INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
SHORT ABSTRACT OF THESIS

Name of the Student	:	Seshadri Majumder
Roll Number	:	196121111
Programme of Study	:	Ph.D.

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

Name of Thesis Supervisor(s)	:	Dr. Santabrata Das & Dr. Anuj Nandi
Thesis Submitted to the Academic Division	:	Physics
Date of completion of Thesis Viva-Voce Exam	:	17-10-2025
Key words for description of Thesis Work	:	Accretion Physics, Accretion Disc, Black Hole Physics, X-ray Polarization, Radiation Mechanisms, X-rays Binaries, Ultraluminous X-ray Sources

SHORT 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, coronae 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_disc-T_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.