14} _{-0.16}	7.93 ^{+2.51} _{-2.27}	423/337	0.01	2.21 ^{+0.02} _{-0.02}	0.39 ^{+0.01} _{-0.01}	4.99 ^{+0.03} _{-0.03}	1.38 ± 0.01	
	0500750101	54478.79	0.11 ^{+0.01} _{-0.01}	0.17 ^{+0.01} _{-0.01}	0.77 ^{+0.06} _{-0.04}	2.14 ^{+0.25} _{-0.29}	6.61 ^{+4.10} _{-2.96}	320/294	0.14	1.84 ^{+0.03} _{-0.03}	0.49 ^{+0.02} _{-0.02}	4.29 ^{+0.05} _{-0.05}	1.18 ± 0.01	
	0653380201	55394.13	0.11 ^{+0.01} _{-0.01}	0.17 ^{+0.01} _{-0.01}	0.80 ^{+0.13} _{-0.09}	2.46 ^{+0.15} _{-0.17}	14.08 ^{+3.63} _{-3.84}	321/301	0.21	2.26 ^{+0.02} _{-0.02}	0.39 ^{+0.02} _{-0.02}	5.34 ^{+0.04} _{-0.04}	1.47 ± 0.01	
	0653380301	55396.13	0.09 ^{+0.01} _{-0.01}	0.18 ^{+0.01} _{-0.01}	0.99 ^{+0.18} _{-0.12}	2.53 ^{+0.13} _{-0.12}	19.75 ^{+3.79} _{-3.61}	429/364	0.01	1.87 ^{+0.01} _{-0.01}	0.31 ^{+0.01} _{-0.01}	4.48 ^{+0.03} _{-0.03}	1.24 ± 0.01	
	0653380401	55587.67	0.10 ^{+0.01} _{-0.01}	0.18 ^{+0.01} _{-0.01}	0.81 ^{+0.06} _{-0.04}	2.23 ^{+0.19} _{-0.16}	8.73 ^{+3.96} _{-2.50}	398/356	0.06	1.97 ^{+0.02} _{-0.02}	0.51 ^{+0.01} _{-0.01}	4.49 ^{+0.03} _{-0.03}	1.24 ± 0.01	
	0653380501	55589.65	0.12 ^{+0.01} _{-0.01}	0.18 ^{+0.01} _{-0.01}	0.81 ^{+0.03} _{-0.03}	1.30 ^{+0.24} _{-0.14}	16.40 ^{+3.02} _{-1.20}	402/341	0.01	1.90 ^{+0.03} _{-0.03}	0.94 ^{+0.02} _{-0.02}	4.24 ^{+0.04} _{-0.04}	1.17 ± 0.01	
	0723130301	56699.02	0.11 ^{+0.01} _{-0.01}	0.16 ^{+0.01} _{-0.01}	0.81 ^{+0.05} _{-0.04}	1.45 ^{+0.11} _{-0.09}	1.99 ^{+1.07} _{-0.53}	280/244	0.06	1.91 ^{+0.04} _{-0.04}	0.71 ^{+0.02} _{-0.02}	4.20 ^{+0.06} _{-0.06}	1.16 ± 0.02	
	0723130401	56701.02	0.11 ^{+0.02} _{-0.01}	0.18 ^{+0.01} _{-0.02}	0.93 ^{+0.12} _{-0.09}	2.34 ^{+0.25} _{-0.25}	11.09 ^{+5.08} _{-4.33}	268/262	0.38	1.91 ^{+0.03} _{-0.03}	0.44 ^{+0.02} _{-0.02}	4.44 ^{+0.05} _{-0.05}	1.22 ± 0.01	

†Non-detection of QPO. *Frozen parameter value. $\boxtimes P_{\text{null}} < 0.1$ yielded due to excess residuals at 0.56 keV and 1 keV in some of the observations of NGC 1313 X-1 and NGC 5408 X-1. ^cLuanqtip et al. (2021), ^eTully et al. (2016), ^bAnand et al. (2018), ^dMiddleton et al. (2015).

Table 5.4: Continued.

		Model fitted parameters			Estimated parameters								
Source	ObsID	MJD	n_{H} (10^{22} cm^{-2})	$k_{\text{B}}T_{\text{in}}^{\text{soft}}$ (keV)	$k_{\text{B}}T_{\text{in}}^{\text{hard}}$ (keV)	Γ_{simpl}	f_{scatt} (%)	$\chi^2/d.o.f$	$P_{\text{null}}^{\boxtimes}$	$F_{\text{disc}}^{\text{soft}}$ ($0.3 - 10 \text{ keV}$) ($10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$)	$F_{\text{disc}}^{\text{hard}}$ ($0.1 - 100 \text{ keV}$) ($10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$)	L_{bol} ($10^{40} \text{ erg s}^{-1}$)	
NGC 6946 X-1 ($D = 7.72 \text{ Mpc}^b$)	0500730201	54406.91	$0.31^{+0.04}_{-0.04}$	$0.17^{+0.02}_{-0.01}$	$1.13^{+0.11}_{-0.10}$	$2.40^{+0.24}_{-0.22}$	$16.49^{+3.52}_{-2.45}$	93/104	0.77	$1.32^{+0.04}_{-0.04}$	$0.15^{+0.02}_{-0.02}$	$3.08^{+0.07}_{-0.07}$	2.20 ± 0.05
	0500730101	54412.94	$0.27^{+0.03}_{-0.03}$	$0.20^{+0.01}_{-0.01}$	$0.84^{+0.13}_{-0.13}$	$1.50^{+0.35}_{-0.23}$	$4.64^{+2.00}_{-0.93}$	195/181	0.21	$1.19^{+0.06}_{-0.06}$	$0.31^{+0.03}_{-0.03}$	$2.66^{+0.07}_{-0.06}$	1.90 ± 0.04
	0691570101	56221.74	$0.31^{+0.03}_{-0.02}$	$0.18^{+0.01}_{-0.01}$	$1.12^{+0.40}_{-0.23}$	$2.41^{+0.24}_{-0.20}$	$14.07^{+4.02}_{-3.77}$	325/330	0.56	$1.83^{+0.03}_{-0.03}$	$0.18^{+0.02}_{-0.02}$	$4.07^{+0.05}_{-0.05}$	2.90 ± 0.04
	0870830101	59038.93	$0.32^{+0.06}_{-0.06}$	$0.21^{+0.03}_{-0.02}$	$1.30^{+0.17}_{-0.14}$	—	—	142/135	0.32	$1.89^{+0.08}_{-0.08}$	$0.67^{+0.05}_{-0.04}$	$3.48^{+0.15}_{-0.16}$	2.48 ± 0.11
	0870830201	59198.32	$0.37^{+0.08}_{-0.08}$	$0.18^{+0.03}_{-0.02}$	$1.07^{+0.14}_{-0.11}$	—	—	87/82	0.31	$2.85^{+0.20}_{-0.19}$	$0.69^{+0.05}_{-0.05}$	$5.34^{+0.37}_{-0.37}$	3.81 ± 0.26
	0870830301	59308.22	$0.28^{+0.05}_{-0.05}$	$0.22^{+0.03}_{-0.02}$	$1.30^{+0.14}_{-0.12}$	—	—	122/134	0.75	$1.44^{+0.07}_{-0.06}$	$0.62^{+0.03}_{-0.03}$	$2.74^{+0.06}_{-0.06}$	1.95 ± 0.04
0870830401	59359.89	$0.32^{+0.07}_{-0.06}$	$0.19^{+0.03}_{-0.02}$	$1.22^{+0.14}_{-0.12}$	—	—	88/100	0.78	$1.62^{+0.07}_{-0.07}$	$0.56^{+0.03}_{-0.03}$	$3.07^{+0.08}_{-0.07}$	2.19 ± 0.06	
IC 342 X-1 ($D = 3.61 \text{ Mpc}^d$)	0093640901 [†]	51951.06	$0.58^{+0.08}_{-0.06}$	$0.42^{+0.08}_{-0.06}$	$2.78^{+0.38}_{-0.27}$	—	—	136/138	0.52	$0.91^{+0.08}_{-0.08}$	$2.41^{+0.11}_{-0.11}$	$3.91^{+0.18}_{-0.18}$	0.61 ± 0.03
	0206890101 [†]	53055.31	$0.63^{+0.03}_{-0.03}$	$0.54^{+0.06}_{-0.06}$	$2.13^{+0.13}_{-0.11}$	—	—	284/304	0.79	$2.35^{+0.11}_{-0.11}$	$5.83^{+0.13}_{-0.13}$	$9.02^{+0.23}_{-0.22}$	1.41 ± 0.03
	0206890201 [†]	53234.82	$0.65^{+0.04}_{-0.03}$	$0.43^{+0.03}_{-0.03}$	$2.68^{+0.17}_{-0.15}$	—	—	290/276	0.26	$1.49^{+0.03}_{-0.03}$	$2.57^{+0.05}_{-0.05}$	$4.72^{+0.05}_{-0.05}$	0.74 ± 0.01
	0693850601	56150.83	$0.74^{+0.04}_{-0.04}$	$0.29^{+0.02}_{-0.02}$	$1.74^{+0.18}_{-0.16}$	$1.30^{+0.12}_{-0.13}$	$13.43^{+2.93}_{-2.47}$	330/360	0.86	$2.09^{+0.07}_{-0.07}$	$1.48^{+0.07}_{-0.07}$	$5.96^{+0.08}_{-0.08}$	0.93 ± 0.01
	0693851301 [†]	56156.84	$0.59^{+0.02}_{-0.02}$	$0.48^{+0.03}_{-0.02}$	$2.44^{+0.09}_{-0.08}$	—	—	402/377	0.17	$1.46^{+0.04}_{-0.04}$	$3.05^{+0.06}_{-0.06}$	$5.13^{+0.06}_{-0.06}$	0.80 ± 0.01

[†]Non-detection of QPO. *Frozen parameter value. $\boxtimes P_{\text{null}} < 0.1$ yielded due to excess residuals at 0.56 keV and 1 keV in some of the observations of NGC 1313 X-1 and NGC 5408 X-1. ^eLuangtip et al. (2021), ^cTully et al. (2016), ^bAnand et al. (2018), ^dMiddleton et al. (2015).

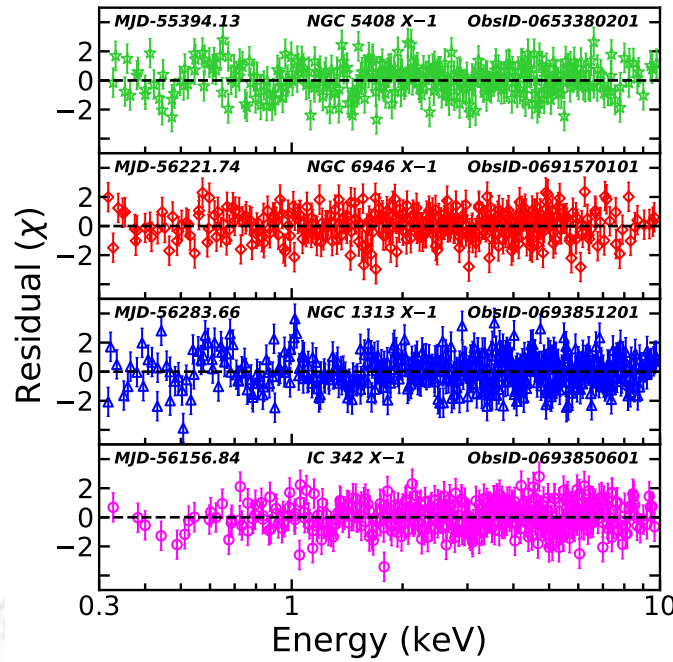


Figure 5.4: Variation of the residuals in units of σ . In each panel, the residuals obtained from the model fitting of combined *EPIC*-PN and *EPIC*-MOS energy spectra with the model $\text{TBabs} \times (\text{diskbb} + \text{nthcomp})$ are shown. See text for details.

Next, we examine the spectral behaviour of the four BH-ULXs considering a physically motivated model. While doing so, we begin with the model combination $\text{TBabs} \times \text{nthcomp}$ to fit the spectra, where nthcomp (Zdziarski et al., 1996, Życki et al., 1999) represents the thermally Comptonized continuum. The obtained fit yields poor $\chi^2_{\text{red}} = 2.87$ ($\chi^2/\text{dof} = 1309/456$) for NGC 1313 X-1 (ObsID-0693851201) with noticeable residuals at lower energy. Hence, we include a diskbb model to fit the soft excess below ~ 2 keV. Further, we tie the seed photon temperature of nthcomp to the inner disc temperature of diskbb (Gladstone et al., 2009). Accordingly, the model combination $\text{TBabs} \times (\text{nthcomp} + \text{diskbb})$ (hereafter M2) provides a good fit ($\chi^2_{\text{red}} = 1.20$ for NGC 1313 X-1; ObsID-0693851201). In Fig. 5.4, the variations of residuals (χ) in units of σ are presented in terms of energy in keV. In each panel of Fig. 5.4, we choose one particular observation for a given source and obtain the variation of χ from the spectral fitting of that observation using model M2. We further put efforts into fitting the spectra with an alternative Comptonization model compTT (Titarchuk, 1994, Hua and Titarchuk, 1995), which results in statistically acceptable fits; however, the electron temperature remains unconstrained in most observations. Moreover, we adopt the slim disc prescription (diskpbb in XSPEC (Mineshige et al., 1994, Hirano et al., 1995, Watarai et al., 2000, Kubota and Makishima, 2004)) for spectral fitting which yields worse fit with χ^2_{red} exceeding 2 for all the sources. This evidently rules out the possibility of having a slim accretion disc structure in these four BH-ULXs under consideration. Based on the above findings on the spectral nature of BH-ULXs, we attempt to model the spectra of the remaining four sources (NGC 55 ULX1, NGC 5204 X-1, NGC 4395 ULX-1, and NGC 4190 ULX-1) using the physically motivated model M2. As before, we find that M2 provides the best description of the data for these sources as well. This indicates that the spectra of all the BH-ULXs considered in this work are generally well described by two-component spectral models comprising a thermal disc component and a Comptonized component. However, there are a few

exceptions where a single spectral component can satisfactorily fit the spectra. For example, the disc contribution is observed to be negligible and the Comptonization component remains adequate to delineate the spectra in a few observations. In contrast, we notice that for a few observations (XMM11–XMM17) of NGC 4395 ULX1, the disc component alone remains adequate to fit the spectra. This is mostly because of the extremely faint nature of the source in higher energies ($\gtrsim 2$ keV) during these observations, in which high-quality data remains up to $\lesssim 2$ keV only for spectral modeling.

5.3.2 Spectral Morphologies

In Fig. 5.5, we present the energy spectra of eight BH-ULXs considered for the spectral study, fitted with the model combination M2. The source names and observation details are marked in the figure. The best fitted model parameters and estimated parameters corresponding to the models M1 and M2 are tabulated in Tables 5.4, 5.5, 5.6, respectively. We find that model M1 satisfactorily describes the spectral curvature of BH-ULXs in terms of two disc temperatures varying in the range of $0.16^{+0.01}_{-0.01}$ – $0.60^{+0.09}_{-0.05}$ keV and $0.75^{+0.03}_{-0.01}$ – $3.13^{+0.28}_{-0.21}$ keV, respectively. In addition, the photon index (Γ_{simpl}) and the scattered fraction of seed photons (f_{scatt}) in **simpl** component of the model M1 are obtained in the range of $1.09^{+0.15}_{-0.01}$ – $2.53^{+0.13}_{-0.12}$ and $1.99^{+1.07}_{-0.53}$ – $60.64^{+3.18}_{-2.55}\%$, respectively. The spectral fitting using model M2 constrains the electron temperature ($k_B T_e$) and **nthcomp** photon index (Γ_{nth}) as $1.62^{+0.13}_{-0.12}$ – $3.76^{+1.15}_{-0.67}$ keV and $1.48^{+0.04}_{-0.11}$ – $3.86^{+0.25}_{-0.29}$, respectively. The inner disc temperature ($k_B T_{\text{in}}$) is found to be in the range of $0.14^{+0.03}_{-0.02}$ – $0.54^{+0.15}_{-0.06}$ keV suggesting a cool accretion disc around the sources. Note that in a few observations of the sources, we are unable to constrain the errors associated with the electron temperature and hence, it is kept fixed at its fitted values.

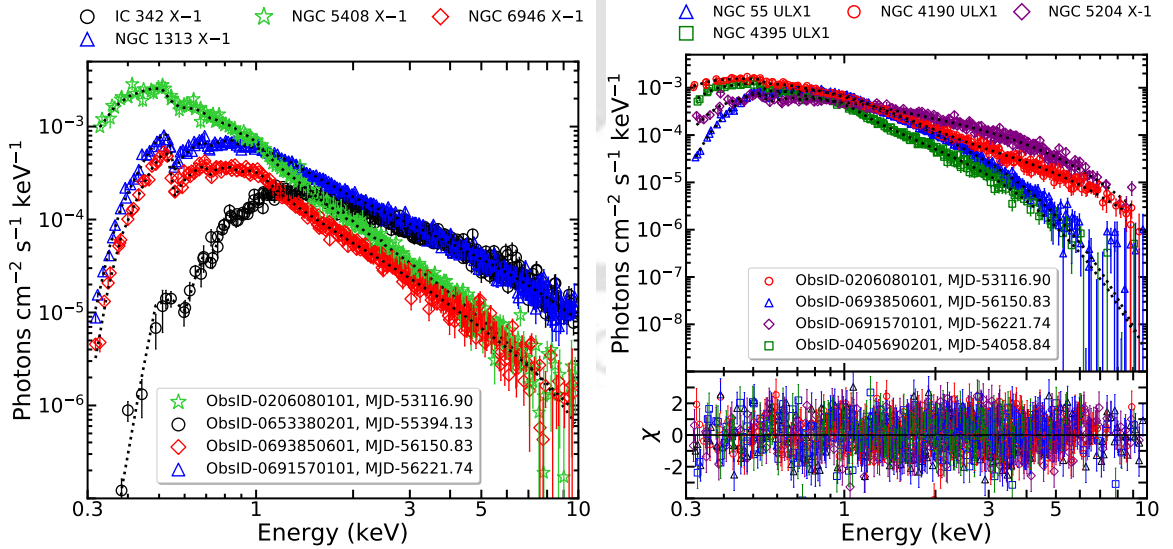


Figure 5.5: Combined *EPIC-PN* and *EPIC-MOS* energy spectra (0.3 – 10 keV) of eight BH-ULXs under consideration. Each spectrum is fitted with the model **TBabs** × (**diskbb** + **nthcomp**). The observation details are mentioned in the inset. See text for details.

In order to understand the emission properties of BH-ULXs, we estimate the flux associated with each spectral component used in the model fitting. The flux is obtained by introducing the convolution model **cflux** (in **XSPEC**) after the absorption column

Table 5.5: Best fitted spectral parameters obtained with the model **TBabs**(**diskbb** + **nthcomp**) for four ULXs in the sample. In the table, n_H is the hydrogen column density, $k_B T_e$ is the electron temperature in keV, Γ_{nth} is the **nthcomp** photon index, τ is the optical depth and $k_B T_{\text{in}}$ is the inner disc temperature in keV. $\chi^2/d.o.f$ and P_{null} refer the reduced χ^2 and null hypothesis probability values. F_{disc} and F_{nth} are the flux values in units of $\text{erg cm}^{-2} \text{s}^{-1}$ associated with **diskbb** and **nthcomp** components, respectively. F_{bol} , L_{bol} and L_{disc} are the bolometric flux, total luminosity, and disc luminosity, respectively. All the errors are computed with 90 per cent confidence level. See text for details.

Source	ObsID	MJD	n_{H}	$k_{\mathrm{B}}T_{\mathrm{e}}$	Γ_{nth}	$k_{\mathrm{B}}T_{\mathrm{in}}$	$\chi^2/d.o.f$	$P_{\mathrm{null}} \%$	Estimated parameters							
									F_{disc}	F_{nth}	F_{bol}	F_{disc}	L_{bol}	L_{disc}	τ	y_{part}
(Distance)			(10^{22} cm^{-2})	(keV)		(keV)			$(0.3 - 10 \text{ keV})$	$(10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1})$	$(0.1 - 100 \text{ keV})$		$(10^{40} \text{ erg s}^{-1})$			
NGC 1313 X-1 ($d = 4.25 \text{ Mpc}$)	0106860101 [†]	51834.14	$0.25^{+0.03}_{-0.04}$	$2.22^{+0.51}_{-0.31}$	$1.66^{+0.07}_{-0.09}$	$0.24^{+0.04}_{-0.03}$	128/130	0.52	$1.44^{+0.08}_{-0.08}$	$2.87^{+0.09}_{-0.09}$	$5.32^{+0.11}_{-0.10}$	$2.00^{+0.11}_{-0.11}$	1.15 ± 0.02	0.43 ± 0.02	15.49 ± 2.36	4.16 ± 0.57
	0205230601 [†]	53408.48	$0.36^{+0.08}_{-0.07}$	2*	$1.74^{+0.08}_{-0.04}$	$0.19^{+0.04}_{-0.03}$	232/207	0.11	$3.44^{+0.16}_{-0.16}$	$3.43^{+0.11}_{-0.11}$	$9.31^{+0.24}_{-0.24}$	$5.44^{+0.25}_{-0.25}$	2.01 ± 0.05	1.18 ± 0.05	15.22 ± 1.07	3.62 ± 0.51
	0405090101	54023.98	$0.31^{+0.01}_{-0.01}$	$2.31^{+0.14}_{-0.12}$	$1.71^{+0.08}_{-0.03}$	$0.19^{+0.01}_{-0.01}$	532/446	0.02	$2.07^{+0.02}_{-0.02}$	$3.22^{+0.02}_{-0.01}$	$6.90^{+0.05}_{-0.05}$	$3.21^{+0.05}_{-0.05}$	1.49 ± 0.01	0.69 ± 0.01	14.46 ± 0.62	3.77 ± 0.21
	0693850501	56277.67	$0.28^{+0.02}_{-0.02}$	$2.53^{+0.22}_{-0.17}$	$1.73^{+0.04}_{-0.04}$	$0.23^{+0.02}_{-0.01}$	479/440	0.10	$1.93^{+0.04}_{-0.04}$	$3.60^{+0.05}_{-0.05}$	$6.95^{+0.07}_{-0.07}$	$2.77^{+0.05}_{-0.05}$	1.50 ± 0.02	0.59 ± 0.01	13.51 ± 0.81	3.61 ± 0.26
	0693851201	56283.66	$0.28^{+0.02}_{-0.02}$	$2.72^{+0.25}_{-0.19}$	$1.78^{+0.03}_{-0.03}$	$0.22^{+0.01}_{-0.01}$	547/455	0.01	$1.98^{+0.03}_{-0.03}$	$3.80^{+0.04}_{-0.04}$	$7.35^{+0.05}_{-0.05}$	$2.90^{+0.05}_{-0.05}$	1.59 ± 0.01	0.63 ± 0.01	12.42 ± 0.71	3.28 ± 0.17
	0742590301 [†]	56843.97	$0.33^{+0.03}_{-0.03}$	$2.16^{+0.21}_{-0.16}$	$2.10^{+0.04}_{-0.04}$	$0.19^{+0.02}_{-0.01}$	592/434	0.01	$2.34^{+0.06}_{-0.06}$	$7.87^{+0.05}_{-0.05}$	$12.86^{+0.06}_{-0.06}$	$3.69^{+0.10}_{-0.10}$	2.78 ± 0.01	0.80 ± 0.02	11.14 ± 0.67	2.10 ± 0.11
	0742490101 [†]	57111.19	$0.29^{+0.03}_{-0.02}$	$2.86^{+0.25}_{-0.50}$	$1.74^{+0.04}_{-0.05}$	$0.21^{+0.02}_{-0.02}$	355/267	0.03	$1.69^{+0.04}_{-0.04}$	$3.05^{+0.04}_{-0.04}$	$6.16^{+0.06}_{-0.06}$	$2.51^{+0.06}_{-0.06}$	1.33 ± 0.01	0.54 ± 0.01	12.51 ± 3.06	3.49 ± 0.26
	0803990101 [†]	57918.89	$0.34^{+0.01}_{-0.01}$	$2.69^{+0.16}_{-0.14}$	$2.04^{+0.02}_{-0.02}$	$0.20^{+0.01}_{-0.01}$	684/540	0.01	$2.69^{+0.04}_{-0.04}$	$7.31^{+0.03}_{-0.03}$	$12.74^{+0.05}_{-0.05}$	$4.16^{+0.07}_{-0.07}$	2.75 ± 0.01	0.90 ± 0.02	10.25 ± 0.37	2.21 ± 0.06
	0803990301 [†]	57996.68	$0.33^{+0.02}_{-0.02}$	$2.25^{+0.16}_{-0.13}$	$1.70^{+0.02}_{-0.02}$	$0.20^{+0.01}_{-0.01}$	471/420	0.05	$2.62^{+0.05}_{-0.05}$	$3.43^{+0.01}_{-0.01}$	$7.99^{+0.09}_{-0.09}$	$4.07^{+0.07}_{-0.07}$	1.72 ± 0.02	0.88 ± 0.02	14.80 ± 0.64	3.85 ± 0.15
	0803990601 [†]	58096.46	$0.32^{+0.02}_{-0.01}$	$2.14^{+0.13}_{-0.11}$	$2.08^{+0.02}_{-0.02}$	$0.20^{+0.01}_{-0.01}$	642/456	0.01	$1.99^{+0.05}_{-0.05}$	$7.13^{+0.07}_{-0.07}$	$11.16^{+0.09}_{-0.09}$	$2.97^{+0.08}_{-0.08}$	2.41 ± 0.02	0.64 ± 0.02	11.35 ± 0.41	2.15 ± 0.06
NGC 5408 X-1 ($d = 4.8 \text{ Mpc}$)	0112290501 [†]	52121.54	0.11*	2.01*	$2.65^{+0.19}_{-0.17}$	$0.16^{+0.01}_{-0.01}$	125/129	0.57	$2.73^{+0.12}_{-0.12}$	$1.82^{+0.09}_{-0.09}$	$7.11^{+0.20}_{-0.20}$	$4.78^{+0.21}_{-0.21}$	1.96 ± 0.06	1.32 ± 0.06	8.62 ± 0.77	1.16 ± 0.21
	0112291001 [†]	52484.35	$0.12^{+0.04}_{-0.03}$	1.97*	$2.13^{+0.43}_{-0.43}$	$0.18^{+0.03}_{-0.03}$	126/136	0.71	$1.85^{+0.09}_{-0.09}$	$1.47^{+0.07}_{-0.07}$	$4.72^{+0.13}_{-0.13}$	$3.01^{+0.14}_{-0.14}$	1.30 ± 0.04	0.83 ± 0.04	11.51 ± 3.26	2.04 ± 1.10
	0112291201 [†]	52667.01	$0.13^{+0.06}_{-0.05}$	2.01*	$2.19^{+0.21}_{-0.21}$	$0.18^{+0.03}_{-0.03}$	92/96	0.58	$1.89^{+0.11}_{-0.11}$	$1.30^{+0.09}_{-0.09}$	$4.64^{+0.16}_{-0.16}$	$3.10^{+0.17}_{-0.17}$	1.28 ± 0.04	0.85 ± 0.05	10.97 ± 1.39	1.89 ± 0.48
	0302900101	53748.77	$0.12^{+0.01}_{-0.01}$	$1.62^{+0.16}_{-0.14}$	$2.31^{+0.07}_{-0.07}$	$0.16^{+0.01}_{-0.01}$	438/338	0.01	$1.87^{+0.01}_{-0.01}$	$1.45^{+0.01}_{-0.01}$	$5.27^{+0.02}_{-0.02}$	$3.36^{+0.04}_{-0.04}$	1.45 ± 0.01	0.93 ± 0.01	11.54 ± 0.78	1.69 ± 0.13
	0500750101	54478.79	$0.12^{+0.01}_{-0.01}$	$1.62^{+0.18}_{-0.14}$	$2.24^{+0.08}_{-0.08}$	$0.16^{+0.01}_{-0.01}$	333/295	0.07	$1.50^{+0.03}_{-0.03}$	$1.42^{+0.03}_{-0.03}$	$4.49^{+0.05}_{-0.05}$	$2.65^{+0.04}_{-0.04}$	1.24 ± 0.01	0.73 ± 0.01	12.01 ± 0.93	1.83 ± 0.17
	0653380201	55394.13	$0.11^{+0.01}_{-0.01}$	$1.69^{+0.19}_{-0.14}$	$2.27^{+0.07}_{-0.06}$	$0.16^{+0.01}_{-0.01}$	334/303	0.11	$1.72^{+0.02}_{-0.02}$	$1.90^{+0.02}_{-0.02}$	$5.40^{+0.04}_{-0.04}$	$2.98^{+0.07}_{-0.07}$	1.49 ± 0.01	0.82 ± 0.02	11.53 ± 0.86	1.76 ± 0.14

[†]Non-detection of QPO. *Frozen parameter value. $\boxtimes P_{\text{null}} < 0.1$ yielded due to excess residuals at 0.56 keV and 1 keV in some of the observations of NGC 1313 X-1 and NGC 5408 X-1.

Table 5.5: Continued.

Model fitted parameters			Estimated parameters													
Source	ObsID	MJD	n_{H}	$k_{\text{B}}T_e$	Γ_{nth}	$k_{\text{B}}T_{\text{in}}$	$\chi^2/d.o.f$	$P_{\text{null}}^{\boxtimes}$	F_{disc}	F_{nth}	F_{bol}	F_{disc}	L_{bol}	L_{disc}	τ	y_{par}
(Distance)			(10^{22} cm^{-2})	(keV)		(keV)			($0.3 - 10 \text{ keV}$)	($10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$)	($0.1 - 100 \text{ keV}$)		($10^{40} \text{ erg s}^{-1}$)			
NGC 6946 X-1 (d = 7.72 Mpc)	0653380301	55396.13	$0.10^{+0.01}_{-0.01}$	$1.84^{+0.20}_{-0.15}$	$2.27^{+0.07}_{-0.07}$	$0.17^{+0.01}_{-0.01}$	419/366	0.03	$1.41^{+0.02}_{-0.02}$	$1.79^{+0.02}_{-0.02}$	$4.57^{+0.03}_{-0.03}$	$2.34^{+0.05}_{-0.05}$	1.26 ± 0.01	0.65 ± 0.01	11.00 ± 0.80	1.74 ± 0.14
	0653380401	55587.67	$0.11^{+0.01}_{-0.01}$	$1.62^{+0.13}_{-0.12}$	$2.24^{+0.01}_{-0.01}$	$0.17^{+0.01}_{-0.01}$	404/358	0.05	$1.58^{+0.02}_{-0.02}$	$1.64^{+0.02}_{-0.02}$	$4.75^{+0.03}_{-0.03}$	$2.68^{+0.06}_{-0.06}$	1.31 ± 0.02	0.74 ± 0.02	12.01 ± 0.54	1.83 ± 0.03
	0653380501	55589.65	$0.11^{+0.01}_{-0.01}$	$1.62^{+0.17}_{-0.15}$	$2.21^{+0.08}_{-0.01}$	$0.17^{+0.01}_{-0.01}$	415/342	0.01	$1.53^{+0.02}_{-0.02}$	$1.56^{+0.02}_{-0.02}$	$4.50^{+0.04}_{-0.04}$	$2.56^{+0.03}_{-0.03}$	1.24 ± 0.01	0.71 ± 0.01	12.22 ± 0.92	1.89 ± 0.18
	0723130301	56699.02	$0.12^{+0.01}_{-0.01}$	$1.62^{+0.24}_{-0.19}$	$2.18^{+0.13}_{-0.12}$	$0.17^{+0.01}_{-0.01}$	297/244	0.02	$1.54^{+0.04}_{-0.04}$	$1.45^{+0.04}_{-0.04}$	$4.36^{+0.06}_{-0.06}$	$2.59^{+0.05}_{-0.05}$	1.20 ± 0.02	0.71 ± 0.01	12.44 ± 1.41	1.96 ± 0.31
	0723130401	56701.02	$0.11^{+0.01}_{-0.01}$	$1.62^{+0.18}_{-0.16}$	$2.17^{+0.02}_{-0.02}$	$0.17^{+0.01}_{-0.01}$	272/263	0.34	$1.58^{+0.03}_{-0.03}$	$1.55^{+0.03}_{-0.03}$	$4.62^{+0.04}_{-0.04}$	$2.67^{+0.05}_{-0.05}$	1.27 ± 0.01	0.74 ± 0.01	12.52 ± 0.78	1.98 ± 0.05
	0500730201	54406.91	$0.28^{+0.11}_{-0.10}$	2.19*	$2.18^{+0.06}_{-0.07}$	$0.18^{+0.04}_{-0.02}$	179/203	0.88	$0.82^{+0.04}_{-0.04}$	$0.93^{+0.04}_{-0.04}$	$2.42^{+0.06}_{-0.06}$	$1.29^{+0.06}_{-0.06}$	1.73 ± 0.04	0.93 ± 0.04	10.52 ± 0.45	1.89 ± 0.16
IC 342 X-1 (d = 3.61 Mpc)	0500730101	54412.94	$0.28^{+0.07}_{-0.05}$	3.20*	$2.11^{+0.11}_{-0.06}$	$0.18^{+0.03}_{-0.03}$	163/180	0.81	$1.04^{+0.05}_{-0.05}$	$0.96^{+0.04}_{-0.04}$	$2.87^{+0.07}_{-0.07}$	$1.69^{+0.08}_{-0.08}$	2.05 ± 0.05	1.21 ± 0.06	8.87 ± 0.64	1.97 ± 0.28
	0691570101	56221.74	$0.32^{+0.04}_{-0.05}$	$2.23^{+0.07}_{-0.07}$	$2.25^{+0.14}_{-0.15}$	$0.16^{+0.01}_{-0.01}$	326/331	0.57	$1.64^{+0.04}_{-0.04}$	$1.31^{+0.03}_{-0.03}$	$4.38^{+0.10}_{-0.10}$	$2.77^{+0.06}_{-0.06}$	3.12 ± 0.07	1.98 ± 0.04	9.98 ± 0.84	1.74 ± 0.30
	0870830101	59038.93	$0.43^{+0.10}_{-0.09}$	2.69*	$2.22^{+0.15}_{-0.14}$	$0.16^{+0.03}_{-0.02}$	135/135	0.48	$3.61^{+0.17}_{-0.16}$	$1.25^{+0.09}_{-0.08}$	$7.96^{+0.36}_{-0.36}$	$6.47^{+0.31}_{-0.29}$	5.68 ± 0.26	4.61 ± 0.22	9.14 ± 0.83	1.75 ± 0.32
	0870830201	59198.32	$0.47^{+0.12}_{-0.11}$	1.72*	$2.23^{+0.18}_{-0.16}$	$0.14^{+0.03}_{-0.02}$	84/82	0.42	$5.17^{+0.36}_{-0.36}$	$1.28^{+0.09}_{-0.09}$	$11.23^{+0.82}_{-0.81}$	$10.17^{+0.74}_{-0.71}$	8.01 ± 0.58	7.25 ± 0.51	12.37 ± 1.18	1.94 ± 0.22
	0870830301	59308.22	$0.34^{+0.08}_{-0.07}$	1.62*	$2.03^{+0.12}_{-0.12}$	$0.17^{+0.03}_{-0.02}$	119/134	0.81	$1.92^{+0.08}_{-0.08}$	$0.97^{+0.05}_{-0.04}$	$4.27^{+0.10}_{-0.09}$	$3.16^{+0.15}_{-0.14}$	3.05 ± 0.07	2.25 ± 0.08	13.69 ± 1.10	2.37 ± 0.38
	0870830401	59359.89	$0.37^{+0.10}_{-0.08}$	1.62*	$2.06^{+0.13}_{-0.12}$	$0.16^{+0.03}_{-0.02}$	85/100	0.85	$2.37^{+0.11}_{-0.10}$	$0.91^{+0.04}_{-0.04}$	$5.23^{+0.12}_{-0.12}$	$4.18^{+0.20}_{-0.19}$	3.73 ± 0.09	2.98 ± 0.14	13.42 ± 1.14	2.28 ± 0.39
(d = 3.61 Mpc)	0093640901 [†]	51951.06	$0.58^{+0.09}_{-0.08}$	2.01*	$1.48^{+0.04}_{-0.11}$	$0.40^{+0.05}_{-0.04}$	136/138	0.53	$0.78^{+0.13}_{-0.12}$	$2.56^{+0.08}_{-0.08}$	$3.80^{+0.12}_{-0.12}$	$0.89^{+0.04}_{-0.04}$	0.59 ± 0.02	0.14 ± 0.01	19.94 ± 2.78	6.24 ± 0.63
	0206890101 [†]	53055.31	$0.71^{+0.02}_{-0.02}$	$2.19^{+0.22}_{-0.16}$	$1.86^{+0.03}_{-0.03}$	—	282/305	0.82	—	$3.62^{+0.09}_{-0.09}$	$10.73^{+0.17}_{-0.17}$	—	1.67 ± 0.03	—	13.11 ± 0.79	2.94 ± 0.14
	0206890201 [†]	53234.82	$0.74^{+0.07}_{-0.07}$	$2.98^{+1.56}_{-0.61}$	$1.74^{+0.06}_{-0.06}$	$0.30^{+0.02}_{-0.02}$	287/275	0.29	$1.28^{+0.06}_{-0.06}$	$3.49^{+0.06}_{-0.06}$	$5.83^{+0.12}_{-0.12}$	$1.68^{+0.05}_{-0.05}$	0.91 ± 0.02	0.26 ± 0.01	12.23 ± 3.69	3.48 ± 0.57
	0693850601	56150.83	$0.78^{+0.08}_{-0.07}$	$2.51^{+0.31}_{-0.23}$	$1.70^{+0.06}_{-0.07}$	$0.24^{+0.02}_{-0.01}$	336/361	0.82	$1.82^{+0.08}_{-0.08}$	$3.45^{+0.06}_{-0.06}$	$6.59^{+0.09}_{-0.09}$	$2.55^{+0.07}_{-0.07}$	1.03 ± 0.01	0.40 ± 0.01	13.94 ± 1.31	3.81 ± 0.50
	0693851301 [†]	56156.84	$0.68^{+0.05}_{-0.05}$	$2.79^{+0.52}_{-0.35}$	$1.82^{+0.05}_{-0.03}$	$0.28^{+0.05}_{-0.02}$	394/376	0.25	$0.83^{+0.05}_{-0.04}$	$4.46^{+0.04}_{-0.04}$	$6.32^{+0.05}_{-0.05}$	$1.11^{+0.06}_{-0.06}$	0.99 ± 0.08	0.17 ± 0.01	11.84 ± 1.32	3.06 ± 0.26

†Non-detection of QPO. *Frozen parameter value. $\boxtimes P_{\text{null}} < 0.1$ yielded due to excess residuals at 0.56 keV and 1 keV in some of the observations of NGC 1313 X-1 and NGC 5408 X-1.

Table 5.6: Best-fitted and estimated spectral parameters obtained from the simultaneous modeling of *EPIN-PN* and *EPIN-MOS* spectra of the *XMM-Newton* observations of respective sources in 0.3 – 10 keV energy range using the model combination `constant×TBabs×(diskbb + nthcomp)`. All the quantities mentioned in the table have their usual meanings. The flux and luminosity values are presented in units of $\times 10^{-12}$ erg cm^{-2} s^{-1} and $\times 10^{39}$ erg s^{-1} , respectively.

Parameters	XMM1	XMM2	XMM3	XMM4	XMM5	XMM6	XMM7	XMM8	XMM9	XMM10	XMM11
NGC 55 ULX1 (D = 1.94 Mpc)											
n_{H} (10^{22} cm^{-2})	$0.16^{+0.04}_{-0.03}$	$0.33^{+0.05}_{-0.06}$	$0.11^{+0.02}_{-0.02}$	$0.15^{+0.03}_{-0.03}$	$0.38^{+0.04}_{-0.04}$	$0.41^{+0.12}_{-0.08}$	$0.43^{+0.12}_{-0.13}$	$0.40^{+0.11}_{-0.18}$	$0.11^{+0.02}_{-0.02}$	0.11^*	—
$k_{\text{B}}T_{\text{in}}$ (keV)	—	$0.16^{+0.02}_{-0.03}$	—	—	$0.15^{+0.03}_{-0.03}$	$0.14^{+0.03}_{-0.02}$	$0.14^{+0.01}_{-0.01}$	$0.15^{+0.03}_{-0.04}$	—	—	—
Γ_{nth}	$3.01^{+0.06}_{-0.05}$	$2.65^{+0.02}_{-0.05}$	$3.64^{+0.07}_{-0.07}$	$3.42^{+0.05}_{-0.06}$	$3.27^{+0.08}_{-0.07}$	$3.31^{+0.15}_{-0.13}$	$3.32^{+0.21}_{-0.30}$	$3.31^{+0.26}_{-0.33}$	$3.56^{+0.08}_{-0.07}$	$3.48^{+0.04}_{-0.04}$	—
$k_{\text{B}}T_{\text{e}}$ (keV)	1.62^*	1.62^*	1.62^*	2^*	1.89^*	1.62^*	2^*	2^*	1.62^*	2^*	—
$\chi^2/\text{d.o.f}$	338/283	383/261	470/319	422/312	207/169	164/145	152/107	99/96	456/337	476/287	—
F_{disc}	—	2.88 ± 0.19	—	—	5.36 ± 0.49	9.03 ± 0.41	4.95 ± 0.34	7.40 ± 0.34	—	—	—
F_{nth}	6.21 ± 0.14	8.39 ± 0.18	2.89 ± 0.07	2.60 ± 0.06	9.32 ± 0.21	10.04 ± 0.52	3.63 ± 0.17	5.10 ± 0.23	2.88 ± 0.19	4.71 ± 0.04	—
F_{bol}	7.46 ± 0.17	16.04 ± 0.36	3.57 ± 0.08	3.39 ± 0.08	23.62 ± 0.54	33.78 ± 0.75	16.21 ± 0.72	21.76 ± 1.47	3.58 ± 0.08	4.75 ± 0.03	—
L_{bol}	3.36 ± 0.08	7.22 ± 0.16	1.60 ± 0.04	1.53 ± 0.04	10.64 ± 0.24	15.21 ± 0.33	7.30 ± 0.32	9.81 ± 0.66	1.61 ± 0.06	2.14 ± 0.01	—
L_{disc}	—	2.44 ± 0.09	—	—	4.58 ± 0.22	8.10 ± 0.18	4.89 ± 0.16	6.51 ± 0.15	—	—	—
τ	8.32 ± 0.21	9.72 ± 0.23	6.62 ± 0.15	6.30 ± 0.13	6.88 ± 0.21	7.42 ± 0.41	6.53 ± 0.72	6.55 ± 0.79	6.80 ± 0.18	6.16 ± 0.08	—
y_{par}	0.88 ± 0.04	1.19 ± 0.06	0.55 ± 0.03	0.62 ± 0.03	0.70 ± 0.04	0.69 ± 0.08	0.67 ± 0.15	0.67 ± 0.16	0.58 ± 0.03	0.59 ± 0.02	—

*Frozen to best-fitted value.

Table 5.6: Continued.

Parameters	XMM1	XMM2	XMM3	XMM4	XMM5	XMM6	XMM7	XMM8	XMM9	XMM10	XMM11
NGC 5204 X-1 (D = 4.8 Mpc)											
η_{H} (10^{22} cm^{-2})	$0.04^{+0.02}_{-0.02}$	—	$0.05^{+0.03}_{-0.02}$	$0.06^{+0.01}_{-0.02}$	$0.06^{+0.01}_{-0.01}$	$0.04^{+0.01}_{-0.01}$	$0.06^{+0.03}_{-0.03}$	$0.04^{+0.01}_{-0.01}$	$0.04^{+0.02}_{-0.02}$	$0.06^{+0.01}_{-0.01}$	$0.07^{+0.01}_{-0.01}$
$k_{\mathrm{B}}T_{\mathrm{in}}$ (keV)	$0.26^{+0.04}_{-0.02}$	—	$0.28^{+0.06}_{-0.06}$	$0.29^{+0.05}_{-0.03}$	$0.28^{+0.03}_{-0.03}$	$0.28^{+0.03}_{-0.03}$	$0.24^{+0.04}_{-0.04}$	$0.25^{+0.05}_{-0.04}$	$0.25^{+0.04}_{-0.03}$	$0.24^{+0.01}_{-0.01}$	$0.25^{+0.03}_{-0.02}$
Γ_{nth}	$1.66^{+0.13}_{-0.06}$	—	$2.07^{+0.14}_{-0.16}$	$2.16^{+0.29}_{-0.11}$	$2.12^{+0.15}_{-0.16}$	$1.85^{+0.11}_{-0.12}$	$1.69^{+0.11}_{-0.09}$	$1.77^{+0.13}_{-0.16}$	$1.76^{+0.09}_{-0.11}$	$1.79^{+0.05}_{-0.05}$	$2.17^{+0.12}_{-0.12}$
$k_{\mathrm{B}}T_{\mathrm{e}}$ (keV)	$1.62^{+0.38}_{-0.27}$	—	2.5^*	1.62^*	$2.07^{+1.04}_{-0.42}$	2.65^*	$1.73^{+0.49}_{-0.25}$	2.13^*	$1.98^{+0.61}_{-0.34}$	$2.09^{+0.29}_{-0.21}$	$2.49^{+0.88}_{-0.43}$
$\chi^2/\text{d.o.f}$	236/225	—	167/164	103/133	327/328	319/296	223/212	238/208	268/247	525/395	393/332
F_{disc}	0.46 ± 0.02	—	0.68 ± 0.05	0.95 ± 0.02	0.76 ± 0.02	0.57 ± 0.01	0.52 ± 0.02	0.42 ± 0.02	0.37 ± 0.02	0.85 ± 0.02	0.86 ± 0.03
F_{nth}	1.29 ± 0.03	—	1.95 ± 0.09	2.27 ± 0.10	2.10 ± 0.05	1.58 ± 0.04	1.35 ± 0.06	1.46 ± 0.07	1.34 ± 0.03	1.76 ± 0.02	2.41 ± 0.02
F_{bol}	2.04 ± 0.03	—	3.15 ± 0.07	3.76 ± 0.09	3.37 ± 0.03	2.64 ± 0.06	2.21 ± 0.05	2.24 ± 0.05	2.02 ± 0.05	2.61 ± 0.03	3.24 ± 0.04
L_{bol}	5.62 ± 0.08	—	8.69 ± 0.02	10.37 ± 0.03	9.29 ± 0.08	7.31 ± 0.02	6.09 ± 0.14	6.18 ± 0.14	5.57 ± 0.16	7.19 ± 0.05	8.93 ± 0.03
L_{disc}	1.71 ± 0.06	—	2.48 ± 0.14	3.45 ± 0.06	2.78 ± 0.06	2.10 ± 0.03	1.98 ± 0.06	1.59 ± 0.06	1.71 ± 0.05	2.34 ± 0.04	2.37 ± 0.05
τ	18.37 ± 3.26	—	10.47 ± 1.11	12.60 ± 1.54	11.27 ± 2.42	11.89 ± 1.14	17.23 ± 3.17	14.33 ± 1.72	15.04 ± 2.35	14.24 ± 1.27	3.31 ± 0.28
y_{par}	4.27 ± 1.07	—	2.14 ± 0.46	2.01 ± 0.48	2.05 ± 0.42	2.93 ± 0.56	4.01 ± 0.83	3.42 ± 0.82	3.51 ± 0.67	3.31 ± 0.28	1.89 ± 0.28

*Frozen to best-fitted value.

Table 5.6: Continued.

Parameters	XMM2	XMM3	XMM4	XMM7	XMM8	XMM9	XMM10	XMM11	XMM12	XMM13	XMM14	XMM15	XMM17
NGC 4395 ULX1 (D = 4.76 Mpc)													
n_H (10^{22} cm^{-2})	—	—	$0.10^{+0.03}_{-0.03}$	$0.10^{+0.02}_{-0.02}$	$0.10^{+0.02}_{-0.02}$	$0.11^{+0.03}_{-0.02}$	$0.11^{+0.03}_{-0.02}$	$0.03^{+0.01}_{-0.01}$	0.03^*	0.03^*	0.04^*	0.05^*	0.05^*
$k_B T_{in}$ (keV)	—	—	$0.15^{+0.02}_{-0.02}$	$0.15^{+0.02}_{-0.02}$	$0.16^{+0.03}_{-0.03}$	$0.15^{+0.03}_{-0.03}$	—	$0.32^{+0.02}_{-0.02}$	$0.31^{+0.01}_{-0.01}$	$0.31^{+0.01}_{-0.01}$	$0.31^{+0.01}_{-0.01}$	$0.29^{+0.01}_{-0.01}$	$0.31^{+0.01}_{-0.01}$
Γ_{nth}	—	—	$3.34^{+0.17}_{-0.18}$	$3.33^{+0.18}_{-0.16}$	$3.20^{+0.09}_{-0.08}$	$3.86^{+0.25}_{-0.29}$	$3.05^{+0.05}_{-0.05}$	—	—	—	—	—	—
$k_B T_e$ (keV)	—	—	2^*	1.92^*	2^*	2^*	1.62^*	—	—	—	—	—	—
$\chi^2/d.o.f$	—	—	179/155	180/155	259/212	179/146	313/237	118/77	96/86	123/82	141/87	127/79	131/108
F_{disc}	—	—	0.23 ± 0.02	0.24 ± 0.02	0.24 ± 0.03	0.27 ± 0.03	—	0.55 ± 0.01	0.43 ± 0.01	0.41 ± 0.02	0.52 ± 0.01	0.49 ± 0.01	0.55 ± 0.02
F_{nth}	—	—	0.63 ± 0.03	0.62 ± 0.02	1.34 ± 0.03	0.74 ± 0.03	1.81 ± 0.03	—	—	—	—	—	—
F_{bol}	—	—	1.37 ± 0.03	1.40 ± 0.03	2.37 ± 0.03	1.76 ± 0.04	2.71 ± 0.04	0.57 ± 0.01	0.45 ± 0.01	0.42 ± 0.02	0.54 ± 0.01	0.51 ± 0.01	0.57 ± 0.02
L_{bol}	—	—	3.71 ± 0.08	3.80 ± 0.08	6.43 ± 0.08	4.77 ± 0.11	7.35 ± 0.08	1.55 ± 0.02	1.22 ± 0.01	1.14 ± 0.02	1.46 ± 0.02	1.38 ± 0.01	1.55 ± 0.02
L_{disc}	—	—	1.27 ± 0.05	1.31 ± 0.03	1.28 ± 0.04	1.61 ± 0.05	—	1.49 ± 0.02	1.17 ± 0.01	1.11 ± 0.02	1.41 ± 0.02	1.33 ± 0.01	1.49 ± 0.02
τ	—	—	6.48 ± 0.41	6.67 ± 0.44	6.83 ± 0.23	5.43 ± 0.51	8.13 ± 0.16	—	—	—	—	—	—
y_{par}	—	—	0.66 ± 0.08	0.67 ± 0.09	0.73 ± 0.05	0.46 ± 0.08	0.85 ± 0.03	—	—	—	—	—	—
NGC 4190 ULX1 (D = 3 Mpc)													
n_H (10^{22} cm^{-2})	$0.06^{+0.01}_{-0.01}$	$0.15^{+0.06}_{-0.02}$	—	—	—	—	—	—	—	—	—	—	—
Γ_{nth}	$2.09^{+0.19}_{-0.12}$	$1.69^{+0.03}_{-0.03}$	—	—	—	—	—	—	—	—	—	—	—
$k_B T_e$ (keV)	1.62^*	$1.67^{+0.11}_{-0.11}$	—	—	—	—	—	—	—	—	—	—	—
$\chi^2/d.o.f$	317/293	335/337	—	—	—	—	—	—	—	—	—	—	—
F_{nth}	3.31 ± 0.06	7.13 ± 0.09	—	—	—	—	—	—	—	—	—	—	—
F_{bol}	3.53 ± 0.07	8.17 ± 0.12	—	—	—	—	—	—	—	—	—	—	—
L_{bol}	3.80 ± 0.07	8.79 ± 0.13	—	—	—	—	—	—	—	—	—	—	—
τ	13.16 ± 1.61	17.56 ± 0.79	—	—	—	—	—	—	—	—	—	—	—
y_{par}	2.19 ± 0.53	4.03 ± 0.23	—	—	—	—	—	—	—	—	—	—	—

*Frozen to best-fitted value.

density in the spectral fitting. While doing so, we freeze the normalizations of the spectral components at their best fitted values. With this, we compute the bolometric luminosity $L_{\text{bol}} = F_{\text{bol}} \times 4\pi D^2$, where F_{bol} is the bolometric flux in 0.1 – 100 keV energy range, and D is the source distance. In Table 5.4 and Table 5.5, we present the computed L_{bol} for all the observations. We also compute the L_{disc} by calculating the bolometric disc flux F_{disc} in 0.1 – 100 keV range as $L_{\text{disc}} = F_{\text{disc}} \times 4\pi D^2$. Following Zdziarski et al. (1996), Majumder et al. (2022), we calculate the optical depth (τ) and Compton y-parameter (y_{par}) for all the observations and obtain their ranges as $6 < \tau < 20$ and $0.46 \lesssim y_{\text{par}} \lesssim 6.24$, respectively. These findings eventually indicate the existence of an optically thick and ‘cool’ corona surrounding the BH-ULXs under consideration.

5.3.3 Evolution of Spectral Characteristics

In this section, we study the long-term spectral evolution of the eight BH-ULXs namely NGC 1313 X–1, IC 342 X–1, NGC 4395 ULX1, NGC 5408 X–1, NGC 55 ULX1, NGC 4190 ULX1, NGC 6946 X–1 and NGC 5204 X–1 using the *XMM-Newton* observations over a decade. In Fig. 5.6, the variation of inner disc temperature ($k_{\text{B}}T_{\text{in}}$ in keV), electron temperature ($k_{\text{B}}T_{\text{e}}$ in keV), photon index (Γ_{nth}), disc flux (F_{disc} in $\text{erg cm}^{-2} \text{s}^{-1}$), Comptonized flux (F_{nth} in $\text{erg cm}^{-2}\text{s}^{-1}$), Compton y-parameter (y_{par}) and bolometric luminosity (L_{bol} in erg s^{-1}) are depicted from top to bottom panels, respectively, over different Epochs of observation. The best-fitted parameters of all the sources are tabulated in Tables 5.4, 5.5 and 5.6.

We observe that the spectral properties of the BH-ULXs generally exhibit significant variation over the long-term evolution of the sources and manifest several spectral states. In particular, we find the dominance of the Comptonization flux over the disc contribution ($F_{\text{nth}} \gtrsim F_{\text{disc}}$) for NGC 5204 X–1, IC 342 X–1, NGC 4190 ULX1 and NGC 1313 X–1, respectively. As expected, the photon index is observed to be in the harder limit of $\Gamma_{\text{nth}} \lesssim 2$, and the y_{par} , indicative of the amount of Comptonization, remains $\gtrsim 2$ for all the four sources (see Fig. 5.6). Further, we find a low disc temperature ($k_{\text{B}}T_{\text{in}} \lesssim 0.3 \text{ keV}$) for these sources except NGC 4190 ULX1 in which the disc is absent and the Comptonization contribution is noticeably high. In contrast, NGC 6946 X–1 manifests disc dominated spectral characteristics with $F_{\text{disc}} \gtrsim F_{\text{nth}}$ and $\Gamma_{\text{nth}} \gtrsim 2$ (see Fig. 5.6). Interestingly, comparable disc and Comptonized flux contributions are seen in the spectra of NGC 55 ULX1 and NGC 5408 X–1. However, the source NGC 55 ULX1 replicates relatively softer nature with $\Gamma_{\text{nth}} \gtrsim 3$ and $y_{\text{par}} \lesssim 1$, whereas NGC 5408 X–1 remains in the intermediate regime ($F_{\text{disc}} \approx F_{\text{nth}}$, $\Gamma_{\text{nth}} \lesssim 2$ and $1 < y_{\text{par}} \lesssim 2$). Finally, for NGC 4395 ULX1, we observe a negligible disc contribution with $y_{\text{par}} \lesssim 1$ and high photon index ($\Gamma_{\text{nth}} \gtrsim 3$). This possibly resulted from the appearance of a broad emission feature at lower energy ($\sim 1 \text{ keV}$), suggesting distinct and rather complex spectral characteristics of NGC 4395 ULX1. Note that the spectral parameters of NGC 4395 ULX1 show marginal variations during later epochs (XMM11–XMM17) (see Fig. 5.6), hence we present only the results for XMM11 and XMM15 in Fig. 5.6. A significant variation in the luminosity is noticed over the entire observation period of more than a decade for most of the sources. Note that a low electron temperature within $1 \text{ keV} \lesssim k_{\text{B}}T_{\text{e}} \lesssim 3 \text{ keV}$ is obtained for all the sources, indicating the presence of a relatively cool Compton corona, generally seen in ULXs.

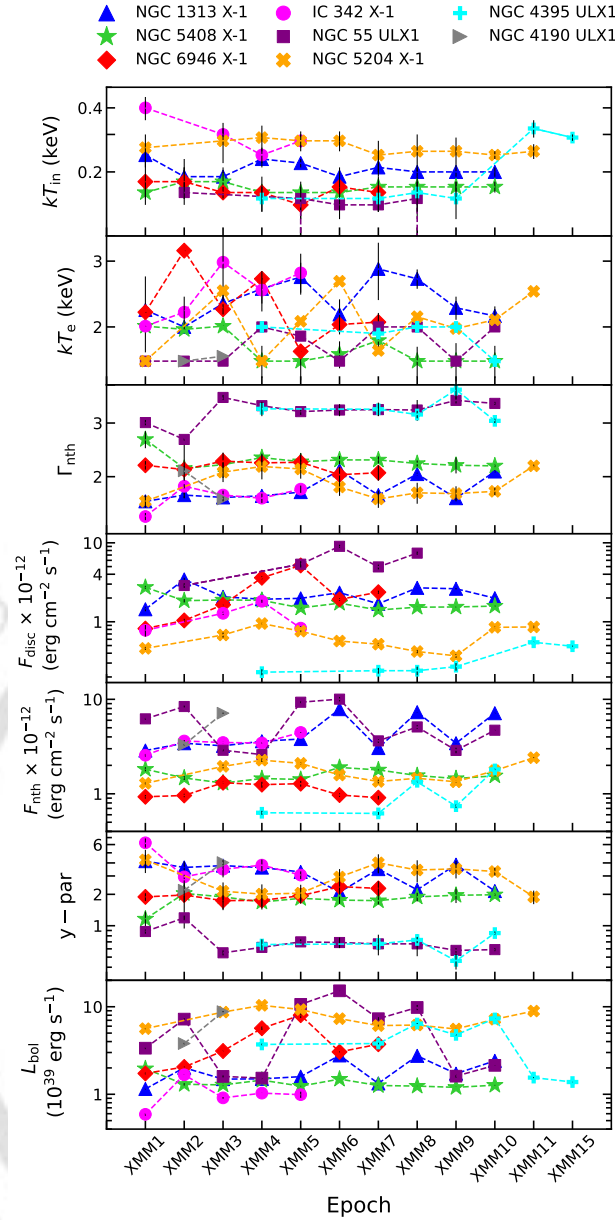


Figure 5.6: Evolution of the spectral parameters over the long-term monitoring are shown with distinct colored markers for the respective sources. The variation of inner disc temperature, electron temperature, photon index, disc flux, Comptonized flux, Compton y -parameter and bolometric luminosity over different Epochs are shown from top to bottom panels, respectively. See the text and Majumder et al. (2025a) for details.

5.4 Correlations Among Spectro-Temporal Observables

In this section, we examine the correlations among the various observables obtained from both timing and spectral analyses of the four BH-ULXs. With this, we put efforts to understand the spectro-temporal properties of these sources.

5.4.1 Diverse $L_{disc} - T_{col}$ Correlations

We explore intrinsic correlations among the best-fitted and estimated spectral parameters for the respective sources. In doing so, we investigate the correlation between the bolometric disc luminosity (L_{disc}) and color-corrected disc temperature (T_{col}) of the respective sources. Note that, the inner disc temperature (T_{in}) is multiplied with

the spectral hardening factor ($f_h = 1.7$) following Done and Davis (2008) to obtain the T_{col} . In Fig. 5.7, we present the obtained results, where, the L_{disc} (in $\times 10^{40}$ erg s $^{-1}$) is plotted as a function of T_{col} (in keV).

We notice the trend of possible correlations of distinct characteristics between L_{disc} and T_{col} for all the sources. To deduce the firmness of the correlations, we estimate the Pearson correlation coefficient (ρ) of the distributions in $L_{\text{disc}} - T_{\text{col}}$ plane for the respective cases. It is found that NGC 55 ULX1 shows a negative correlation between L_{disc} and T_{col} with $\rho \sim -0.74$. However, the variation in L_{disc} is found to be marginal for NGC 4395 ULX1 and the corresponding distribution in the $L_{\text{disc}} - T_{\text{col}}$ plane appears to form two distinct regimes of lower and higher temperatures (see Fig. 5.7), indicating no evidence of correlation with $\rho \sim -0.11$ only. It may be noted that the higher disc temperatures (~ 0.3 keV) are obtained for the observations in which only the disc component fits the entire spectra of narrow energy coverage ($\sim 0.3 - 2$ keV) in NGC 4395 ULX1. Therefore, the two distinct regions of different disc temperatures (see Fig. 5.7) perhaps resulted from the difference in model prescriptions for the respective cases. Contrarily, NGC 5204 X-1 is seen to exhibit a clear positive correlation with $\rho \sim +0.7$. Moreover, a strong negative correlation is obtained with $\rho \sim -0.81$ for the combined results of NGC 1313 X-1 and IC 342 X-1, and $\rho \sim -0.89$ for NGC 6946 X-1. Although, we find a weak anti-correlation with $\rho \sim -0.27$ in $L_{\text{disc}} - T_{\text{col}}$ plane of NGC 5408 X-1.

Further, we proceed to delineate the observed correlations of the sources with the empirical power-law profile $L_{\text{disc}} \propto T_{\text{col}}^\alpha$ (Rybicki and Lightman, 1979) using the `curve_fit`⁴ module in Python. The individual fits result the power-law exponent (α) as -6.01 ± 0.25 , -8.93 ± 0.11 , -10.31 ± 0.10 and 1.4 ± 0.1 for NGC 55 ULX1, NGC 6946 X-1, NGC 5408 X-1 and NGC 5204 X-1, respectively. However, the combined fitting of the correlation distributions for IC 342 X-1 and NGC 1313 X-1 indicates $\alpha = -3.58 \pm 0.04$. It may be noted that because of the marginal variation observed in L_{disc} and T_{col} , we refrain from modeling the luminosity-temperature distribution for NGC 4395 ULX1. In Fig. 5.7, we present the best-fitted power-law functional form in the top panel for the respective sources and the residuals in the bottom panel, respectively. In addition, we show the positive correlation between the disc luminosity and temperature of the form $L_{\text{disc}} \propto T_{\text{col}}^{+\alpha}$, typically observed for BH-XRBs, with a blue shade in Fig. 5.7. Note that the data associated with these correlation properties are adopted from Gierliński and Done (2004), Abe et al. (2005), Vierdayanti et al. (2010), Baby et al. (2021) and the disc temperature values are color-corrected using the same hardening factor ($f_h = 1.7$), considered for the present work.

5.4.2 Spectro-Temporal Correlations

Next, we examine the correlations among the spectro-temporal properties of the four BH-ULXs (NGC 1313 X-1, NGC 5408 X-1, NGC 6946 X-1 and IC 342 X-1) for which mHz QPOs are observed in multiple occasions. We depict the obtained results in Fig. 5.8, where the variation of $F_{\text{nth}}/F_{\text{tot}}$ (in per cent), $F_{\text{disc}}/F_{\text{tot}}$ (in per cent), Γ_{nth} , and f_{scatt} with QPO rms amplitudes (rms_{QPO}) are presented from top to bottom panels, respectively. Here, F_{nth} is the `nthcomp` flux, F_{disc} is the `diskbb` flux, F_{tot} is the total spectral flux, and f_{scatt} denotes the scattered fraction of the seed photons. In each panel, filled points with different styles and colors denote results corresponding to

⁴https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html

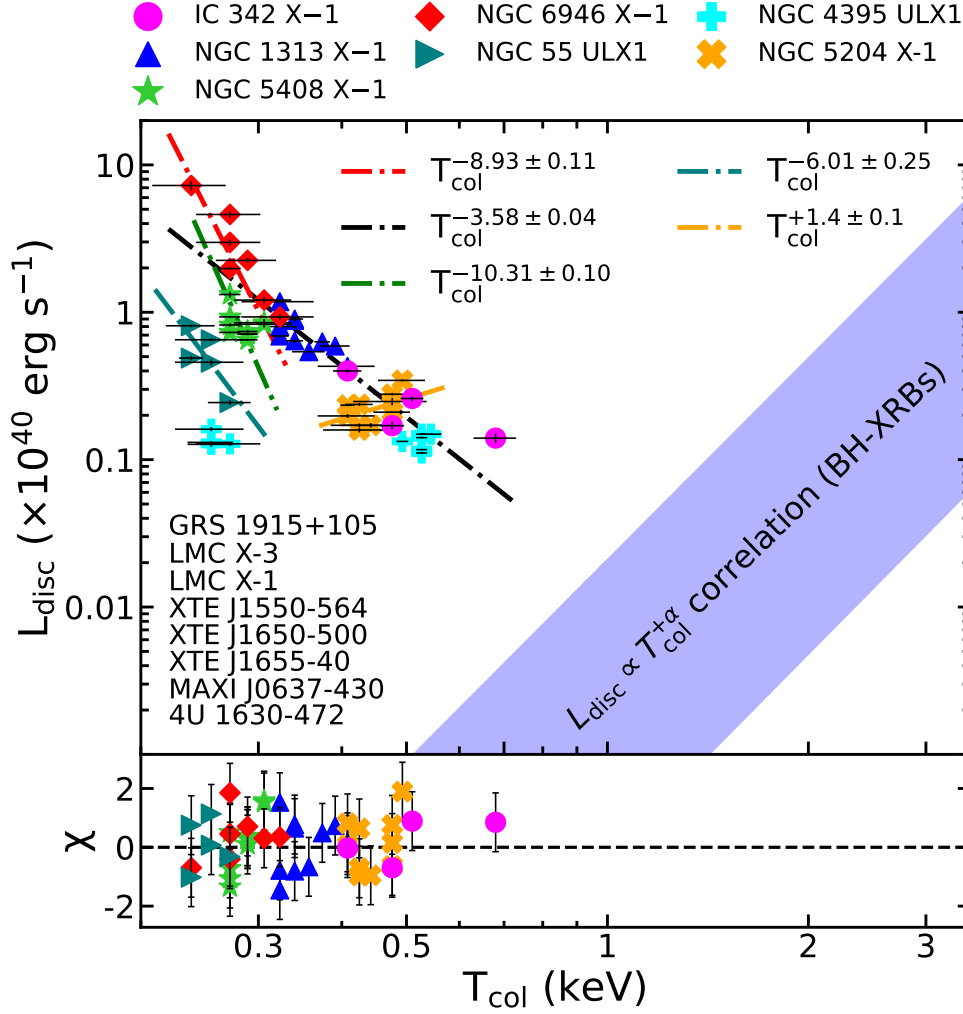


Figure 5.7: Correlation between the bolometric disc luminosity and color-corrected inner disc temperature of all BH-ULXs. The dash-dot lines of different colors represent the best fit in describing the $L_{\text{disc}} - T_{\text{col}}$ distribution of each source with the functional form mentioned in the figure. The blue-shaded region represents the correlation between the luminosity and disc temperature of the form $L_{\text{disc}} \propto T_{\text{col}}^{+\alpha}$ for eight BH-XRBs, adopted from Gierliński and Done 2004, Abe et al. 2005, Vierdayanti et al. 2010, Baby et al. 2021. See the text for details.

different sources as marked at the top of the figure. We observe that Comptonized flux generally contributes about 50 – 90%, whereas disc flux ranges within 3 – 50% across the overall range of rms_{QPO} (%). However, we notice that the flux contributions for NGC 5408 X–1 seem coarsely dependent on rms_{QPO} (%). In addition, f_{scatt} is seen to vary in the range of 2 – 20% that eventually corroborates the signature of Comptonization of the seed photons. Further, the photon index (Γ_{nth}) is found to vary in the range of 1.48 – 2.65 for all the sources. Note that NGC 6946 X–1 and NGC 5408 X–1 show relatively softer spectral characteristics ($\Gamma_{\text{nth}} \gtrsim 2$) compared to other sources ($\Gamma_{\text{nth}} \lesssim 2$) which is consistent with the variation of emission components (F_{disc} and F_{nth}) to the total flux of the sources.

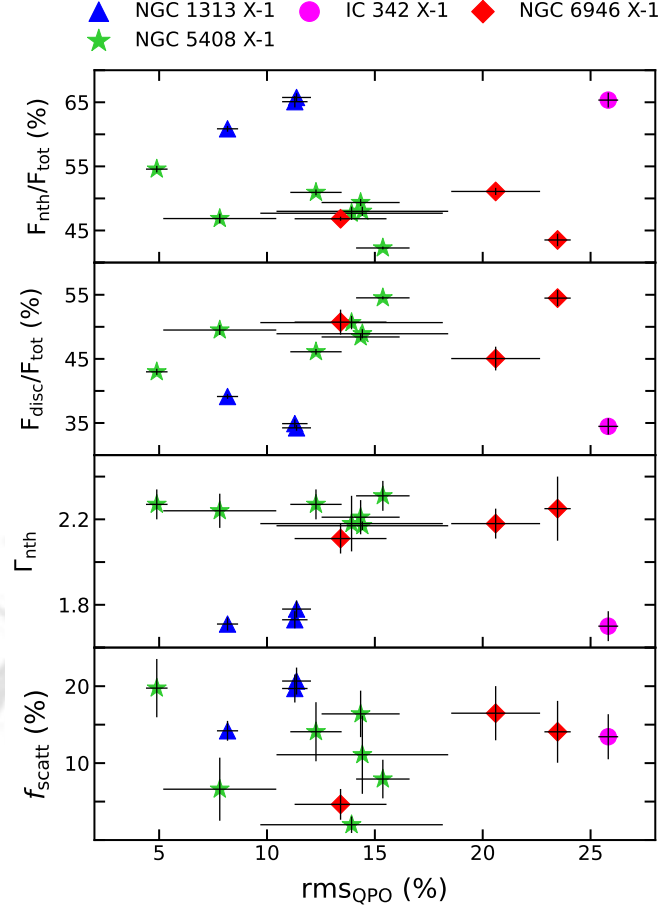


Figure 5.8: Variations of the percentage of Comptonized flux (F_{nth}) and disc flux (F_{disc}) to the total spectral flux (F_{tot}), nthcomp photon index (Γ_{nth}) and scattered fraction of Comptonized seed photons (f_{scatt}) with QPO rms amplitude (rms_{QPO} (%)) for four BH-ULXs are depicted from top to bottom panel, respectively. Results from different BH-ULXs are presented using filled points with different styles and colors as marked at the top of the figure. See text for details.

5.5 Accretion Disc-Wind Regulated Scenarios in BH-ULXs

5.5.1 Dichotomy in $L_{\text{disc}} \propto T_{\text{col}}^{\alpha}$ Correlation

As presented in §1.4.1, in this study, we observe both positive and negative correlations between L_{disc} and T_{col} for the BH-ULXs under consideration. Needless to mention that the appearance of ‘unusual’ correlation including anti-correlations (‘ $-\alpha$ ’) leads to the possible dichotomy between the present findings and the existing theoretical frameworks. Moreover, the BH-XRBs are also seen to deviate from the standard picture on several occasions as pointed out in the preceding section. Nevertheless, several attempts have been made to explain this, although the origin of the dichotomy remains elusive. Depending on α , the correlations are coarsely summarized in three different regimes for several BH-XRBs and BH-ULXs and briefly described as,

$$\begin{aligned}
 &\alpha = 4, && \text{(Standard disc)} \\
 L_{\text{disc}} \propto T_{\text{col}}^{\alpha}; & 0 \leq \alpha < 4, && \text{(Slim disc)} \\
 & -10 \leq \alpha < 0. && \text{(Anomalous)}
 \end{aligned}$$

- Standard disc scenario: Needless to mention that the luminosity associated with

the disc emission is expected to follow $L_{\text{disc}} \propto T_{\text{col}}^4$ as predicted from the standard accretion disc prescription (Shakura and Sunyaev, 1973). In general, the Keplerian disc component of the accretion flow locally emits as a multi-color blackbody at different disc radii, resulting in the expected correlation (Frank et al., 2002).

- Slim disc scenario: Several BH-XRBs including 4U 1630 – 472, XTE J1550 – 564 and GRS 1915 + 105 are seen to deviate from the standard disc and mostly follow a flatter correlation as $2 \lesssim \alpha < 4$ (Kubota and Makishima, 2004, Abe et al., 2005, Vierdayanti et al., 2010). It has also been suggested that different accretion scenarios exist for these BH-XRBs, which determine the nature of the correlations. In this study, we observe that NGC 5204 X–1 is the only BH-ULX that manifests a positive correlation of the form $L_{\text{disc}} \propto T_{\text{col}}^{1.4}$, however this relation is not generally determined by the spectral states. Moreover, at relatively higher luminosity, close to the Eddington limit, the deviation from $\alpha \sim 4$ becomes more prominent (Kubota and Makishima, 2004). A geometrically thin ($H/r \ll 1$) and radiatively efficient standard Keplerian disc is characterized with moderately low accretion rate. However, the ‘slim disc’ appears with relatively higher luminosity ($\gtrsim 0.3L_{\text{Edd}}$) yielding thicker disc geometry ($H/r \lesssim 1$), where the angular momentum remains sub-Keplerian (Abramowicz et al., 1988, Chakrabarti, 1995, Beloborodov, 1998, Abramowicz and Fragile, 2013). Interestingly, a more flatter correlation, *i.e.*, $L_{\text{disc}} \propto T_{\text{col}}^2$, is predicted for such discs (Watarai et al., 2001). Therefore, a possible explanation of the observed anomaly in the deviation of the power-law exponent could be the transition from the standard disc ($\alpha \sim 4$) to the ‘slim disc’ scenario ($\alpha \sim 2$).
- Anomalous scenario: Intriguingly, the negative correlations with $\alpha < 0$ observed in several BH-ULXs offer challenges, with only a few attempts made to explain these findings. King and Puchnarewicz (2002) proposed that the anti-correlation ($\alpha \sim -4$) is possibly resulted in due to the strong beamed emission in ULXs. Interestingly, the detection of coherent QPO features in BH-ULXs (Atapin et al., 2019, Majumder et al., 2023) indicates the presence of axisymmetric geometrically thin accretion disc, which contradicts the presence of strong beaming (Matteo and Psaltis, 1999, Strohmayer and Mushotzky, 2003). Furthermore, Middleton et al. (2019) reported that the Lense-Thirring precession of the inner accretion flow can attribute to the origin of the QPOs in ULXs. Meanwhile, Das et al. (2021) argued that the aperiodic modulation of the inner hot ‘Comptonizing corona’ successfully explains QPO features of BH-ULXs. All these findings clearly indicate the need for an alternative model prescription of accretion dynamics to explain the negative α values in the presence of QPO features.

5.5.2 Alternative Physical Scenario

The limitations of the standard disc and slim disc models in explaining $L_{\text{disc}} - T_{\text{col}}$ correlations prompt us to explore alternative physically motivated accretion-ejection model prescriptions for BH-ULXs. Such a model prescription appears to be capable in explaining the overall spectro-temporal properties, including $L_{\text{disc}} - T_{\text{col}}$ correlation and QPO features.

Table 5.7: Summary of the observed correlation properties between L_{disc} and T_{col} in different spectral states and the predicted inclinations of the BH-ULXs.

Source	Spectral State	$L_{\text{disc}} - T_{\text{col}}$ Correlation Exponent (α)	Predicted Inclination
NGC 5204 X-1	HUL	1.4 ± 0.1	Low
IC 342 X-1	HUL	-3.58 ± 0.04	Moderate
NGC 1313 X-1	HUL	-3.58 ± 0.04	Moderate
NGC 55 ULX1	IUL	-6.01 ± 0.25	High
NGC 6946 X-1	SUL	-8.93 ± 0.11	High
NGC 5408 X-1	IUL	-10.31 ± 0.10	High
NGC 4190 ULX1	HUL	—	Low
M82 X-1	—	—	Low
NGC 4395 ULX1	HUL	—	Moderate

HUL: Hard-ultraluminous state, SUL: Soft-ultraluminous state, IUL: Intermediate-ultraluminous state.

The accretion-ejection model formalism relies on the coexistence of Keplerian and sub-Keplerian flows (Chakrabarti and Titarchuk, 1995) and it explains the aspects of spectro-temporal variabilities of BH-XRBs (Chakrabarti and Manickam, 2000, Chakrabarti et al., 2009, Debnath et al., 2010, Nandi et al., 2012, Iyer et al., 2015, Sreehari et al., 2019a, and references therein). Similarly, this model is expected to explain the spectro-temporal variabilities of BH-ULXs. Further, the non-steady modulation of the Comptonizing corona (with radius r_s), formed by the sub-Keplerian component, leads to aperiodic variations in the emitted hard X-rays, which may give rise to QPO features (Molteni et al., 1996, Lee et al., 2011, Das et al., 2014a, Garain et al., 2014, Debnath et al., 2024). This conjecture effectively explains the mHz QPOs, which have become key observables for constraining the mass, spin, and accretion rate in several BH-ULXs (Das et al., 2021, Majumder et al., 2023). Moreover, by regulating the Keplerian and sub-Keplerian flow components and depending on system inclinations, different spectral states (HUL, SUL, and IUL) can be identified for BH-ULXs (see Table 5.7). Furthermore, powerful winds are also expected to eject from (a) the boundary of hot coronal region in the inner accretion flow (Chakrabarti, 1999, Das et al., 2001, Chattopadhyay and Chakrabarti, 2002, Das et al., 2014a), (b) standard thin Keplerian disc (Proga et al., 1998, Yang et al., 2018, Raychaudhuri et al., 2021) and (c) super-Eddington (super-critical) slim disc (Poutanen et al., 2007, Dotan and Shaviv, 2011), respectively. Moreover, we mention that a model formalism in the framework of relativistic dissipative accretion flow around a rotating black hole has been developed to interpret the luminosity and mHz QPO characteristics of BH-ULXs (Das et al., 2021, Majumder et al., 2023). However, a more comprehensive model of the spectral energy distribution is yet to be developed to explain the observed spectral characteristics of BH-ULXs. We depict a schematic representation of the accretion-ejection configuration for the BH-ULXs in Fig. 5.9.

For super-critical accretion state of BH-ULXs, the slim disc model seems relevant, where radiation pressure balances gravity at the spherization radius (r_{sp}), resulting in a sub-Keplerian geometrically thick ($H/r \lesssim 1$) disc at $r_s \leq r \leq r_{\text{sp}}$ (see Fig. 5.9 and

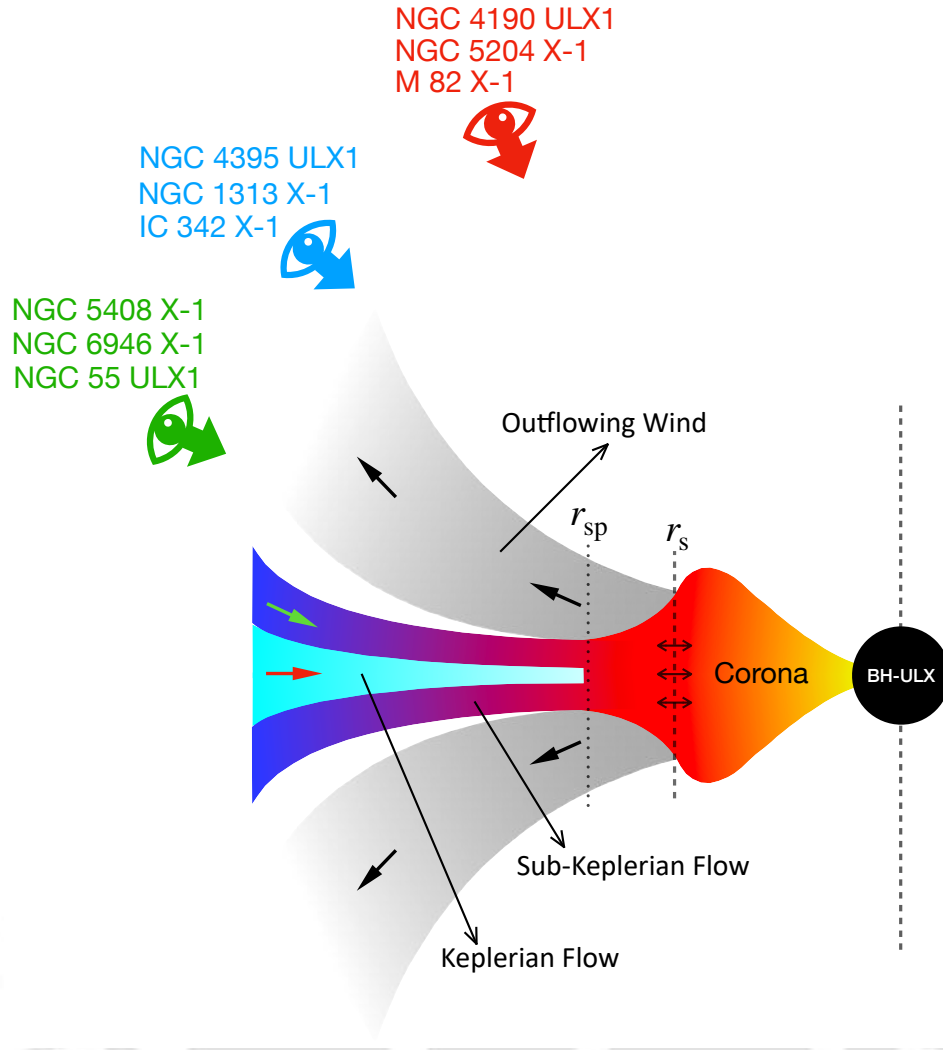


Figure 5.9: Schematic representation of disc-corona-wind regulated two-component accretion scenario of BH-ULXs. Thick arrows in green, blue and red colors represent the viewing angles of the observer corresponding to high, moderate and low inclinations of sources, respectively. The red, green and black small arrows indicate the direction of the Keplerian flow, sub-Keplerian flow and winds. Here, r_s and r_{sp} denote the boundary of the corona and spherization radius. The region $r_{sp} < r < r_s$ refers the geometrically thick ‘slim disc’. The two-sided black arrows show the radial oscillation of the coronal region around r_s . See the text for details.

Fabrika et al. 2021). With this, it is apparent that the emission associated with the Keplerian disc ($r > r_{sp}$) is consistent with the standard disc prediction ($L_{\text{disc}} \propto T_{\text{col}}^4$), whereas the interplay between the inner slim disc and the standard disc at larger radii likely leads to the deviation observed as $L_{\text{disc}} \propto T_{\text{col}}^{1.4}$ for NGC 5204 X–1. As NGC 4190 ULX1 and NGC 5204 X–1 are observed in the HUL state throughout their long-term spectral evolution, the inner Comptonizing corona, which is the source of non-thermal emission, at $r < r_s$ is expected to be visible to the observer, suggesting a low inclination for these two sources (see Fig. 5.9). In addition, the absence of QPO features in NGC 4190 ULX1 and NGC 5204 X–1 possibly indicates that the radial modulation of the coronal region is either absent or very feeble to be detected. A similar accretion scenario seems to be relevant for M82 X–1 with the exception that oscillation of the corona is prominent enough to produce the observed mHz QPOs. Indeed, the prediction of M82 X–1 inclination from the spectral analysis using *XMM-Newton* data could be uncertain because of high contamination. However, it may

be noted that M82 X–1 exhibits coherent mHz QPO features on several occasions that are perhaps associated with the Comptonizing corona. Further, the *Chandra* resolved spectra of the source prefer a slim disc scenario over the standard accretion disc (Brightman et al., 2016a). These evidences possibly suggest that M82 X–1 could be a low inclination system, where the inner Comptonizing corona coupled with a slim accretion disc is visible to the observer, somewhat similar to the case of NGC 5204 X–1.

In the presence of winds, the emitted radiations from the disc interact substantially with the outflowing matter before reaching out to the observer. Due to this, the thermal emission is expected to be cooler with increasing luminosity for super-critical discs in the presence of strong outflowing winds (Poutanen et al., 2007). Considering this, the bolometric luminosity (L_{bol}) is estimated as,

$$L_{\text{bol}} \approx L_{\text{Edd}} \left(1 + \frac{3}{5} \ln \dot{m}\right); \quad T_{\text{col}} \approx 1.5 f_{\text{h}} M_{\text{BH}}^{-1/4} \dot{m}^{-1/2}, \quad (5.1)$$

where T_{col} denote the color-corrected temperature at the spherization radius and $\dot{m}$ is the accretion rate. Note that Eq. 5.1 leads to an anti-correlation between L_{bol} and T_{col} , with a steeper exponent (α) (Poutanen et al., 2007). Furthermore, the outflows from the region $r < r_{\text{sp}}$ appear to remain optically thick, and a part of the energy generated within the disc is carried away by the winds. This process is expected to reduce the disc temperature and modify the disc luminosity.

The relatively flatter negative correlations ($\alpha \sim -3.58$) observed in the HUL state of IC 342 X–1, NGC 1313 X–1, and NGC 4395 ULX1 suggest an accretion-ejection scenario, where the primary emission is significantly influenced by disc winds. However, the existence of the HUL state indicates that a part of the coronal emission is directly accessible to the observer, suggesting a moderate inclination of the sources (see Fig. 5.9, Table 5.7). In contrast, for NGC 55 ULX1, NGC 5408 X–1, and NGC 6946 X–1, the steeper negative correlations ($-10 \lesssim \alpha \lesssim -6$) in the SUL/IUL state likely indicate significant modification of the primary emission due to enhanced winds covering the line of sight. This suggests relatively higher inclinations for these sources (see Fig. 5.9, Table 5.7). In both scenarios, it is plausible that the outflowing winds could carry the imprints of oscillations in the Comptonizing region, as predicted by Das et al. (2014a), thereby providing a self-consistent explanation for the QPO features observed in IC 342 X–1, NGC 1313 X–1, NGC 5408 X–1, and NGC 6946 X–1. However, the irregular appearance of QPOs throughout the entire *XMM-Newton* monitoring of these sources suggests that either the necessary resonance condition for modulating the coronal region is not being satisfied, or the oscillation is weak enough to remain undetected. Moreover, we speculate that the disc-corona-wind symbiosis for the two-component super-critical accretion scenario seems to be realistic to explain the spectro-temporal features of BH-ULXs across different spectral states. We also indicate that radiative pressure-driven winds from the super-critical disc possibly govern the correlation between disc luminosity and temperature, and such correlation depends on the source inclination.

5.6 On the Mass and Accretion State of BH-ULXs

We utilize the observational findings of the four BH-ULXs namely NGC 1313 X–1, NGC 5408 X–1, NGC 6946 X–1 and IC 342 X–1 and estimate their possible mass

(M_{BH}) range in terms of the accretion rate ($\dot{m}$) and the spin (a_*) of the source. Owing to the presence of prominent QPO features, with the QPO frequency serving as a key observable, we restrict our analysis of mass and accretion state to these four sources only. We note that due to contamination from nearby sources in the *XMM-Newton* observation of M82 X-1, the luminosity estimation is unreliable (Majumder et al., 2023), and hence we exclude this source from our study. In addition, we exclude NGC 55 ULX1 from our analysis owing to the low significance of the QPO-like feature. Next, we follow the formalism developed by Das et al. (2021) in order to study the relativistic viscous accretion flow around a rotating black hole. In the work of Das et al. (2021), a model of relativistic, steady, viscous, optically thin, advective accretion flow around a ULX source is developed, where the space-time geometry around the rotating black holes is satisfactorily described using a recently formulated effective potential (Dihingia et al., 2018). With this, we solve the flow equations that govern the vertically averaged flow motion in the presence of radiative coolings, namely, bremsstrahlung, cyclo-synchrotron, and Comptonization processes. While solving the

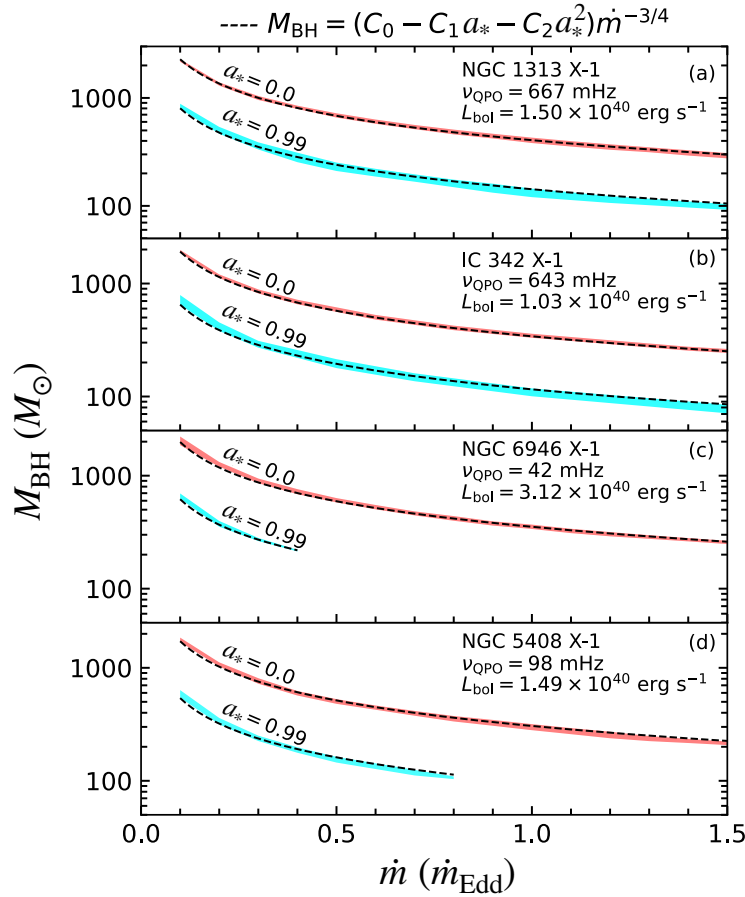


Figure 5.10: Correlation between mass accretion rate ($\dot{m}$) and black hole mass (M_{BH}) for different spin parameters of each source. In each panel, the regions shaded with orange and cyan indicate the mass ranges for spin parameter $a_* = 0.0$ and 0.99 , respectively. The source details and corresponding luminosity and QPO frequency values are also mentioned in each panel. See the text for details.

governing equations, we adopt a closer equation in the form of relativistic equation of state to describe a thermally relativistic flow and calculate the shock induced global

accretion solutions around the BH-ULXs utilizing the input model parameters, namely energy and angular momentum of the flow at the inner critical point, mass accretion rate ($\dot{m}$), mass (M_{BH}) and spin (a_*), respectively. Using the shock properties, *i.e.*, shock location (r_s) and post-shock velocity (v_{sh}), we pragmatically calculate the QPO frequency as $\nu_{\text{QPO}} \sim t_{\text{infall}}^{-1}$, where $t_{\text{infall}} = \int_{r_s}^{r_i} v_{\text{sh}}^{-1} dr$, r_i being the inner edge of the disc (Molteni et al., 1996, Das et al., 2021, and references therein). In addition, we also calculate the bolometric luminosity corresponding to the shocked accretion solutions as $L_{\text{bol}} = 4\pi \int_{r_f}^{r_i} \mathcal{G} Q_c r H dr$, where r_f is the outer edge of the disk, Q_c is the total cooling rates, H is the local disk half-thickness, and $\mathcal{G} (\approx 1 - \frac{2r}{r^2 + a_*^2})$ denotes the gravitational red-shift factor (Das et al., 2021). In this work, total cooling (Q_c) involves bremsstrahlung, cyclo-synchrotron, and comptonization processes (Mandal and Chakrabarti, 2005).

Using the input model parameters, namely energy and angular momentum, we compute the shock induced global accretion solutions for a given set of ($\dot{m}$, M_{BH} , a_*), that provide the observed ν_{QPO} and L_{bol} of the BH-ULX sources. Here, we choose viscosity as $\alpha_s = 0.01$ for the purpose of representation. Subsequently, by tuning energy and angular momentum, we calculate the maximum observed QPO frequency ($\nu_{\text{QPO}}^{\text{max}}$, see Table 5.3) and the corresponding luminosity (L_{bol} , see Table 5.5) of a given BH-ULX source. Here, we consider $\nu_{\text{QPO}}^{\text{max}}$ as a reference frequency to corroborate the theoretical model prediction. The obtained results are presented in Fig. 5.10, where the correlation between the accretion rate ($\dot{m}$) and the mass (M_{BH}) of a given BH-ULXs is depicted as function of a_* . In each panel, regions shaded with orange and cyan colors denote the results computed for $a_* = 0$ and 0.99, respectively. Using these results, we obtain the empirical functional form $M_{\text{BH}} = (C_0 - C_1 a_* - C_2 a_*^2) \dot{m}^{-3/4}$, which is found to vary as seemingly exponential with $\dot{m}$ denoted by the dashed curves. Note that the coefficients C_0 , C_1 and C_2 are source specific and their values depend on a_* as well (see Table 5.8).

In Fig. 5.10a, we depict the results for NGC 1313 X-1, where $\nu_{\text{QPO}}^{\text{max}} = 667$ mHz and $L_{\text{bol}} = 1.50 \times 10^{40}$ erg s $^{-1}$ are considered. With this, we find that the source NGC 1313 X-1 can accrete at both sub- and super-Eddington accretion rate ($0.1 \leq \dot{m} \leq 1.5$). Considering its limiting spin values, we compute the mass range of the central source which is obtained as $275 \lesssim (M_{\text{BH}}/M_{\odot}) \lesssim 2283$ for $a_* = 0$, and $92 \lesssim (M_{\text{BH}}/M_{\odot}) \lesssim 883$ for $a_* = 0.99$, respectively (see Table 5.8). We present the results for IC 342 X-1 in Fig. 5.10b. For this source, we obtain maximum QPO frequency as $\nu_{\text{QPO}}^{\text{max}} = 643$ mHz and the corresponding luminosity as $L_{\text{bol}} = 1.03 \times 10^{40}$ erg s $^{-1}$. We observe that the BH-ULX source IC 342 X-1 may accrete at both sub- and super-Eddington accretion rate ($\dot{m}$) irrespective to its spin value (a_*). Given that the mass of the central source (M_{BH}) is initially seen to decrease rapidly with $\dot{m}$ and then gradually tends to follow its asymptotic value for larger $\dot{m}$. In particular, for $0.1 \leq \dot{m} \leq 1.5$, we obtain $255 \lesssim (M_{\text{BH}}/M_{\odot}) \lesssim 1985$ when $a_* = 0$, and $71 \lesssim (M_{\text{BH}}/M_{\odot}) \lesssim 791$ for $a_* = 0.99$, respectively (see Table 5.8).

In case of NGC 6946 X-1, we consider $\nu_{\text{QPO}}^{\text{max}} = 42$ Hz and $L_{\text{bol}} = 3.12 \times 10^{40}$ erg s $^{-1}$ and obtain the $\dot{m} - M_{\text{BH}}$ correlation by means of the source spin (a_*). The obtained results are presented in Fig. 5.10c, where we observe that the central source accretes at a sub-Eddington accretion rate only ($\dot{m} \lesssim 0.4$) when $a_* \rightarrow 1$. On the contrary, the source can accrete at both sub- and super-Eddington accretion rates provided the central source is weakly rotating ($a_* \rightarrow 0$). Considering this, we obtain the limiting range of the source mass and the results are obtained as $248 \lesssim (M_{\text{BH}}/M_{\odot}) \lesssim 2221$

Table 5.8: Coefficients of the fitted functional form $M_{\text{BH}} = (C_0 - C_1 a_* - C_2 a_*^2) \dot{m}^{-3/4}$ along with the black hole mass and accretion rate correlation for spin parameter $a_* = 0.0$ and 0.99 . The obtained mass and accretion rate ranges are also tabulated for each source.

Source	$\nu_{\text{QPO}}^{\text{max}}$ (mHz)	L_{bol} ($10^{40} \text{ erg s}^{-1}$)	$a_* = 0$			$a_* = 0.99$			M_{BH} ($M_{\odot}$)	Remarks
			C_0	M_{BH}	Remarks	C_0	C_1	C_2		
NGC 1313 X-1	667	1.50	405.73	275 – 2283	$\dot{m} \lesssim \dot{m}_{\text{Edd}}$	352.73	31.83	182.32	92 – 883	$\dot{m} \lesssim \dot{m}_{\text{Edd}}$
IC 342 X-1	643	1.03	340.82	255 – 1985	$\dot{m} \lesssim \dot{m}_{\text{Edd}}$	336.78	54.72	170.36	71 – 791	$\dot{m} \lesssim \dot{m}_{\text{Edd}}$
NGC 6946 X-1	42	3.12	352.72	248 – 2221	$\dot{m} \lesssim \dot{m}_{\text{Edd}}$	325.72	37.51	182.24	214 – 696	$\dot{m} < \dot{m}_{\text{Edd}}$
NGC 5408 X-1	98	1.49	305.61	207 – 1851	$\dot{m} \lesssim \dot{m}_{\text{Edd}}$	315.54	28.62	195.21	104 – 635	$\dot{m} < \dot{m}_{\text{Edd}}$

Note: $M_{\odot}$ refers the solar mass, and $\dot{m}_{\text{Edd}}$ denotes the Eddington accretion rate

when $a_* = 0$, and $214 \lesssim (M_{\text{BH}}/M_{\odot}) \lesssim 696$ for $a_* = 0.99$, respectively (see Table 5.8). For NGC 5480 X-1, we choose $\nu_{\text{QPO}}^{\text{max}} = 98 \text{ Hz}$ and $L_{\text{bol}} = 1.49 \times 10^{40} \text{ erg s}^{-1}$ and compute $\dot{m} - M_{\text{BH}}$ correlation in terms of the spin parameter (a_*). The results are shown in Fig. 5.10d, where we find that the central source accretes at a sub-Eddington accretion rate ($\dot{m} \lesssim 0.8$), provided it is rapidly rotating ($a_* \rightarrow 1$). However, if the central source is weakly rotating ($a_* \rightarrow 0$), it may accrete at both sub- and super-Eddington accretion rates. For this source, the mass range is calculated as $207 \lesssim (M_{\text{BH}}/M_{\odot}) \lesssim 1851$ when $a_* = 0$, and $104 \lesssim (M_{\text{BH}}/M_{\odot}) \lesssim 635$ for $a_* = 0.99$, respectively (see Table 5.8).

5.7 Summary

In this Chapter, we carry out a comprehensive analysis of the long-term evolution of eight BH-ULXs using *XMM-Newton* observations. Our findings provide compelling evidence for varied accretion scenarios that can explain the observed spectro-temporal variabilities seen in the selected BH-ULXs. The key results from our investigation, along with their potential implications, are summarized below.

- Out of the eight BH-ULXs, we reconfirm the presence of significant QPO features in five sources (NGC 1313 X-1, M82 X-1, NGC 5408 X-1, NGC 6946 X-1 and IC 342 X-1) in the frequency range of 8.4 – 667.3 mHz, while NGC 55 ULX1 shows a possible QPO-like feature at $\sim 20 \text{ mHz}$.
- The decadal long-term spectral evolution of the eight BH-ULXs reveals distinct spectral states for the sources. More specifically, we find the presence of hard-ultraluminous state (HUL) in NGC 5204 X-1, IC 342 X-1, NGC 4190 ULX1, and NGC 1313 X-1, respectively. In contrast, NGC 6946 X-1 exhibits a typical soft-ultraluminous state (SUL), whereas intermediate-ultraluminous state (IUL) is observed for NGC 55 ULX1 and NGC 5408 X-1.
- The positive correlation of $L_{\text{disc}} \propto T_{\text{col}}^{1.4}$ observed for NGC 5204 X-1 suggests a transition from the standard geometrically thin disk ($H/r \ll 1$) to a slim disk ($H/r \lesssim 1$) prescription at relatively higher luminosities in the HUL state.

This behavior is reminiscent of an accretion scenario where both Keplerian and sub-Keplerian flow components coexist.

- A steeper negative correlation with $-10 \lesssim \alpha \lesssim -6$ between L_{disc} and T_{col} is observed for sources NGC 6946 X-1, NGC 55 ULX1, NGC 5408 X-1, which exhibit softer and intermediate spectral characteristics. In contrast, a relatively flatter anti-correlation with $\alpha \sim -3.58$ is seen for IC 342 X-1 and NGC 1313 X-1, which display harder spectral features.
- The diverse $L_{\text{disc}} - T_{\text{col}}$ correlations along with the overall spectro-temporal characteristics suggest a connection with the disc-corona-wind regulated two-component super-critical accretion scenario. Such a scenario is also potentially viable to explain the observed QPO features in BH-ULXs. In particular, we infer that the anti-correlations are possibly resulted due to the modification of disc emissions by the outflowing winds, which is also likely to be influenced by moderate to high inclinations of the respective BH-ULXs.
- Based on the proposed model of the accretion dynamics of BH-ULXs, we attempt to constrain the mass and accretion state of some of the sources in our sample. In particular, we find that NGC 6946 X-1 and NGC 5408 X-1 appear to accrete at sub-Eddington rates, provided their central sources are rapidly rotating. In contrast, IC 342 X-1 and NGC 1313 X-1 can accrete at sub- or super-Eddington rates, irrespective of their spin values. Moreover, we find that the BH-ULXs considered in this work can harbour massive stellar-mass to intermediate-mass black holes at their central core.



Summary and Conclusions

Accretion is the fundamental process that powers a wide range of astrophysical compact objects. Out of this, BH-XRBs and BH-ULXs serve as natural laboratories to probe accretion physics and test the effects of strong gravity. Despite several decades of extensive studies, the geometry, emission processes, and variability signatures of these systems are still not fully understood, leading to significant research opportunities. Motivated by these persistent challenges, this thesis focuses on investigating the accretion dynamics of several BH-XRB and BH-ULX sources using high quality observational data from various space-based X-ray astronomy missions. As a foundational step, **Chapter 1** introduces the basic principles of accretion onto black holes along with relevant theoretical frameworks. It also covers the discussion on radiative processes that are relevant in such extreme environments near black holes. In **Chapter 2**, we present the techniques and methodologies employed throughout this thesis, with a focus on the key analysis domains in X-ray astronomy: imaging, timing, spectroscopy, and polarimetry. With this background, we then move on to the main research chapters of the thesis.

In **Chapter 3**, we investigate the fast spectro-temporal variability of galactic BH-XRBs across different timescales. As a case study, we first examine the variability signatures of the BH-XRB transient Swift J1727.8 – 1613, using quasi-simultaneous data from *AstroSat* and *NICER* missions. The source was discovered during its first outburst in 2023 by *Swift*/BAT with an exceptionally high flux level of ~ 7 Crab. *AstroSat* captured the source in the early rising phase of the outburst, specifically during the HIMS. Using unique capabilities of the *AstroSat*/LAXPC instrument, we detect LFQPOs in Swift J1727.8 – 1613 over the hard X-ray band (up to ~ 100 keV) for the first time in the *AstroSat* era. Furthermore, a rapid evolution of the QPO frequency from 0.4 Hz to 2.7 Hz over a time span of just ~ 25 days is observed. Interestingly, both *NICER* and *AstroSat* observations reveal a strong thermal Comptonization component in the emission spectra within the 0.7 – 40 keV energy range. Specifically, the energy spectrum is seen to be dominated by Comptonized photons, contributing nearly 80% of the total emission. This results in a relatively hard spectral shape, characterized by a photon index $\Gamma_{\text{nth}} < 2$, along with a weak signature of a disc component with a temperature of ~ 0.4 keV. Collectively, these observational findings point towards the accretion dynamics of the source in the HIMS, characterized by a weak disc located far from the black hole and a large scale corona in the equatorial plane dominating the emission at higher energies. Accordingly, the evolving LFQPOs observed in hard

X-rays are likely associated with radial aperiodic modulations at the boundary of the coronal region. Notably, the QPO oscillation timescale roughly matches the infall timescale of accreting matter from the corona to the black hole (Molteni et al., 1996, Chakrabarti et al., 2008). As the outburst progresses, the mass accretion rate gradually increases in BH-XRBs, causing the accretion disc to move closer to the black hole and thereby reducing the size of the coronal region. This, in turn, decreases the oscillation timescale, resulting in a gradual increase in the LFQPO frequency over time, as observed for Swift J1727.8 – 1613.

In the second part of **Chapter 3**, we investigate the HFQPO phenomena in the galactic BH-XRB GRS 1915 + 105. To this end, we utilize *AstroSat* observations of the source spanning about five years. Power spectral analysis reveals the presence of HFQPO features at ~ 70 Hz in five softer variability classes, namely δ , γ , ω , κ and τ . Further, our study reports the detection of the new variability class (τ) in GRS 1915 + 105, characterized by aperiodic low-count dips, spike-like features in the light curve, and twin-peak HFQPO signatures at ~ 70 Hz and ~ 152 Hz in the power spectra. Notably, the HFQPOs exhibit strong energy dependence and appear only in the 6 – 25 keV energy band, which suggests that photons within this energy range participate in the observed oscillation. Further, we examine the spectral characteristics of the source using broadband (0.7 – 50 keV) energy spectra obtained from *SXT* and *LAXPC* instruments onboard *AstroSat*. It is observed that in the presence of HFQPOs, the effects of thermal Comptonization remain prominent in the energy spectra up to ~ 25 keV, beyond which a powerlaw component dominates the spectral distribution. This possibly indicates the presence of a compact corona in the inner region of the accretion disc, surrounded by an extended corona. Furthermore, the HFQPOs are found to be associated with the high-count (non-dip) intervals in the light curves of the ω and κ class observations, whereas they are absent during the low-count (dip) segments. A deeper analysis of the spectral characteristics over the dip and non-dip intervals suggests that the non-dip durations are generally associated with harder spectral components compared to the dip durations (see Harikesh et al. 2025 for details). In addition, it is found that the radial extent of the compact corona remains $\lesssim 6 r_g$ in the presence of HFQPOs during the high-count duration in the light curve (Harikesh et al., 2025). Moreover, we deduce spectro-temporal correlation between *rms* amplitude of HFQPOs and the characteristics of emission spectra and infer that Comptonization possibly plays a viable role in the generation of HFQPOs. Overall, these results suggest a accretion disc-corona system emitting in the sub-Eddington regime ($L_{\text{bol}} \sim 9 - 29\% L_{\text{Edd}}$), involving a compact corona located very close to the black hole (within $\lesssim 6 r_g$) during softer variability classes of GRS 1915 + 105. Furthermore, the radial oscillations of this compact corona plausibly give rise to the rapid temporal variability observed in the form of HFQPOs.

In Chapter 3, we investigated the fast timing variabilities, such as LFQPOs and HFQPOs, in galactic BH-XRBs and explored their association with the Comptonizing corona located in the equatorial plane of the accretion disc system. However, the geometry of the corona in BH-XRBs has remained a subject of debate for several decades. Motivated by this, **Chapter 4** focuses on the accretion-ejection geometry and dynamics of eleven BH-XRBs through a comprehensive study combining X-ray spectro-polarimetry and timing analysis. For this study, we consider multi-mission X-ray observations from *IXPE*, *NICER*, *NuSTAR*, *AstroSat*, *MAXI/GSC* and *Swift/BAT* of nine galactic BH-XRB candidates namely Cyg X–1, 4U 1957 + 115, 4U 1630 – 47,

Swift J1727.8–1613, IGR J17091–3624, MAXI J1744–294, Swift J151857.0–572147, GX 339–4, and Cyg X–3 along with two extragalactic black hole sources: LMC X–1 and LMC X–3. A detailed timing study of the sources reveals the presence of LFQPOs and power spectral breaks in the LHS, HIMS, and SIMS of IGR J17091–3624, Cyg X–1, Swift J1727.8–1613 and GX 339–4, respectively. In contrast, the remaining sources exhibit negligible variability in the power density spectra during canonical soft state. Modeling of the energy spectra of these sources using accretion disc and thermal Comptonization components further confirms the presence of distinct canonical spectral states, namely LHS, HIMS, SIMS, SPL and HSS, each characterized by variations in spectral parameters such as photon index (Γ_{th}), covering fraction (cov_{frac}) and relative flux contributions of different components. This suggests that the accretion dynamics and the associated spectral states of the sources are predominantly regulated by the relative emission contributions from the disc and corona. Moreover, we find that the Comptonized emission arising from both spherical and disc-like coronae adequately fits the spectra of the sources. In addition, during HSS of GX 339–4, Swift J1727.8–1613, and Cyg X–1, we detect strong reflection features, including a prominent iron $K\alpha$ emission line around ~ 6.4 keV and a reflection hump extending beyond ~ 20 keV. These features are explained by the reflection of coronal emission, arising from either a spherical or lamppost geometry. Collectively, these results suggest a possible degeneracy in constraining the disc-corona geometry in BH-XRBs.

Next, we study the polarimetric properties of the sources by estimating the polarization degree (PD) and polarization angle (PA). Out of the eleven sources, a significant degree of polarization is detected in eight, whereas the remaining three sources do not show polarization signatures. Our study reports the first ever detection of X-ray polarization in the extragalactic BH-XRB source LMC X–3, along with a non-detection in MAXI J1744–294. We find that PD spans a range of 1.2–21.4% across various sources and spectral states. Notably, 4U 1630–47 exhibits a PD of $\sim 8.4\%$ in a purely disc-dominated thermal state, whereas IGR J17091–3624 shows a PD of $\sim 9\%$ in the LHS, the highest reported for any confirmed BH-XRB to date. Furthermore, we find that PD exhibits a strong energy dependence ($\gtrsim 4\sigma$) in Cyg X–1, 4U 1630–47, and Cyg X–3, whereas a moderate dependence ($< 3\sigma$) is observed in Swift J1727.8–1613 and 4U 1957+115. We also study spectro-polarimetric correlation and find that, for most of the sources with some exceptions, PD tends to increase with the strength of Comptonized emission, as indicated by an increase in the covering fraction (cov_{frac}) and a corresponding decrease in the disc flux. The overall findings suggest that PD is primarily contributed by Comptonization in Cyg X–1, IGR J17091–3624, Swift J1727.8–1613, and GX 339–4, whereas disc emission appears to play a dominant role in 4U 1630–47, LMC X–3, and 4U 1957+115. Furthermore, the polarization angle is found to align with the radio jet position angle in Cyg X–1, Swift J1727.8–1613, and GX 339–4. Given that the polarization degree is primarily contributed by the corona, these results favor a horizontally extended wedge shaped corona located in the equatorial plane of the accretion disc. For this, the emission is dominated by vertically polarized photons, those scattered sideways at 90° . Notably, the LFQPOs detected in various sources can plausibly be attributed to the modulation of the coronal boundary, which further supports the above geometry. However, for 4U 1630–47, 4U 1957+115 and LMC X–3, the coronal geometry remains inconclusive due to the absence of resolved radio jets and the marginal contribution of coronal emission in the polarimetric data. At the same time, for LMC X–1, MAXI J1744–294, and

Swift J151857.0 – 572147, the polarimetric data fail to provide additional insights into the disc-corona geometry, showing a null detection of significant X-ray polarization. Finally, we note that although the interplay between a standard thin accretion disc and a wedge shaped corona in the equatorial plane is preferred for most of the sources across various spectral states, several ambiguities still persist in explaining all the observational findings.

Building on the insights gained from the study of spectro-temporal variabilities in BH-XRBs presented in the previous two chapters, in **Chapter 5**, we undertake an in-depth study of nine extragalactic BH-ULXs, namely NGC 1313 X–1, NGC 5408 X–1, NGC 6946 X–1, IC 342 X–1, NGC 55 ULX–1, NGC 4395 ULX–1, NGC 5204 X–1, M82 X–1, and NGC 4190 ULX–1, using decade-long *XMM-Newton* observations. The primary goal of this study is to probe the accretion dynamics and constrain the black hole masses in these systems. We begin by analyzing the temporal variability of all the sources and find that they exhibit significant short-term variability amplitudes throughout the long-term monitoring. Out of the nine sources, we detect QPO features of frequency 8 – 667 mHz in five (NGC 1313 X–1, NGC 5408 X–1, NGC 6946 X–1, IC 342 X–1, and M82 X–1), along with a QPO-like peak in NGC 55 ULX–1. The energy spectra obtained from the *EPIC* data onboard *XMM-Newton* for each source are modeled using the combination of thermal Comptonization and standard disc components. This results in a more physically motivated description of the spectra as compared to the commonly used twin disc models for ULXs. More precisely, the results indicate the presence of a ‘cool’ ($k_B T_e \sim 2$ keV) and optically thick ($\tau \sim 8 - 20$) corona in the vicinity of the accretion disc. Further, a detailed correlation study between the disc luminosity (L_{disc}) and the color-corrected inner disc temperature (T_{col}), described by the relation $L_{\text{disc}} \propto T_{\text{col}}^\alpha$, reveals both positive and negative trends in the $L_{\text{disc}} - T_{\text{col}}$ plane. This, in turn, indicates complex accretion dynamics in these sources. In particular, the positive correlations characterized by $0 < \alpha < 4$ appear consistent with the transitions from standard to slim accretion disc configurations. In contrast, the anti-correlations, exhibiting a range of negative powerlaw exponents ($-10.3 < \alpha < -3.6$), are plausibly resulted from the modification of the direct disc-corona emission by strong disc winds, which are commonly observed in ULXs. Furthermore, we investigate the long-term evolution of the emission characteristics of each source and identify the presence of three spectral states: soft-ultraluminous state (SUL), hard-ultraluminous state (HUL), and intermediate-ultraluminous state (IUL) in different sources. Collectively, the mHz QPO features, spectral states, and correlation properties favor disc-corona-wind driven accretion scenarios for BH-ULXs, observed at low to high system inclinations for various sources. Finally, we employ a model formalism describing relativistic, advective accretion flows around black holes to explain the observed QPO frequencies and bolometric luminosities, and to constrain the mass, spin, and accretion regime of the sources. Based on this analysis, some sources (NGC 6946 X–1 and NGC 5408 X–1) appear to accrete at sub-Eddington rates, provided their central black holes are rapidly rotating, whereas others (IC 342 X–1 and NGC 1313 X–1) can accrete at sub- or super-Eddington rates irrespective of their spin values.

In a nutshell, this thesis investigates the variability properties of various BH-XRB and BH-ULX sources across galactic and extragalactic scales using multi-mission X-ray observations. The study yields several key insights into their accretion dynamics, which are expected to enrich the theoretical frameworks of black hole accretion physics.

However, the findings presented across different chapters of this thesis bear certain limitations. For instance, in Chapter 4, our results are unable to explain the disc-corona configurations in some of the selected BH-XRBs due to limited observational constraints. Similarly, in Chapter 5, we propose a disc-corona-wind driven accretion scenario for BH-ULXs, depending on system inclination, varying from low to high. However, the inclinations remain poorly constrained due to the non-detection of optical counterparts for most the BH-ULXs. These limitations frame the future research directions, which we discuss in the next chapter.





Future Prospects

As pointed out in Chapter 4, X-ray timing and spectral studies provided glimpses into the accretion-ejection geometry of BH-XRBs, though with notable limitations over the past few decades. These limitations are mostly due to the degeneracy between different models of accretion disc-corona geometry while explaining the observations. For example, in our study, we observe that the broadband energy spectral distribution of the sources is best described by thermal Comptonization models assuming alternative coronal geometries, such as spherical and disc-like configurations (see Chapter 4). Furthermore, the prominent reflection features observed in the HSS of Cyg X–1, GX 339–4, and Swift J1727.8–1613 are found to be delineated by the reflected component from high energy coronal emission, originating from spherical and lamppost geometries of the corona. The inherent degeneracy in determining the disc-corona geometry becomes even more complex when considering the origin of simultaneously observed distinct temporal features, including QPOs (see Chapter 4). In this context, X-ray polarization studies emerge as a powerful tool to provide additional insights into the accretion-ejection dynamics and geometries in BH-XRBs.

Indeed, the first X-ray polarization measurements were conducted in the 1970s by *OSO-8*, revealing significant polarization in Cyg X–1 with PD $\sim 2.4\%$ at 2.6 keV and $\sim 5.3\%$ at 5.2 keV (Long et al., 1980). Although several missions since then including the *Einstein* Observatory and *Spectrum-X* were planned to carry X-ray polarimeters, none of them ultimately succeeded in launching one (Weisskopf et al., 2006). Thereafter, higher polarization was observed in hard X-rays for Cyg X–1 with *INTEGRAL* as $\lesssim 20\%$ in the 130 – 230 keV band (Jourdain et al., 2012) and $\sim 75\%$ above 400 keV (Rodriguez et al., 2015). Understandably, this four decade gap occurred primarily due to technical limitations in detector design and sensitivity, as X-ray polarimetry requires highly sensitive instruments with specialized detectors, a task far more challenging than X-ray spectroscopy or timing techniques (Weisskopf et al., 2006). Recently, Chattopadhyay et al. (2024) detected $\sim 23\%$ polarization in the HIMS of Cyg X–1 above ~ 100 keV using *AstroSat/CZTI*. Despite these advances, low-energy X-ray polarimetry remained relatively underexplored until the launch of *IXPE* (Weisskopf et al., 2022), which has made substantial progress in this domain during its first three and a half years of operation (Dovčiak et al., 2024). Nevertheless, several fundamental questions remain unanswered, paving the way for future research.

At present, Swift J1727.8 – 1613 is the only BH-XRB transient observed during its outburst with *IXPE* exhibiting polarization over four spectral states (HIMS, SIMS,

HSS and LHS) along with QPO features. To establish robust spectro-polarimetric correlations across different spectral states, coordinated *IXPE* observations along with simultaneous spectro-temporal coverage from other missions are indispensable. Further, since the effects of Comptonization become prominent beyond the coverage of *IXPE* up to 8 keV, complementary wideband X-ray spectro-polarimetry and timing studies are crucial to constrain the coronal geometry. Thus, the four windows of X-ray astronomy (imaging, timing, spectroscopy and polarimetry) with wide energy coverage are crucial to unravel the complete understanding of BH-XRBs.

In this context, the recently launched *X-ray Polarimeter Satellite (XPoSat)*¹ mission (Paul, 2022) and the *XL-Calibur* mission (Abarr et al., 2021) are set to play a crucial role in investigating polarimetric properties of BH-XRBs in medium to hard X-rays. In particular, *POLIX* (8 – 30 keV) and *XSPECT* (0.8 – 15 keV) onboard *XPoSat* are suitable for medium energy polarimetry and simultaneous spectro-temporal studies, respectively. The balloon-borne *XL-Calibur* mission, operating in 15 – 80 keV energy range, completed a successful flight² in July 2024, aiming to measure polarization in Cyg X–1. This eventually led to the recent measurement of a polarization degree of $\sim 5\%$ in the LHS of Cyg X–1 in $\sim 19 - 64$ keV energy range (Awaki et al., 2025), which is comparable to the low energy (2 – 8 keV) polarimetric results of Cyg X–1 (PD $\sim 4.8\%$) in the LHS observed with *IXPE* (see Chapter 4). The consistency of the measured PDs and PAs across the 2 – 64 keV range observed with *IXPE* and *XL-Calibur* indicates that the same underlying physical processes likely govern the observed polarization in both energy bands. However, the sharp rise in polarization beyond ~ 100 keV observed with *AstroSat* for Cyg X–1 indicates that the underlying physical processes undergo a significant change at hard X-ray energies. Most likely, the low to semi-hard X-ray polarization (< 100 keV) in Cyg X–1 is associated with Comptonized emission, with a significant contribution from reflection, whereas the polarization at very hard X-rays (> 100 keV) is possibly attributable solely to the jet component (Awaki et al., 2025). These recent developments in X-ray polarimetry open up new challenges and prospects, guiding future research directions. Additionally, the future soft X-ray spectro-polarimetric mission *eXTP*³ (2 – 10 keV), expected to launch in 2030, will offer improved sensitivity for low energy polarization measurements. Needless to mention that these dedicated missions will significantly advance our understanding of the accretion dynamics and coronal geometries in BH-XRBs. However, simultaneous observations combining wideband timing and spectro-polarimetric measurement are still lacking, which emphasizes the need for future missions with broader energy ranges and enhanced capabilities.

Apart from observational constraints, theoretical predictions of X-ray polarization from alternative disc-corona configurations help to constrain the geometry and explain the observed findings. Meanwhile, several models have been proposed to explain the polarimetric results of some BH-XRBs observed with *IXPE* (see Poutanen et al. 2023, Dexter and Begelman 2024, Nitindala et al. 2025 and references therein). However, most of these models have their limitations and, more importantly, fail to explain the simultaneously observed timing properties. Thus, the development of sophisticated spectro-polarimetric models is essential, serving as a key stepping stone toward resolving the disc-corona geometry in BH-XRBs.

¹<https://www.isro.gov.in/XPoSat.html>

²<https://sscspace.com/nasa-xl-calibur-balloon-launched/>

³<https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/extp.html>

On the other hand, ULXs are often found to eject strong radiation pressure-driven disc winds under a super-Eddington accretion scenario, which are expected to interact with the ambient medium. These outflows demand prime importance in X-ray astronomy because of their rich characteristics and potential impact in probing the physics of ULXs. In general, these outflows leave footprints in high-resolution X-ray spectra in the form of absorption and/or emission lines, which correspond to the atomic transitions of various astrophysical metals, including the most abundant element, iron. Modeling of such spectral features using different photoionization models reveals a wealth of information about the ionization state of the plasma, the velocity of the outflowing winds, the launching radius, and the associated column density. So far, a number of studies have been conducted using high-resolution *Chandra* grating and *XMM-Newton*/RGS spectra of ULXs (Kosec et al., 2018, Pinto and Kosec, 2023). However, several ambiguities remain in constraining the parameters that describe wind properties, arising from the limited spectral resolution of existing previous missions (Pinto and Kosec, 2023). In this context, the recently launched, highly sophisticated, microcalorimeter-based high-resolution X-ray spectroscopic mission *X-Ray Imaging and Spectroscopy Mission (XRISM)* (Tashiro, 2022) is expected to play a pivotal role, offering an enhanced spectral resolution ($\lesssim 7$ eV FWHM at 6 keV) (Mochizuki et al., 2024) that is nearly five times better than that of previous instruments. Similarly, the upcoming ESA-led mission *NewAthena* (Cruise et al., 2025), expected to launch in 2037, is anticipated to bring a revolution in the study of compact objects with its most sophisticated microcalorimeter based observational techniques.

Considering these future prospects, I aim to address the challenges and limitations outlined above in the study of accretion powered compact objects, building on the expertise and insights gained through the research conducted in this thesis.

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