Various manifestations of accretion onto stellar-mass black holes

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

by

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INDIAN INSTITUTE OF TECHNOLOGY GANDHINAGAR

to *my family*

Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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I have read this dissertation and in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

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(Sandeep Kumar Rout)

Abstract

The very definition of black holes makes their study extremely challenging by using electromagnetic waves as conventionally done for other astronomical objects. It is only through their impact on matter within their gravitational influence that any reasonable understanding about them can be obtained. Accretion of matter onto black holes results in X-ray emission and such X-ray observations provide the best opportunity to study their properties. The only other possibility being a study of black hole mergers using gravitational waves, which is still a nascent field. As a corollary, black hole accretion systems also provide fertile conditions for understanding the complicated process of accretion.

X-ray binaries with black hole as a component exhibit rich phenomenology in radiation due to accretion of mass from the companion star. The X-ray spectrum of a black-hole binary consists of three main components, i.e., thermal emission from the disk, power law due to inverse Comptonization of the disk photons from geometrically thick and optically thin cloud of electrons (called as corona), and reflected emission of the Comptonized hard photons that hit the disk. Likewise, a power spectrum, which is the Fourier transform of a time series, consists of many peaked and broad noise components. Following five decades of extensive study, these aspects of black-hole binary outbursts stand on a fairly strong observational footing. In general, the process of state transition during an outburst and the associated spectral and timing variability are reasonably well understood, although, every now and then some exceptions crop up. Despite considerable advancement in understanding the phenomenology, some fundamental questions regarding the inner geometry of the accretion flow and the origin of certain observed phenomena remains debatable.

The accretion disk in the vicinity of a black hole is strongly influenced by two of its fundamental properties - mass and angular momentum (or spin), which makes their accurate measurement extremely important. Mass and spin estimates of a large sample of black holes are also necessary for constraining the stellar evolution theories. The best measurement of mass is done using the dynamical methods i.e., by measuring the radial velocity of the secondary star from Doppler shifted lines and feeding it to the binary mass function. However, in many cases the secondary is too faint to be detectable. An estimate of mass can also be obtained by correctly modeling the thermal X-ray emission from the accretion disk during a disk-dominant state. The measurement of spin is more tricky. It can either be done by modeling the fluorescent Fe K α line reflected from the inner accretion disk or by modeling the soft X-ray continuum. This is based on the rationale that the inner boundary of the accretion disk is determined by spin of the black hole. The measurement of the spin is also important as it can constrain the models positing that the jets are powered by the spin of the black hole.

In order to gain deeper insights into the accretion process we have studied black-hole binaries using X-ray spectroscopy and timing analysis as primary tools. We analyzed three low-mass X-ray binaries, namely GRS 1716–249, MAXI J1631–479, and MAXI J1659–152 and one high-mass X-ray binary, namely Cygnus X–1, using data from six X-ray observatories and one ground based infrared telescope. With our work, we were able to comprehend the geometry of the inner accretion flow by studying the properties of the QPOs in MAXI J1631–479. We have delineated the radiation emitting from inner accretion region in GRS 1716–249. We have also constrained the two fundamental parameters of a black hole, i.e., spin and mass, for two systems -MAXI J1659–152 and MAXI J1631–479, which has far reaching consequences on the binary evolution and jet propagation theories.

Keywords: X-ray binaries, accretion disks, black holes, quasi-periodic oscillations, general theory of relativity

List of Publications

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- 5. Sandeep K. rout, Santosh Vadawale, et al., "AstroSat view of Cygnus X–1 during the 2017 hard to soft transition", under preparation.

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Chapter 1

Introduction

1.1 Black hole X-ray binaries

1.1.1 Historical overview

Black holes are one of the most enigmatic objects in the universe. The conception of these objects dates back to the late 18th century when Michell (1784), and later independently Laplace (1799), speculated the existence of stars so massive that even lights cannot escape their gravitational pull. An increased confidence in Newton's particle theory of light and Ole Rømer's discovery of the finiteness and subsequent calculation of the speed of light (c) led these early pioneers conjecture that if the escape velocity of a star ($v_{esc} = \sqrt{2GM/R}$, where G is the gravitational constant, M is the mass, and R is the radius) equals c, then that star would become invisible. Therefore, such objects were referred to as *dark stars*. By substituting c for v_{esc} , the radius of the so-called *dark star* can be written as

$$R_s = \frac{2GM}{c^2} \quad . \tag{1.1}$$

Michell (1784) calculated that a star, having the same density as the Sun and radius 500 times would be so massive that light particles originating from it would return back to the star due to its own gravity. He also noted that such stars could be detected by their gravitational effects on other visible bodies (Montgomery et al., 2009). Further development had to wait for over a century until Schwarzschild (1916) presented the

first exact solution for the gravitational field of a stationary mass in vacuum using Einstein's general theory of relativity (see Schwarzschild, 1999, for an English translation by S. Antoci and A. Loinger). Two notable aspects of his solution are (1) the existence of a singularity at the centre, i.e., at radius r = 0, where the space-time curvature becomes infinite and ill defined and (2) the presence of a hypothetical sphere, known as event horizon, with radius given by equation 1.1 from the surface of which nothing can escape. Schwarzschild's solution was improved and reinterpreted during the following decades by several researchers to pave the way for the explanation of, what we now know as, black holes (e.g., Eddington, 1924; Finkelstein, 1958). For the inception of an event horizon, according to the condition in equation 1.1, a given mass has to be squeezed into its Schwarzschild radius. As an illustration, the Sun has to be compressed into a sphere of radius 3 km to become a black hole. Oppenheimer & Snyder (1939) showed for the first time how a spherically symmetric collapse of a non-rotating star, after the exhaustion of its nuclear fuel, could form an event horizon from within which even light cannot escape. Owing to the simplicity of their assumptions, which were of course unreal, doubts lingered on about the physicality of such collapses. However, Penrose (1965) decisively proved that the space-time singularities were an inevitability even after discounting spherical symmetry. In 2020, Roger Penrose received Nobel prize in physics for the above work along with Andrea Ghez and Reinhard Genzel for discovering the supermassive black hole at the centre of Milky Way.

Meanwhile, significant development was underway toward the understanding of compact objects and collapsing stars. Chandrasekhar (1931) had calculated the maximum mass of a white dwarf which could balance the gravitational pull with electron degeneracy pressure (see Schatzman, 1958). A similar limit for neutron stars was calculated by Oppenheimer & Volkoff (1939) drawing upon the work of Tolman (1939) (hence, the name Tolman-Oppenheimer-Volkoff limit), where the neutron degeneracy pressure balanced the star's self gravitation (see Bombaci, 1996; Kalogera & Baym, 1996, for an updated limit). Not much before Baade & Zwicky (1934) had proposed the existence of neutron stars as a consequence of supernova explosions. In the early 1960s, the high redshift of radio galaxies, such as 3C 273 and 3C 48, had prompted the proposition of very distant and powerful objects (Schmidt, 1963; Greenstein, 1963; Greenstein & Schmidt, 1964; Lynden-Bell, 1969). In 1964, Edwin Salpeter and Yakov Zeldovich suggested that the properties of these quasi-stellar objects, or quasars, could be explained by matter falling onto massive compact objects (Salpeter, 1964; Shields, 1999). Their idea was not widely accepted as black holes were still considered to be too exotic. This was to change with the advancement in radio and X-ray astronomy. Shklovsky (1967) identified the first extra-solar X-ray source Sco X–1 (Giacconi et al., 1962) to be a neutron star. In the same year Jocelyn Bell discovered radio pulsations from the pulsar PSR B1919+21 (Hewish et al., 1968). Toward the end of 1960s, people had started taking seriously the idea of compact objects and even supermassive black holes (Wolfe & Burbidge, 1970). The galactic X-ray source Cygnus X–1 was the first object identified to host a black hole (Giacconi et al., 1967; Bolton, 1972; Webster & Murdin, 1972; Shipman, 1975). Since their discovery, black holes have been found to exist in variety of astronomical objects and having a wide range of mass (Kormendy & Richstone, 1995; Celotti et al., 1999; McClintock et al., 2006; Remillard & McClintock, 2006; Done et al., 2007; Kormendy & Ho, 2013).

As predicted by Salpeter & Zeĺdovich, the process of mass accretion was established with a firm footing as the primary source of radiation from compact objects (Prendergast & Burbidge, 1968; Pringle & Rees, 1972; Thorne & Price, 1975). Binary stars, hosting a compact object at their centre and emitting most of their energy in X-rays, played a significant role in understanding of the process of accretion. The study of these systems, known as X-ray binaries, is therefore essential in understanding accretion and its geometry surrounding the compact objects. Additionally, accretion around black holes serves as excellent laboratories for testing Einstein's theory of general relativity in the strong field limit. This is because the inner accretion disk can reach as close as $\sim 2 - 10 R_g$ from the black hole and emission from there experiences strong relativistic effects (Cunningham, 1976; Fabian et al., 1989, 2000; Abramowicz & Fragile, 2013; Bambi et al., 2016, 2017; Bambi, 2018).

1.1.2 Accretion onto compact objects

Accretion is a highly efficient mechanism for extracting gravitational potential energy from a material. Therefore, it was invoked to explain the X-ray flux from the early Xray binaries and active galaxies. Accretion onto compact objects involves matter, with high angular momentum, spiralling into its gravitational field. This matter can be interstellar gas and dust in case of active galaxies and plasma from the donor star in X-ray binaries. The infalling matter forms an accretion disk where the angular momentum is lost due to viscosity which results in the gravitational energy being converted to heat that is radiated away (Shakura & Sunyaev, 1973; Novikov & Thorne, 1973). The origin of the viscosity mechanism remained unknown for long. Balbus & Hawley (1991) have suggested that magneto-rotational instability (MRI) in the accretion disk could lead to viscous dissipation and enhance the angular momentum transport.

The efficiency with which rest-mass energy is converted to heat is extremely high for accretion. For example, during nuclear reaction which powers the Sun the efficiency of conversion of mass to energy is $\approx 0.7\%$ and during accretion the efficiency varies between 5.7% - 32.4% depending on the disk's inner extent (Thorne, 1974). The luminosity (L) due to accretion is dependent on the rate, \dot{M} , at which mass is accreted, i.e., $L = \eta \dot{M}c^2$ where η is the efficiency. The accretion rate is governed by the outward force on the accreting material by the radiation due to absorption and scattering. This results in a maximum limit on the luminosity for a given mass, known as the Eddington luminosity. The expression for Eddington luminosity (L_{Edd}) is derived by equating the radiative force to the gravitational force.

$$L_{Edd} = \frac{4\pi G m_p c}{\sigma_T} M \approx 1.26 \times 10^{38} \left(\frac{M}{M_{\odot}}\right) \mathrm{ergs}^{-1} \quad , \tag{1.2}$$

where m_p is the mass of proton and σ_T is the Thomson scattering cross-section (Section 1.2.4.2). This is only a crude approximation as it assumes a steady and spherically symmetric accretion of fully ionized hydrogen atoms. At luminosities greater than L_{Edd} the outward radiative pressure would exceed the gravitational attraction halting the accretion.

If the accretion disk is optically thick then each element of the disk will radiate roughly as a blackbody with temperature as a function of radius given by

$$T(R) \approx 2 \times 10^7 \left(\frac{M}{M_{\odot}}\right)^{-1/4} R^{-3/4} \,\mathrm{K}$$
, (1.3)

where R is in units of R_s and \dot{M} is the mass accretion rate in Eddington units (Frank

et al., 2002). According to equation 1.3, the inner-disk temperature for stellar-mass black holes is about 10^7 K and for supermassive black holes it is of the order of 10^5 K. So, the disk emits in X-rays for stellar-mass black holes and in optical or ultraviolet for supermassive black holes. The emitted radiation interacts with the surrounding and gets reprocessed across the electromagnetic spectrum (Section 1.2.4). It is also possible that the accretion flow becomes optically thin with the accretion rate becoming too low. This results in a radiatively inefficient accretion as the electrons and protons can no longer be thermalized by collisions (King, 2003). The protons, being more massive, gain most of the gravitational energy and lose very little, whereas, the electrons gain very little energy by collisions and radiate away most of it, resulting in the formation of a two-temperature plasma (Shapiro et al., 1976; Ichimaru, 1977; Narayan & Yi, 1995). Since the flow is optically thin, the electron radiation primarily takes place by bremsstrahlung, Comptonization, or cyclo/synchrotron processes and not blackbody radiation (Section 1.2). This accretion flow possibly has a large scale height as the proton temperature is close to virial and pressure forces along with centrifugal force balance gravity (Narayan & Yi, 1995). The detailed structure of the optically thin, geometrically thick, and hot two-temperature plasma has been a subject of several studies and there is yet to be a consensus on the same (Narayan & Yi, 1995; Chakrabarti & Titarchuk, 1995; Blandford & Begelman, 1999; Yuan, 2001; Abramowicz & Igumenshchev, 2001; Hawley & Balbus, 2002; Falcke et al., 2004; Meier, 2005).

The accretion of matter onto the compact object is not merely confined to thin and thick inflows, but is also accompanied by ejection of matter out of the system as collimated jets and equatorial winds (Done et al., 2007; Belloni & Motta, 2016). The formation of jets requires ordered magnetic field and a way to transfer matter into this field. The optically thin flow, introduced above, serves as an ideal candidate for both (Meier, 2005). Radio emission from jets have been observed in many black-hole binaries (BHBs), hence, prompting the name "microquasar" (Tananbaum et al., 1972; Fabian & Rees, 1979; Mirabel & Rodríguez, 1994). While considerable development has been made on the phenomenology of the jets (Fender et al., 2004; Belloni & Motta, 2016), there remains open issues about the launching mechanism and energetics (Done et al., 2007). Blandford & Znajek (1977) suggested a mechanism by which jets can be powered by tapping the spin energy of the black hole. For such jets, it is imperative to have black holes with high spin. However, observations have shown that black holes can have low or even, possibly, negative spin * (Rout et al., 2020). This leads to the alternative explanation that jets would be powered by tapping the gravitational potential energy (Done et al., 2007). Simulations of MRI driven accretion disks have shown that a jet can have two components - (1) a matter driven "funnel wall" jet and (2) an electromagnetic "Poynting flux" jet. It has been suggested that while the electromagnetic jet, being highly relativistic, is powered by spin, the funnel wall jet is powered by gravity of the accretion flow (McKinney & Gammie, 2004; McKinney, 2005; Hawley & Krolik, 2006).

Equatorial outflows, or winds, are a newer addition to the phenomenology of compact objects. This has been made possible by the advent of high resolution X-ray spectrometers which have aided diagnostics of absorption dips that are an identifying feature of winds (Ueda et al., 1998; Kotani et al., 2000; Kubota et al., 2007; Miller et al., 2008; Díaz Trigo et al., 2009; King et al., 2014). Winds can be primarily driven by three mechanisms - (1) radiation pressure in which the disk photons impart momentum on the ions whose resonance transition energies are comparable to that of the incident photons from the disk (Cordova & Mason, 1982; Proga et al., 1998); (2) thermal heating by Compton interaction at the outer disk due to irradiation by the central heating source can evaporate the gas and given that thermal velocity gained is higher than the local escape velocity, the gas is driven out as a wind or else it remains as an atmosphere (Begelman et al., 1983; Woods et al., 1996); (3) magnetic pressure by open rotating field lines anchored to the disk that accelerate the ions along with them (Blandford & Payne, 1982; Proga, 2003). Determining the wind driving mechanism depends on accurately estimating the density of the wind and radius of its origin. Deduction of density requires sensitive line-ratio measurements and/or photo-ionization modeling of high resolution spectra. Winds complement relativistic-jets in driving away the accreted matter along with angular momentum and are considered to play an important role in the accretionejection equilibrium in X-ray binaries (Frank et al., 2002; Proga, 2003; Ponti et al., 2012; Marcel et al., 2018; Dihingia et al., 2021).

All these manifestations of accretion, along with their interaction with the

^{*}Negative (or retrograde) spin means that the angular momentum vectors for the black hole and accretion disk are oriented opposite to each other.
surrounding, result in emission of radiation in the entire electromagnetic spectrum. The inner edge of the accretion disk near the compact object attains temperature of the order of $\sim 10^{5-7}$ K scaled according to the mass. While stellar-mass black holes attain the highest temperature and emit in X-rays, the suppermassive ones peak in the ultraviolet to optical regime. As one moves farther away from the disk the temperature falls as $R^{-3/4}$ and the thermal emission peaks in longer wavebands, going upto infrared. This is why accretion disks are generally modeled as a multi-temperature blackbody. The atmosphere in the vicinity of the compact object consists of an even hotter (~ 100 keV or ~ 10⁹ K), but optically thin, cloud of electrons and protons called as the Corona. The emission from the disk are inverse Compton scattered in the Corona and are detected in the hard X-rays. The outer parts of the accretion disk can be irradiated by X-rays from the inner regions as well as the back-scattered Coronal emission leading to an increase in their temperature and consequently emission in higher energies (Gierliński et al., 2008). The jet is known to primarily emit in radio and submm wavebands by Synchrotron radiation as the accreting plasma is accelerated through the collimated magnetic field. However, it has been shown that the jet synchrotron emission can also dominate in shorter wavelengths and sometimes even in hard X-rays (Vadawale et al., 2001). In X-ray binaries, the secondary star can also act as a major source of emission in optical or infrared and during outbursts emit in ultraviolet due to X-ray irradiation from the central source. As the different components of the system emit in different energies, it is imperative to study these objects in as many wavebands as possible to get the complete picture.

1.1.3 Classification of X-ray binaries

X-ray binaries are classified into low-mass (LMXB) and high-mass (HMXB) varieties based on the nature of the secondary (companion or donor) star. In LMXBs the companion is a low-mass evolved star ($< 2M_{\odot}$), while in HMXBs the companion is a massive star ($> 8M_{\odot}$). Having two different types of donor stars result in different modes of mass transfer, which affect some observable properties. In LMXBs, mass transfer predominantly takes place by Roche-lobe overflow (Figure 1.1). In this process, the donor star first fills its Roche lobe (equipotential surface) owing to its evolutionary

expansion and/or shrinkage in the orbital size owing to loss of angular momentum. Subsequently, under some perturbations like pressure forces, the matter spills over to the primary's Roche lobe via the inner-Lagrangian point (Frank et al., 2002). The infalling matter spirals into the primary due to the huge angular momentum gained from the orbital motion. The stream of matter first forms an annular ring and then spreads out in both directions due to transfer of angular momentum by viscous stress forming an accretion disk. The HMXBs, on the other hand, accrete matter from the stellar wind of their massive companion stars. The mass-loss rate of an early O- or B-type star is a humongous $10^{-6} - 10^{-5} M_{\odot}$ per year. These winds travel with the escape velocity of their host stars which is of the order of a few thousand km s^{-1} and greatly exceed the local sound speed ($\sim 10 \text{ km s}^{-1}$). Owing to their supersonic speed, the gas pressure in the winds becomes less important. So, when the wind particles pass close to the compact object, the gravitational potential energy overwhelms the kinetic energy of the particles getting captured and accreted. Although accretion by this process is highly inefficient, the huge mass-loss rate more than compensates the inefficiency and provides enough matter to be accreted. These differences in mass transfer mechanism in the two systems have significant ramifications on the long term variability (see Section 1.3.1).

1.2 Radiative processes

Astronomy is all about understanding the radiative processes occurring in distant objects that emit light in various wavebands. We tend to go backward from collecting photons to analyzing them, then deciphering the mechanisms of electromagnetic radiation and finally interpreting the nature and properties of the celestial source. Hence, it becomes imperative to understand the various mechanisms by which light is emitted.

Radiation from an astronomical source is the summation of emission from a large number of particles. The energy (or velocity) distribution of these particles defines the shape of the spectrum. If the particles follow Maxwell-Boltzmann distribution, then the spectrum will be thermal and if the distribution is non-Maxwellian (e.g., power law) the spectrum becomes non-thermal. In the following subsections, four commonly encountered emission processes and two common mechanisms of photon interaction



Figure 1.1: A schematic of a typical low-mass black-hole binary showing accretion through Roche-lobe overflow. The important components of the system are labelled. Courtesy: Rob Hynes

with particles are discussed briefly.

1.2.1 Blackbody radiation

Blackbody emission is radiated from a source whose particles follow a thermal distribution and have a large optical depth. Here, the radiated photons are also in thermal equilibrium with one another and the emission is received mostly from a photosphere. The specific intensity due to blackbody radiation is given by the Planck function

$$I_{\nu} = \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1} \quad , \tag{1.4}$$

where T is the source temperature and k is the Boltzmann constant. One important point to note is that the specific intensity is an exclusive function of temperature (as I_{ν} only depends on T and fundamental constants). The flux from a blackbody radiation can be simply calculated as $F = \sigma T^4$ where σ is the Stefan-Boltzmann constant. In the limits of very low and very high frequencies, Planck's law takes on more simplified and useful forms. For $h\nu \ll kT$, the exponential in the denominator approximates the Rayleigh-Jeans law upon Taylor expansion

$$I_{\nu} = \frac{2\nu^2 c^2}{kT} \quad . \tag{1.5}$$

Similarly, in the limit of $h\nu >> kT$ the denominator dominates the equation yielding the Wien's law

$$I_{\nu} = \frac{2h\nu^3}{c^2} \exp\left(-\frac{h\nu}{kT}\right) \quad . \tag{1.6}$$

It must be noted that the optical depth is dependent on the frequency. A source can be optically thick at some frequencies and optically thin at others.

1.2.2 Bremsstrahlung

Bremsstrahlung, literally meaning "braking radiation", originates when a charged particle (e.g., electron) decelerates due to Coulomb interaction with another charged particle (e.g., ions or atomic nucleus). The moving charge loses kinetic energy, which is then converted into radiation. Bremsstrahlung manifests as a continuous spectrum whose peak intensity move toward higher frequency as the change in energy of the electrons increases. It is sometimes mentioned as free-free radiation because the photon emitting electron remains free (i.e., not bound to any atom or molecule) both before and after the interaction. The basic principle by which free-free radiation works is given by the Larmor's formula

$$P = \frac{2q^2\dot{v}^2}{3c^3} \quad , \tag{1.7}$$

which gives the power emitted due to acceleration (or deceleration) of a charge q. For a simple case of a single electron-ion interaction, the radiated pulse energy W is characterized by the impact factor b and the velocity of the electron v.

$$W = \frac{\pi Z^2 e^6}{4c^3 m_e^2} \left(\frac{1}{b^3 v}\right) \quad . \tag{1.8}$$

The spectrum of radiation for a single particle, given by the above equation, should be integrated over all collisional parameters and over the velocity (energy) distribution (i.e., Maxwellian or power law) to get the complete energy spectrum. In case of a thermal plasma, the low-frequency part is almost constant with an exponential decrease in higher frequencies owing to decrease in electron population in the Maxwellian tail. The spectrum also varies with optical depth. In the compact HII region, the characteristic shape of the spectrum consists of a constant intensity for low optical depth regions and a region where the intensity varies as the square of frequency for high optical depth.

1.2.3 Cyclotron and Synchrotron radiation

According to Larmor's law, the acceleration of charged particles emits electromagnetic radiation. While acceleration due to electric fields causes free-free radiation, acceleration due to magnetic fields produces synchrotron (or cyclotron) radiation which is why it is also known as "magnetobremsstrahlung" or gyromagnetic radiation. In the mildly relativistic regime, i.e., where the electron's kinetic energy is comparable to its rest mass energy (m_ec^2), it produces cyclotron radiation whereas in the ultra-relativistic regime it produces synchrotron radiation. The synchrotron emissivity for an electron in the high frequency limit (Longair, 2011) is given by

$$j(\nu) \propto \nu^{1/2} \exp(-\nu/\nu_c)$$
, (1.9)

where ν_c is the critical frequency. The critical frequency is given by $3c\gamma^3/4\pi a$ where a is the radius of the spiral orbit traversed by the electron and γ is the Lorentz factor. According to the above equation, at frequencies $\nu > \nu_c$ the spectrum is exponentially cut-off and has very little power. For low frequency limits of the frequency $\nu \ll \nu_c$ the spectrum is given by

$$j(\nu) = \left(\frac{eB\sin\alpha}{\gamma m_e}\right)^{2/3} \nu^{1/3} \quad , \tag{1.10}$$

where α is the pitch angle of the spiral magnetic field. In the low frequency limits, the spectrum is proportional to $\nu^{1/3}$. The electrons in most of the synchrotron sources follows a power-law distribution and are not in thermodynamic equilibrium. Thus, these sources are often termed as "non-thermal" sources.

Sources of synchrotron radiation are quite ubiquitous in astronomy. Active galactic nuclei (AGN), which are believed to be fueled by supermassive black holes, emit most of the radio emission by the synchrotron process. At frequencies below 30 GHz, the synchrotron process dominates the radio continuum from star-formation regions in galaxies like ours. Jupiter's magnetosphere is also believed to be a source of synchrotron emission. Although predominantly observed in radio wavebands, synchrotron emission also dominates other wavebands from infrared (IR) through X-ray in various sources like jets in microquasars, AGN, and supernova remnants.

1.2.4 High-energy photon interactions

1.2.4.1 Photoelectric effect

The dominant process by which the interaction of low-energy photons $(h\nu \ll m_ec^2)$ takes place with matter is photoelectric absorption. It is one of the main causes of opacity in ISM (Weingartner & Draine, 2001) and stellar interiors. If the incident energy of a photon, $\epsilon = h\nu$, is greater than the atomic energy level E_1 then the electron from that level can be ejected with kinetic energy $h\nu - E_1$. Thus, it is also called as bound-free emission as the electron is bound to the atom before the interaction and becomes free afterward. The spectrum has an absorption edge at the energy level where $h\nu = E_1$ as the photons with lower energy cannot displace any electron. The cross-section for photoelectric absorption resulting in the ejection of a K-shell electron by photons with energy $h\nu \gg E_1$ and $h\nu \ll m_ec^2$ is given by (Heitler, 1954)

$$\sigma_K = 4\sqrt{2}\sigma_T \alpha^4 Z^5 \left(\frac{m_e c^2}{\hbar\omega}\right)^{7/2} \quad , \tag{1.11}$$

where α is the fine structure constant and σ_T is the Thomson cross-section.

1.2.4.2 Thomson and Compton scattering

Compton scattering is a process in which a high energy photon collides with a stationary electron and transfers some energy and momentum to it. The scattered photon has less energy and momentum than that before the collision and the recoiled electron gains some energy. In the low-energy limit, $h\nu \ll m_e c^2$, the interaction becomes elastic with no change in energy of the photon and the interaction is called as Thomson scattering.

The cross-section for Thomson scattering is given by

$$\sigma_T = \frac{e^4}{6\pi\epsilon_0^2 m_e^2 c^4} = 6.653 \times 10^{-29} \text{m}^2 \quad . \tag{1.12}$$

In the limit where the energy of the incident photon is more than the rest mass energy of the electron the collision increases the wavelength, or decreases the energy, of the scattered photon. This cooling of the electrons is sometimes referred to as the "recoil effect". The change in wavelength due to Compton scattering is given by

$$\frac{\Delta\lambda}{\lambda} = \frac{h\nu}{m_e c^2} (1 - \cos\theta) \quad , \tag{1.13}$$

where θ is the scattering angle. In the limits of Compton scattering the total crosssection is given by the Klein-Nishina formula

$$\sigma_{K-N} = \pi r_e^2 \frac{1}{x} \left\{ \left[1 - \frac{2(x+1)}{x^2} \right] \ln(2x+1) + \frac{1}{2} + \frac{4}{x} - \frac{1}{2(2x_1)^2} \right\} \quad , \tag{1.14}$$

where $x = h\nu/m_ec^2$ and $r_e = e^2/4\pi\epsilon_0 m_ec^2$. At low energy limits the Klein-Nishina cross-section reduces to Thomson cross-section and for ultra-relativistic limit, $\gamma \gg 1$ (where $\gamma = 1/\sqrt{1 - \frac{v^2}{c^2}}$), it becomes

$$\sigma_{K-N} = \pi r_e^2 \frac{1}{x} \left(\ln 2x + \frac{1}{2} \right) \quad . \tag{1.15}$$

When the energy of the electron is higher than the incident photon energy, the photons instead of cooling down are boosted up at the expense of the electron's kinetic energy. This effect is called as inverse Compton scattering and plays an important role in hard X-ray emission from hot plasma.

1.3 Variability

1.3.1 Long-term variability

Based on variability over a time scale of years BHBs are divided into two subclasses - persistent and transient sources. Persistent sources are those which have remained

bright since their discovery, for example the HMXBs Cyg X-1, LMC X-1, and LMC X-3. Whereas transient sources spend most of their lives in a quiescent state (i.e., below the sensitivity of most X-ray detectors) and only get detected during violent episodes of outburst which lasts for a few to several months. The repetition of these outbursts are quasi periodic with periods ranging from less than a year to a few decades (Tetarenko et al., 2016). Almost all LMXBs, like A 0620–00, GRS 1716–249, MAXI J1631–479 etc., show transient behavior. The transients exhibit a wide range of variability, both in spectral and timing properties, across flux levels spanning up to six orders of magnitude. Figure 1.2 shows the long term lightcurves for the two types of sources. Out of all the transients, GRS 1915+105 is a unique source which has remained bright since its discovery and displays about thirteen variability classes at different time scales (Belloni et al., 2000). The reason for the dichotomy in long term variability is believed to be the hydrogen ionization instability scenario (Lasota, 2001; Frank et al., 2002) aided by the different mass transfer rates from the two kinds of companion stars. Due to this instability, the accretion disk becomes unstable in thermal and viscous time scales at temperatures where hydrogen ionizes, i.e., $10^3 - 10^4$ K. At low temperatures, emanating from low accretion rates, the opacity of the disk decreases as hydrogen is mostly neutral. As the temperature reaches the range of hydrogen ionization the opacity increases sharply because the high energy photons from the Wien's tail are able to ionize the hydrogen atoms. Therefore, the photons are trapped in the disk further increasing its temperature. Consequently, more and more photons get trapped in the disk leading to an unstable rise in temperature until a point when all the hydrogen atoms in the disk have been ionized. The thermal runaway then triggers a viscous instability as the increase in temperature increases mass accretion rate and the material is eaten away at that radius. This creates a decrease in pressure and temperature leading to recombination of the hydrogen ions. Another thermal runaway sets in, with the temperature continuing to decrease this time until all the hydrogen ions become neutral and falls below 10^3 K. The accretion rate also falls and the disk starts to build up again for another instability cycle. Although, the disk instability model describes a local phenomenon occurring at a single radius, the large difference in temperature between the adjacent annuli ensures that the instability becomes global. The whole disk undergoes the limit cycle behavior where an enhanced mass accretion rate facilitates



Figure 1.2: From top to bottom: The long term lightcurves of two LMXBs - GX 339-4 and 4U 1630-472, and two HMXBs - LMC X-3 and Cyg X-1 observed with MAXI.

the dumping of most of the material into the black hole on a viscous timescale. This brings back the binary to a quiescent state with the disk comprising mostly of neutral hydrogen. The disk then starts accumulating mass and prepares for the onset of another instability (outburst) after a period which depends roughly on the mass transfer rate and size of the binary. In case of HMXBs, the massive companion star has a large mass transfer rate which more than compensates for the cooling process at the outer radii. This ensures that the disk remains above the hydrogen ionization instability limit throughout (van Paradijs, 1996).

1.3.2 Rapid variability

The emissions from BHBs do not only vary in a time scale of months and years, but also show variability at much shorter time scales, sometimes as low as milliseconds. These time scales are associated with the characteristic time scales of accretion flow, such as radial sound and light crossing, thermal and viscous diffusion, free fall, etc. Furthermore, there are time scales pertaining to the Keplerian motion and general relativistic effects like nodal and Lense-Thirring precession. The identification of any of these time scales to features in the emitted radiation will provide important insights on that process.

The go-to method for studying the rapid variability involves analysis of the time series in frequency space. This is achieved by Fourier transforming the lightcurve and constructing a power spectrum (see Chapter 2.3 for details on the calculation of power spectrum). A power density spectrum (PDS) represents the variation of power as a function of temporal frequency (see Chapter 2.3 for details). Figure 1.3 displays a zoo of typical PDS observed during different states of an outburst (Section 1.4.2). From top to bottom, the PDS belong to states with decreasing hardness and constitute different noise levels and peaked features. Various models have been proposed to explain the broadband noise properties. Models based on shot noise are able to explain the broadband noise properties observed in the PDS (Terrell, 1972). However, their strength lays on their ability to reproduce the observations and are unable to explain the physical processes underlying the noise (also see Narayan & Yi, 1995; Uttley et al., 2005). The origin of the 1/f noise is possibly connected to the fluctuations in the mass accretion rate (Kazanas et al., 1997) as their strength increases with increasing rate (Cui et al., 1997b,c,a). The white noise component can be produced due to thermodynamic fluctuations in the inner regions of the disk.

Broad peaks on the PDS (apparent in the second, third and fourth PDS in Figure 1.3), known as quasi-periodic oscillations (QPO), are fascinating features on the power spectra. Depending on their frequency, they are classified as low frequency (≤ 30 Hz) or high frequency QPOs (≥ 40 Hz). Sometimes, very low frequency (< 0.01 Hz) and very high frequency (> 1000 Hz) QPOs are separately categorized as millihertz and kilohertz QPOs respectively. The low-frequency QPOs (LFQPO) are further divided into three types - A, B, and C depending on their properties and the state of the system they occur in (Casella et al., 2004, 2005). In fact, the presence of absence of one or the other type of QPO has become a defining characteristic of certain states (Section 1.4.2). While the phenomenology of QPOs is fairly well understood, their origin is still debated. Models that attempt to explain the phenomenon of QPOs can be broadly divided into two categories - (1) based on intrinsic variability in the accreting plasma and (2) due to geometric effects. Tagger & Pellat (1999) proposed the Accretion-

Ejection Instability model in which spiral wave instabilities in the density and scale height of a thin accretion disk results in standing wave patterns that form LFQPOs. According to Molteni et al. (1996) and Chakrabarti et al. (2008) LFQPOs can be formed due to oscillations of the shock location in the two-component accretion flow model. Pressure wave oscillations within the boundary of the corona can also lead to resonant modes that modulate the Compton upscattered photons generating LFQPOs and the associated noise component (Cabanac et al., 2010). Apart from these, several other attempts have been made to explain the QPO phenomena due to some sort of oscillation or variability in the accretion flow (eg. Wagoner et al., 2001; Titarchuk & Fiorito, 2004; O'Neill et al., 2011). Time-dependent Comptonization models were developed to explain the various phenomenology of kilohertz QPOs in neutron star low mass X-ray binaries (Lee & Miller, 1998; Kumar & Misra, 2014; Karpouzas et al., 2020). Recently, García et al. (2021) extended this model to explain the root mean square amplitude and phase lag spectra of Type-B QPOs in the BHB MAXI J1348-630 by incorporating two separate Comptonization regions. Under the assumption that there is a dynamical mechanism which excites the oscillations, García et al. (2021) were able to explain the radiative properties, i.e., the rms and lag spectra, of the Type-B QPOs in this source. While most of the models based on intrinsic variability are quite different from each other, the other class of models based on geometric effects attempt to explain the QPOs with the phenomenon of Lense-Thirring precession. Stella & Vietri (1998) and Stella et al. (1999) proposed the relativistic precession model (RPM) in which QPOs are formed due to Lense-Thirring precession at some characteristic radius which decides the frequency. Ingram et al. (2009) extended the model under a truncated disk framework to explain the QPOs and other noise elements by precession of the corona. Schnittman et al. (2006) also proposed a slight variation of the RPM where a precessing ring of matter modulates the X-rays. Although, ascertaining a particular model for the QPOs is still debated, several studies done recently have strongly preferred a geometric origin over intrinsic variability. It has been shown that the Type-C QPOs have a significant inclination dependence in their strength and the Type-B QPOs likely have a different origin than Type-C (Motta et al., 2015; Heil et al., 2015; van den Eijnden et al., 2017). Ingram et al. (2016, 2017) went on to carry out phase-resolved spectroscopy of Type-C QPOs to verify that the reflection spectrum



Figure 1.3: The different types of power-density spectra observed in black-hole binaries during various states (Belloni, 2010).

varies with different phases of the QPO providing strong evidence for a geometric origin. Stevens & Uttley (2016) carried out a similar exercise with Type-B QPOs to suggest a possible origin from precession of an extended object like a jet (also see Kylafis & Reig, 2018, 2019; Kylafis et al., 2020). Moreover, it has also been observed that the occurrence of Type-B QPOs are coincided by radio detection (Belloni, 2010; Fender et al., 2004). Very little is known about Type-A QPOs as they have been detected in only a handful of sources.

1.4 Characterization of black-hole binaries

A typical spectrum of a BHB consists of three principal components - a thermal disk, a power law due to Comptonization, and a reflected component. The origin and different manifestations of each of these components are discussed in the following subsections.

1.4.1 Spectral components

1.4.1.1 Thermal disk

The soft X-ray emission from the accretion disk is a consequence of the conversion of the black hole's strong gravitational potential energy into radiation. The balancing

between the gravitational heating and cooling defines the structure of the accretion flow. According to Shakura & Sunyaev (1973), the viscous stress between the adjacent layers of the accretion disk convert the gravitational energy to heat. The cooling is achieved by the local radiation of this heat. This radiation takes the form of a blackbody if the material in the disk is thermalized and is optically thick. For a blackbody the emission solely depends on the temperature, and the temperature in a disk is a function of the radius. As one moves closer to the hole, more radiation from stronger potential has to be emitted from a smaller space. So, the temperature increases inward and the disk becomes geometrically thin. Due to the assumption of a thermal disk, the spectrum is independent of the viscosity mechanism at least to the zeroth order. Thus, phenomenological descriptions of the viscosity, such as the α prescription by Shakura & Sunyaev (1973) are sufficient to describe the emitted spectrum. Their assumption is that the shear viscous stress is proportional to the total pressure with α serving as the proportionality constant. While the true origin of the viscous stress is a matter of contention, magneto-rotational instability (Balbus & Hawley, 1991) is believed to be a promising candidate.

1.4.1.2 Comptonization

As discussed in Section 1.2.4.2, Compton scattering leads to an exchange of energy between electrons and photons upon collision. The energy of the output photon, ϵ_{out} is given by

$$\epsilon_{out} = \frac{\epsilon_{in}(1 - \beta \cos \theta_{ei})}{1 - \beta \cos \theta_{eo} + (\epsilon_{in}/\gamma)(1 - \cos \theta_{io})} , \qquad (1.16)$$

where θ_{ei} is the angle between electron and input photon, θ_{eo} between electron and output photon, and θ_{io} between input and output photons. The Lorentz factor of the electron $\gamma = (1 - \beta^2)^{1/2}$ and $\epsilon_{in} (h\nu/m_ec^2)$ is the input photon energy. During an interaction, equation 1.16 ensures mutual energy sharing from the more energetic component to the lesser one. This explains both the Compton (downscattering) and inverse-Compton (upscattering) scattering scenarios. In the accretion disk of binaries, inverse Compton scattering plays a more important role as the electron cloud, also called as corona, is much hotter than the thermal seed photons originating from the thin disk. Depending on the energy distribution of the electrons in the corona, the



Figure 1.4: The formation of a thermal Comptonization spectrum by repeated scattering. (Done, 2010)

Compton spectrum will be either thermal or non thermal.

For a thermal electron distribution, the random velocity of electrons is typically set by their temperature $\Phi = kT_e/m_ec^2$ which implies $\beta^2 = 3\Phi$ since $v^2 \sim$ kT_e/m_e . For an isotropic distribution of electrons and photons, the angle-averaged output energy ϵ_{out} can be simplified by Taylor expanding equation 1.16. This gives $\epsilon_{out} = (1 + 4\Phi + 16\Phi^2 + ...)\epsilon_{in} \approx (1 + 4\Phi)\epsilon_{in}$ for $\Phi \ll 1$. During scattering the change in energy $\Delta \epsilon$ becomes $4\Phi \epsilon_{in}$ indicating upscattering of photons. The probability of interaction between the photons and electrons is given by $e^{-\tau} \approx 1 - \tau$ for $\tau \ll 1$. τ is the optical depth of the electron cloud and is given by $\tau = nR\sigma_T$ where n is the number density of the electrons, R is the path length, and σ_T is the Thomson cross-section (equation 1.12). The output energy due to thermal Comptonization is a summation of many orders of Compton scattering. The output photons from the first scattering becomes input for second order scattering which subsequently becomes an input for third order scattering. This process continues till the energy of the output photons reaches the limit of the electron energy after N scatterings, i.e., when $\epsilon_{out,N} = (1+4\Phi)^N \epsilon_{in} \sim 3\Phi$. The final spectrum is a power law from ϵ_{in} up to 3Φ , with the spectral index being determined by both the optical depth and temperature of the electrons. The spectral index, α , is given by $\log \tau / \log(1 + 4\Phi)$.

Non-thermal Compton scattering takes place when the electron number den-



Figure 1.5: The formation of a non-thermal Comptonization spectrum from a single (or at most two) scattering. (Done, 2010)

sity follows a power-law distribution, i.e., $n(\gamma) \propto \gamma^{-p}$ from $\gamma = 1$ to γ_{max} . According to equation 1.16, for relativistic velocity distribution of electrons ($\gamma \gg 1$), the output photon gets beamed along the electron direction into a conical region of angle $1/\gamma$. Again, assuming an isotropic distribution of electrons and photons the angle averaged photon energy becomes $\epsilon_{out} = (4/3\gamma^2 - 1)\epsilon_{in} \approx \gamma^2 \epsilon_{in}$. Thus, non-thermal scattering results in a power-law spectrum from ϵ_{in} to $\gamma_{max}^2 \epsilon_{in}$ formed by a single scatter.

There can also be a scenario when the electron distribution is hybrid, i.e., a Maxwellian with a power-law tail. One way to produce such a distribution is from a single acceleration region, where from the initial non-thermal (power law) distribution the low energy electrons thermalize by Coulomb collisions and the high energy electrons preserve the power-law shape (Coppi, 1999). Another alternative by which a hybrid distribution can be materialized is by considering the electron cloud to consist of two separate regions, one with a non-thermal distribution due to magnetic reconnections in the jet or above the disk, and the other with a thermal distribution from the classical corona or hot inner flow (Done et al., 2007).

1.4.1.3 Reflected emission

While a fraction of Comptonized photons escapes the system, another fraction backscatters to illuminate the geometrically thin and optically thick accretion disk. Some of these illuminated photons can scatter and reflect back to the line of sight. The probability of the reflection depends on the relative strength of scattering compared to photoelectric absorption at a particular incident energy (Figure 1.6). For a neutral disk, photoelectric absorption dominates over scattering at low energies suppressing the reflected continuum. However, the absorption cross-section decreases with energy as E^{-3} resulting in an increase in reflection fraction. From 10 keV onward, the scattering cross-section (σ_T) starts to dominate for solar abundances leading to a steady reflection. As the incident energy becomes too high (≥ 50 keV), Compton downscattering becomes important and the reflection ceases to be elastic. As the number of photons at higher energies is less and the reflected ones have lower energy, a break appears in the spectrum. This forms a characteristic peak in the 20 - 50 keV range, called as the reflection hump, where the high-energy photons are downscattered and the low-energy photons are photoelectrically absorbed (George & Fabian, 1991).

Photoelectric absorption at lower energies excites the atoms wherein one of the K (n=1) shell electron is knocked out. These ions immediately de-excite to the ground state accompanied by a fluorescent emission line (n=2 to n=1 transition generates a K α line, n=3 to n=1 transition generates a K β line, and so on). However, at lower energies the reflection fraction is much smaller compared to the disc continuum and low atomic-number elements preferentially de-excite through Auger effect (ejection of an outer-shell electron rather than a fluorescent line). So, the strongest fluorescent line is from iron owing to its high fluorescence probability and an increased reflection fraction.

The photoelectric absorption cross-section of a material is greatly dependent on its ionization state (Figure 1.6). With increasing ionization state the opacity decreases at low energies enhancing the reflectivity. Consequently, the fluorescent lines from low atomic number material which were diluted by neutral reflection could become prominent over an ionized reflection continuum. Furthermore, for an ionized material the disk is heated upto Compton temperature by irradiation making Compton upscattering as important as downscattering. This causes broadening of the lines and edges (Young et al., 2001). Although, in most applications the disk is assumed to be either neutral or having a constant ionization, in reality a disk in hydrostatic equilibrium has a complex structure. Due to strong illumination, the surface of the disk is highly ionized and has much less density. As one moves from the surface to the interiors the



Figure 1.6: Left panel: Dependence of photoelectric absorption and electron scattering cross-sections with energy. Right panel: Reflected spectrum for different ionization states. The different colors represent the different ionization states of the absorbing material (Done, 2010).

density increases and ionization decreases. The amount of ionization on the skin is also dependent on the hardness of the illuminating flux. A hard spectral illumination gives rise to almost complete ionization of the skin, while a softer illumination leads to high ionization, but not complete. Therefore, the actual reflected spectrum is a composite of different ionization states.

As discussed above, the fluorescent iron $K\alpha$ line is a prominent feature of the reflected spectrum. It appears at 6.4 keV for neutral material and > 6.4 keV for an ionized disk. This emission line is intrinsically broadened only upto a few tens of eV depending on the temperature structure of the emitting material. The broadening is increased further (upto several hundereds of eV) due to various special and general relativistic effects. These effects become more pronounced when the line is emitted from very close to the black hole. At distances farther away the disk is mostly non relativistic and the line has a double-horned structure, with the two horns originating from the receding and approaching sides of the disk. It is to be noted that this effect will only be observed for an inclined disk, a face-on disk will not show any Doppler effects. When the emission is from a smaller radius (i.e., closer to the black hole), the orbital velocity of disk is mildly relativistic beaming the blue horn from each radius. Subsequently, transverse Doppler effect and gravitational redshifts move the red horn to lower energies. The combined effect is a highly skewed and broadened line profile.



Figure 1.7: Top panel shows the a typical HID from a BHB outburst. Bottom panel shows the HRD. Courtesy: (Belloni & Motta, 2016)

By modeling this line, along with the underlying continuum, accurately the inner radius of the disk and inclination can be obtained.

1.4.2 State classification

The classification of BHB outbursts into different states, based on the spectral and timing properties, has been one of the corner stones for understanding the system and its properties. The observation of Cygnus X–1, the first black-hole candidate, with *Uhuru* showed the presence of two states based on the changes in flux in different energy bands. Since the instrument had maximum effective area in the soft band, the increase and decrease in flux in these bands were identified as "high" and "low" states, respectively. The high state was also associated with disappearance of the radio counterpart (Tananbaum et al., 1972). It was further shown by Terrell (1972) that the low state was associated with high aperiodic noise. A few years later, the first black-hole transient source A 0620–00 (Elvis et al., 1975) was also found to display a similar dichotomy in states as Cygnus X–1 (Coe et al., 1976). Over the next two decades, two more states were introduced - very high state (VHS) and intermediate state (IMS) - both of which had properties intermediate to the high and low states. The VHS, as the name suggests, was observed during a high flux state while the IMS was observed during a low flux state (Miyamoto et al., 1991; Belloni et al., 1997). The launch of RXTE in 1995 provided a big impetus to the understanding of the binary systems and helped in delineating the various states during a typical outburst.

Two diagrams that are very useful in mapping the states during an outburst are the hardness-intensity diagram (HID) and the hardness-rms diagram (HRD). In the HID, the hardness ratio (ratio of counts in a hard energy band to counts in a soft band) is plotted against the total count rate. It is similar to the color-magnitude diagrams used in optical astronomy with the difference that in case of black-hole transients a single source can be tracked over a small time scale. The HRD, on the other hand, is the variation of fractional rms (integrated over a range of frequencies) with hardness ratio. The schematic representation of these two diagrams are represented in Figure 1.7. The 'q' shaped curve tracks the evolution of a typical BHB outburst from points A through E. The four branches on the curve can be loosely associated to the four pre-RXTE states described above. The two vertical branches AB and CD correspond to the classical low and high states. The top and bottom horizontal branches (BC and DE) are associated with the VHS and IMS respectively. From a comprehensive spectral and timing analysis of the binary XTE J1550-564 it was inferred that the VHS and IMS likely correspond to a single physical state, merely occurring at different luminosity levels (Homan et al., 2001). This brings down the total states to three. Unlike the hysteresis loop traced in the HID, the HRD follows a linear correlation of fractional rms variability with hardness. The hardest states have the maximum variability (> 20%) and the softest ones have minimum (< 10%). The intermediate states, as the name suggests, have intermediate levels of variability. An interesting point to notice is the presence of a patch of points lying below the main correlation at low/intermediate variability level corresponding to a possible fourth state. Apart from the HID and HRD, a third diagram - corresponding to the third combination of the above three variables - namely the rms-intensity diagram (RID) can also be used as a powerful diagnostic tool to delineate the states (Muñoz-Darias et al., 2011). The RID, shown in Figure 1.8, makes it easier to spot states and transitions as it maps the variation of rms (which differentiated the fourth state) with intensity resulting



Figure 1.8: The absolute rms-intensity diagram for GX 339-4 observed during three epochs. The fractional rms levels are represented by dotted lines (Muñoz-Darias et al., 2011)

in a hysteresis loop similar to the HID. The above pedagogical development can be summarized to establish that an outburst is characterized by four states, the low/hard (LHS) and high/soft (HSS) states corresponding to the classical low and high states, and the hard- (HIMS) and soft- (SIMS) intermediate states. The properties of these four states are discussed below in some detail.

- Low/hard state (LHS): This state is characterized by a hard spectrum where the power-law component due to Comptonization dominates the flux over the intrinsic disc emission. The levels of aperiodic variability is high (~ 30%) which is correlated with hardness and anti-correlated with flux. The power spectrum is composed of a number of Lorentzians, one of which can become a type-C QPO. The characteristic frequency of the PDS components increases with flux. In the HID, the right vertical line (AB, in Figure 1.7) belongs to the LHS indicating that the outburst begins and ends in this state. In the RID, the diagonal line at high RMS value represents the LHS.
- *High/soft state (HSS)*: The spectrum during the HSS is dominated by a thermal disk and subsequently has very little variability. It occupies the left most branches

in all the three diagnostic diagrams. Sometimes, type-C QPOs may be detected.

- *Hard-intermediate state (HIMS)*: In the HID, the HIMS covers a major portion of the horizontal branches clung to the LHS. The spectrum is characterized by an increase in contribution from the thermal disk and a subsequent steepening of the power law. This translates into a decrease in variability to about 10% level. However, the shape and dependencies of the PDS remain similar to that of the LHS. Sometimes the sources make occasional excursions to the HIMS from the HSS (Figure 1.7).
- Soft-intermediate state (SIMS): The SIMS is marked by low levels of hardness and variability and occurs to the left of the HIMS on the HID and RID. Since the variability and hardness are very close to the HSS values, it is difficult to separate the two. However, the SIMS points occupy a small patch below the main track in the HRD. The spectrum, although similar to that of the HIMS, does not show a high-energy cutoff. The PDS makes the identification of the SIMS clear by changing the shape from a band-limited noise to a power law with a type-B QPO.

1.5 Thesis outline

BHBs exhibit rich phenomenology in spectral and timing properties due to accretion of matter from the companion star. Following over five decades of extensive study these aspects of BHB outbursts stand on a fairly strong observational footing. In particular, the process of state transition during an outburst and the associated spectral and timing variability are reasonably well understood, although, every now and then some exceptions crop up. Despite considerable advancement in understanding the phenomenology, some fundamental questions regarding the inner geometry of the accretion flow and the origin of certain observed phenomena remains debatable. For instance, it is generally accepted that an optically thin, geometrically thick cloud of electrons and protons, the so-called corona, is responsible for the power-law emission by Compton upscattering (inverse Comptonization) the seed photons from the optically thick and geometrically thin disk. However, the composition and geometry of the corona are still

unclear. Different competing models have been developed which successfully produce the power law and other variability properties. Some of the geometries that have been incorporated are spherical, sandwich or slab, lamp post etc., but there is no general consensus on any of them. Irrespective of the geometry of the corona, it is known to be highly variable over a large range of timescales which is evident from the power spectrum. The power spectrum, being in the Fourier space, reveals narrow features at very short timescales, known as QPOs. The dynamic origin of the QPOs, as well as their radiative properties, are hotly debated. Several models have been proposed to describe their origin, all of which can be broadly grouped into two categories - (1) originating due to geometric effects and (2) based on the intrinsic variability of the corona and/or the disk. Similarly, to explain the radiative properties of the power spectral components, such as rms and lag spectra, a few models have been introduced. Apart from the thermal Comptonization, emission in the very hard X-ray and γ -ray regime suggest the presence of non-thermal emission. In the soft state, these emissions may be produced by non-thermal Comptonization. The formation mechanism of non-thermal electrons in the vicinity of the black hole still remains uncertain. Most models which describe the non-thermal spectrum assume a non-thermal injection of photons into the source. However, they fail to provide a physical explanation for the same. Flares, like those occurring on the Sun, provide a possible scenario by which non-thermal electrons can be generated. In the hard state, on the other hand, the non-thermal spectrum may be produced by synchrotron process from jet, but the evidence for this is minimal. Synchrotron jets are known to be bright in the entire electromagnetic spectrum ranging from radio to very hard X-rays. Constraining the geometry and composition of a jet rely on correctly calculating and modeling the total energy released. This task becomes challenging due to the difficulty in correctly associating observed radiation from certain wavelength ranges, e.g., infrared, optical, and UV, to their emission processes. This is because multiple emission mechanisms, such as irradiated outer accretion disk, irradiated secondary star, and jet, emit in these wavebands. The separation of fluxes from individual processes is not straightforward and several techniques, often marred by technological limitations, have been developed over the years. The accretion disk in the vicinity of a black hole is strongly influenced by two of its fundamental properties - mass and angular momentum (or spin), which makes their accurate measurement extremely important. Mass and spin estimates of a large sample of black holes are also necessary for constraining the stellar evolution theories. The best measurement of mass is done using the dynamical methods i.e., by measuring the radial velocity of the secondary star from Doppler shifted lines and feeding it to the binary mass function. However, in many cases the secondary is too faint to be detectable. An estimate of mass can also be obtained by correctly modeling the thermal X-ray emission from the accretion disk during the HSS. The measurement of spin can be done by modeling the fluorescent Fe K α line reflected from the inner accretion disk. This is based on the fact that the inner boundary of the accretion disk is determined by spin of the black hole. The measurement of the spin is also important as it can constrain the models positing that the jets are powered by the spin of the black hole. If this were true binaries with strong radio emission should host a rapidly spinning black hole. As we would see, this is not always the case.

Through this thesis, we have attempted to understand the radiation processes as well as accretion geometry in the vicinity of stellar-mass black holes in X-ray binaries. We have also attempted to constrain the fundamental black-hole parameters, i.e., mass and spin, for a couple of newly discovered BHBs. To meet this end, X-ray spectroscopy and timing analysis were used as principal tools. We have investigated three X-ray binaries using observations from six different X-ray observatories and one ground based optical/IR telescope. In the current chapter, a brief overview of the subject matter is presented from explaining the various emission processes to the characterization of the BHBs. Rest of the thesis is organized as follows:

Chapter 2: Instrumentation and data analysis

This chapter gives an overview of all the instruments and techniques used in the thesis. Details of six observatories used in this work - *RXTE*, *XMM Newton*, *Swift*, *NuSTAR*, *AstroSat*, *NICER*, and *MIRO* have been presented along with a detailed description of the spectroscopic and timing techniques.

Chapter 3: Multi-wavelength view of the galactic black-hole binary GRS 1716–249

BHBs emit in the entire electromagnetic spectrum during outbursts. A complete understanding of the system can, therefore, be achieved by studying the emission in all wavebands. Ascertaining the true emission mechanism and segregating the contribution of different mechanisms, if present, will provide a correct estimate of the energetics and hence its geometry. The results of such a study where a multi-wavelength spectral energy distribution fitting of the galactic X-ray binary GRS 1716–249 ranging from near infrared (5×10^{-4} keV) to hard X-rays (120 keV) are presented in this chapter.

Chapter 4: Spectral and timing evolution of MAXI J1631–479 during 2018-19 outburst with *NICER*

The results of a comprehensive timing and spectral analysis from *NICER* monitoring of an X-ray transient MAXI J1631–479 is presented in this chapter. Apart from studying the evolution of the spectral and timing properties, the origin of the LFQPOs observed during the HIMS is also explored by studying spectro-timing correlations.

Chapter 5: The 2016-17 state transitions of Cygnus X–1 observed with AstroSat

This work traces the state transition of Cyg X–1 during 2016-17 with observations from *AstroSat*. The broadband *AstroSat* spectrum in 1 - 80 keV range was fitted with a combination of disk, Comptonization and reflection models to study the evolution of the spectral parameters. Likewise, the broadband PDS in 0.001 - 100 Hz range was modeled with a combination of Lorentzian and power law to trace the power spectral properties during the transition. Finally, the origin of the variability features in the PDS is also explored using correlation studies.

Chapter 6: X-ray spectroscopy of MAXI J1631–479: Implication for a massive black hole

A broadband (0.7 - 78 keV) spectral analysis of a newly discovered X-ray binary MAXI J1631-479 is carried out. Using relativistic reflection modeling, the spin of the black hole was found to be around 0.97 - 0.99 and the inclination laid between 61° - 69° . Using this information a constrain on the mass of the black hole was obtained by fitting the soft X-ray continuum of the source.

Chapter 7: A retrograde spin for the black hole in MAXI J1659–152

The results of spectral analysis of the galactic BHB MAXI J1659-152 in the rising phase of the outburst is presented. The presence of a broad Fe line and a wide energy coverage allowed for a combined reflection spectroscopy and continuum fitting study to estimate the spin of the black hole. The entire parameter range allowed by

the present uncertainties on black-hole mass, inclination, and distance as well as the accretion rate were explored to obtain a robust limit on spin.

Chapter 8: Summary and Future Work

The work that led to the culmination of this thesis primarily involved X-ray spectral and timing study to better understand the various phenomenology associated with accretion disks around BHBs. We have attempted to decipher the origin of LFQPOs and the reasons behind state transitions. We have also constrained the fundamental parameters of a black hole, i.e., spin and inclination for two sources. This chapter discusses these results in detail along with scope for future work.

Chapter 2

Instrumentation and Data Analysis

2.1 Instrumentation

The earth's atmosphere is selective when it comes to allowing photons of different energies to pass through. While it allows visible, parts of infrared, and radio wavebands, it absorbs γ -rays, X-rays, UV, most of far infrared and very long wavelength radio waves. Although the blockage of high-energy photons is beneficial for life on earth, it makes the life of astronomers difficult who have to spend heftily to develop a spacebased instrument. Therefore, the growth in high-energy astrophysics is closely linked to the development in space technology and exploration. Such an opportunity came post the second world war when the technologies developed for war were used for scientific purpose in peace time (Giacconi, 2009). Before 1950s, the Sun was known to be the only source that could emit X-rays and consequently it had substantial impact on the earth's ionosphere. Thus, early rocket and balloon-borne experiments were dedicated towards the study of solar corona and earth's upper atmosphere. The first X-ray detection of the Sun was made using a German V2 sounding rocket on 28 January 1949 (Friedman et al., 1951). The detection of the first extra-solar X-rays took another decade when Gieger counters onboard an *Aerobee* rocket, launched by NASA, serendipitously discovered the neutron star X-ray binary Sco X-1 (Giacconi et al., 1962). This discovery was a breakthrough moment and heralded the field of X-ray astronomy. On 12 December 1970 NASA launched the first dedicated X-ray satellite mission Uhuru. With a modest mission period of a little more than two

years *Uhuru* made many important discoveries and paved the way for numerous X-ray missions (Giacconi et al., 1971a,b; Tananbaum et al., 1971; Oda et al., 1971; Forman et al., 1978). The next five decades saw a huge interest in the field of high-energy astrophysics where the physical understanding of the Universe went hand-in-hand with technological development. From proportional counters to calorimeters and collimators to focusing optics, we have achieved tremendous feats in instrumentation and continue to do so with many new missions lined up to be launched in future.

2.1.1 X-ray detectors

The working of a typical X-ray detector is similar to that of optical or IR detectors with an exception that it operates in event detection mode owing to higher energies of X-ray photons. The photons entering the working volume of a detector ionize the atoms and generate free charge. These charges are converted into electronic signal and stored along with certain useful information about the interaction. The stored information includes the arrival time of the photons, their energy, number, location on the detector, and polarization state. As is most often the case, it is only possible to precisely store information about one or two of these properties with high level of accuracy. Most X-ray detectors do not discriminate between real X-ray photons and other high energy charged particles. Sometimes, they even detect infrared and optical radiation. Therefore, the system must be designed in such a way that it enables the user to differentiate between the real signals and the artificial ones.

Several types of detectors have been developed based on the scientific goals with varying degrees of specifications. Proportional counters are one of the simplest devices and thus, historically most widely used. The PCA and LAXPC onboard *RXTE* and *AstroSat*, respectively, are a couple of examples of proportional counters at their best. A typical counter consists of a grounded box of high pressure inert gas and a window which can allow X-ray radiation. A high voltage wire passes through the middle that attracts the electrons generated during the photon interaction. These electrons while drifting towards the anode ionize other gas atoms causing an avalanche effect. This amplifies the original signal which is then stored and telemetered along with information about the time of arrival. In proportional counters, the charged particles are

most probably generated by the process of photoelectric effect. Because of the very nature of these detectors no positional information can be stored. However, the readout in these counters can be extremely fast. The other most widely used detector is a Charged Coupled Device (CCD). Their high sensitivity and linear brightness response have made them ubiquitous in all of astronomy. Many X-ray instruments such as SXT (AstroSat), EPIC (XMM Newton), XRT (Swift), etc are equipped with state-of-theart CCDs. A CCD is made of an array of semiconductors which generate electron-hole pairs upon a photon interaction. The charge pairs are then collected in pixels by application of electric fields. The charge stored in each pixel is then transferred through the adjacent pixels till the end where a readout amplifier digitizes and stores it. Both positional and spectral information can be stored with high level of accuracy using CCDs. Fast timing response can also be achieved by trading off positional information. Most CCD-based detectors have special modes where only a part of the CCD, illuminated by the source, is read out to decrease the readout time. However, even with such a trade-off time resolutions much better than 100 ms are difficult to attain. The CZT (CdZnTe) detectors are the preferred instrument for detection of hard X-rays (> 10) keV). Most modern hard X-ray detectors such as BAT (Swift), CZTI (AstroSat), and FPM (NuSTAR) use CZT detectors. The operation of these detectors is similar to the CCD with the difference that here each pixel is read out separately unlike the row-wise charge transfer in CCDs. CZT detectors are opted over CCDs for hard X-ray detection owing to their higher cross-section than silicon resulting in better quantum efficiency. More details about different kinds of detectors and their properties are available in Knoll (2000) and Arnaud et al. (2011)

2.1.2 X-ray Observatories

In the following subsections, a brief introduction of the six X-ray telescopes used in this thesis is given.

2.1.2.1 Rossi X-ray Timing Explorer (RXTE)

Launched on 30 December 1995, the Rossi X-ray Timing Explorer (Bradt et al., 1993) is one of the most illustrious X-ray astronomy missions to have orbited earth. *RXTE*

housed three scientific instruments - (1) All Sky Monitor (ASM; Levine et al., 1996), (2) High Energy X-ray Timing Experiment (HEXTE; Rothschild et al., 1998), and (3) Proportional Counter Array (PCA; Jahoda et al., 2006).

With a field-of-view (FOV) of $3' \times 15'$, the ASM scanned 80 % of the sky in each orbit. It operated in the soft X-ray regime of 2 - 12 keV and a time resolution of 1/8 s. The ASM helped in identifying state transitions and outbursts from transient sources, thus, triggering a prompt follow-up with other instruments and satellites.

The HEXTE consisted of two scintillator detectors with an effective area of 800 cm²each. It operated in the energy band of 15 - 250 keV with a modest resolution of $\sim 15\%$ at 60 keV.

The PCA was the primary workhorse of RXTE guiding most of its groundbreaking discoveries. It provided an unprecedented time resolution of ~ 1µs and operated in the energy range of 2 - 60 keV with a nominal resolution of < 18% at 6 keV. It consisted of five Proportional Counter Units (PCUs) amassing a total effective area of ~ 6500 cm². Each PCU had five layers - one propane-filled veto layer on the top, three xenon-filled layers in the middle, and one xenon-filled veto layer at the bottom. The PCA was co-aligned with the HEXTE and had the same collimated FOV of ~ 1°. Together, both these instruments provided a wide energy coverage of 2 - 250 keV.

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

XMM Newton is the Europe's largest and one of the most powerful X-ray telescopes to have been developed in the world. Having been launched on 10 December 1999, it is the past millennium's last satellite and has since then ushered an era of high resolution X-ray spectroscopy. XMM Newton houses three focusing telescopes with a focal length of 7.5 m. Each of its mirror modules consist of 58 Wolter-I wafer-thin concentric mirrors nested together to offer a collecting area of 4650 cm²at 1.5 keV. There are three instrument systems onboard XMM Newton , namely the European Photon Imaging Camera (EPIC; Lumb et al., 2000), the Reflection Grating Spectrometer (RGS; Erd et al., 2000), and the Optical Monitor (OM; Horner & Welty, 1995). Apart from its top-notch specifications, the orbit of XMM Newton is made highly eccentric to allow long uninterrupted observations aiding the study of the early universe.

The OM consists of a Ritchey-Chrétien optical/UV telescope with a 30 cm

aperture and is co-aligned with its X-ray counterparts. It is sensitive in the 180 -650 nm range within which it uses six broad band filters and two grisms. It provides simultaneous visible and UV coverage of the X-ray sources.

All three telescopes of XMM Newton have an EPIC at the focal plane. The system consists of one pn-CCD and two Metal-Oxide Semiconductor (MOS)-CCDs operating in 0.1 - 15 keV range. The EPIC-pn is composed of an array of 12 CCDs totalling an effective area of 1227 cm²at 1 keV and an FOV of 27.5' \times 27.5'. Each EPIC-MOS, on the other hand, consists of 7 CCDs having an effective area of 922 cm²at 1 keV and an FOV 33' \times 33'. The EPICs have a spectral resolution (E/dE) of \sim 20 - 50. They also allow several science modes for data acquisition - (1) Full Frame and Extended Full Frame mode for pn only, (2) Partial Window mode, and (3) Timing mode. Of importance to us is the Timing mode where the CCD is read out with a time resolution of 0.03 ms. This mode is specially designed for bright sources to avoid pile-up and telemetry saturation. In this mode the spatial information is conserved only in one dimension as the charges in the other dimension are collapsed and shifted to be read out at a high rate. For EPIC-pn there is another special mode called as Burst mode with even a higher time resolution of 0.007 ms.

The RGS consists of Reflection Grating Assemblies (RGA) and RGS Focal Cameras enabling high resolution spectroscopy in the 0.3 - 2.5 keV range. These are mounted in the path of two EPIC-MOS cameras and deflect about 50 % of the light onto nine MOS CCDs. It has an effective area of 185 cm²at 1 keV and a high spectral resolution of 200 - 800.

2.1.2.3 Neil Gehrels Swift Observatory (Swift)

The *Swift* observatory (Gehrels et al., 2004) was launched on 2004 November 20 with the objective of detecting gamma-ray bursts (GRB) and then *swiftly* following up the afterglow with multi-wavelength observations. It is still operational and contributes significantly not only to the study of GRBs but all kinds of X-ray sources in the sky. To achieve its primary objective *Swift* employs a hard X-ray wide-field imager, namely, the Burst Alert Telescope (BAT; Barthelmy et al., 2005) which quickly detects a source and sends the position to the spacecraft. Following the detection, the spacecraft slews to point at the source coordinates and carries out observations in X-rays with the X- ray Telescope (XRT; Burrows et al., 2005) and in UV and optical wavebands using the Ultra-violet/Optical Telescope (UVOT; Roming et al., 2005).

The BAT is a highly sensitive coded mask imager with a FOV of 1.4 steradians. It is designed to calculate the position of a burst with an accuracy of ~ 4' within a few seconds. After some onboard merit estimation, it sends the position to the spacecraft to slew to the location for pointed follow-up observations. The CdZnTe detectors of the BAT make it sensitive to high energy photons in the range of 15 - 150 keV with the coded mask and upto about 500 keV without it. The D-shaped coded aperture mask is made of 54000 lead tiles and placed 1 m above the detectors. This arrangement results in a total detection area of 5200 cm². The BAT has two running modes - burst and survey. The burst mode specializes in locating GRB positions and the survey mode scans the hard X-ray sky collecting count-rate data in five-minute bins for 80 energy intervals.

The XRT is a CCD-based focussing X-ray telescope with an effective area of 110 cm^2 at 1.5 keV. The grazing incidence Wolter I optics delivers an FOV of $23.6' \times 23.6'$ and an angular resolution of 18". It operates in the soft X-ray range of 0.3 - 10 keV with a spectral resolution of $\sim 260 \text{ eV}$ at 5.9 keV. The XRT has four operating modes depending on the source brightness. They are (1) Imaging mode (IM), (2) Photo-Diode mode (disabled), (3) Photon Counting mode (PC), and (4) Windowed Timing mode (WT). The XRT operates in the IM only for calculating the X-ray position of new GRBs. It generates only an integrated image without any event recognition. The PC and WT modes provide full energy resolution aiding spectroscopy and are selected onboard based on the count rate so as to avoid pile-up. The PC mode works in the low count rate regime (~ 0.5 counts s⁻¹) where the entire CCD frame is read out in the traditional charge transfer way. This results in a complete 2D image of the source, but at the cost of time resolution which is limited by the read-out time of 2.5 s. The WT mode, on the other hand, operates in a high count rate regime without CCD pile-up for upto ~ 100 counts s⁻¹(Romano et al., 2006). This comes at the expense of losing the spatial information wherein ten rows are compressed together and only the central 200 columns (~ 8') of the FOV are read out. The resultant is a single strip image oriented along the spacecraft roll angle. Since the data is read out rapidly, the WT mode allows a high time resolution of 1.8 ms.

The UV and optical counterparts of the afterglow of GRBs decay rapidly necessitating a quick response camera. This requirement of a rapid response UV/optical telescope is satisfied by the UVOT. The UVOT consists of a modified Ritchey-Chrétien telescope with a 30 cm aperture. It provides simultaneous UV and optical coverage (170 - 650 nm) with a FOV of $17' \times 17'$. It has three UV filters, namely W1 (2600 Å), M2 (2246 Å), and W2 (1928 Å) and three optical filters, namely V (5468 Å), B (4392 Å), and U (3465 Å) (Poole et al., 2008; Breeveld et al., 2011). Along with these six, there is also a white light or open filter. Unlike the ground based telescopes, the UVOT operates in photon counting mode similar to the X-ray detectors.

2.1.2.4 Nuclear Spectroscopic Telescope Array (NuSTAR)

NuSTAR (Harrison et al., 2013) is the first observatory, and the only one so far, to employ focusing optics in the hard X-ray regime of 3 - 79 keV. Employing state-of-theart optics and detector technology NuSTAR extends high sensitivity and resolution to hard X-rays. It was launched on 13 June 2012 under NASA's Small Explorer Mission. The telescopes are developed to have a conical approximation of Wolter-I design having a focal length of 10.15 m. To achieve this huge length, NuSTAR employed a deployable mast. The exact positions of the optics and the focal plane is determined using a laser metrology system.

Each mirror unit consists of 133 concentric shells, each of which is coated with depth-graded multilayers of high and low density materials. The use of Pt/SiC and W/Si multilayers enables NuSTAR to achieve reflectivity upto 78.4 keV. Each of the telescopes has its own detector system called as Focal Plane Modules A & B (FPM). The FPMs are made up of four (2 × 2) pixelated CdZnTe detectors resulting in a FOV of ~ 12' and an energy resolution of 400 eV at 10 keV and 900 eV at 68 keV. The electronics of the FPMs is cleverly designed in such a way that the read-out process of each pixel is individually triggered upon an X-ray interaction. This ensures that NuSTAR observations do not suffer from pile-up until a flux of about 10⁵ counts s⁻¹pixel⁻¹ is reached.

2.1.2.5 AstroSat

AstroSat is a multi-wavelength satellite enabling simultaneous observations in the UV, optical, and X-ray wave bands. Launched on 28 September 2015, it is India's first of its kind. It has five primary science instruments - (1) Ultra Violet Imaging Telescope (UVIT; Tandon et al., 2017), (2) Soft X-ray Telescope (SXT; Singh et al., 2016, 2017), (3) Large Area X-ray Proportional Counter (LAXPC; Yadav et al., 2016b,a; Antia et al., 2017), (4) Cadmium Zinc Telluride Imager (CZTI; Vadawale et al., 2016; Bhalerao et al., 2017), (5) Scanning Sky Monitor (SSM; Ramadevi et al., 2017) and a Charge Particle Monitor (CPM). The CPM measures flux of electrons and protons in the South Atlantic Anomaly (SAA) region and instructs the satellite to lower or switch off the high-voltage to prevent detector damage and ageing of the proportional counters. The capabilities of AstroSat can be likened to the combined capabilities of Swift and RXTE observatories. While the SXT, BAT, and UVOT are analogous to the XRT, CZTI, and UVIT the LAXPC and SSM are similar to the PCA and ASM. However, there does remain significant differences among them.

The SSM surveys the sky in the 2 - 10 keV range with the help of three position sensitive proportional counters equipped with a 1D coded mask. It is intended for long term monitoring of X-ray bright sources, detection and localization of new outbursts.

The UVIT consists of two 38 cm telescopes sensitive in far-UV to optical bands. It operates in three bands: (1) Far-UV (130 - 180 nm), (2) Near-UV (180 - 300 nm), and (3) optical (320 - 530 nm). Each of the bands has their separate detector systems. The UVIT is capable of achieving high angular resolution of 1.8'' in the UV and 2.5'' in the optical bands. Its FOV is a circular region of 28' diameter.

The SXT uses focusing optics and deep depletion CCD to perform imaging and spectroscopy in the 0.7 - 8 keV band. The optics consists of 41 gold-coated conical concentric shells in an approximate Wolter-I configuration. With an effective area of 90 cm²at 1.5 keV, SXT has an FOV of ~ 40' diameter and a focal length of 20 cm. It has an energy resolution of 90 eV at 1.5 keV and 136 eV at 5.9 keV. The readout occurs either in a full-frame or a centered-pixel frame mode with time resolutions of 2.4 s and 0.278 s respectively.

The LAXPC consists of three proportional counters with a large effective area

of about 6000 cm²in 5 - 20 keV. It operates in a broad energy band of 3 - 80 keV. Its huge detector volumes are filled with high pressure (2 atm) Xe gas that results in an enhanced detection efficiency of > 50% in the 30 - 50 keV band. Each LAXPC has five anode layers with each layer having 12 anode cells and is surrounded on three sides with Veto cells. It has a collimated FOV of $0.9^{\circ} \times 0.9^{\circ}$. LAXPC boasts of a very high time resolution of 10 μ s making it ideal for studying fast variability of various sources. It also has a modest spectral resolution of 12 - 15 % in 22 - 60 keV.

The CZTI is a hard X-ray imaging instrument operating in 25 - 150 keV. The detector system of the CZTI consists of 64 CZT modules having a total geometric area of 976 cm². The imaging ability of CZTI is achieved by the use of a 2D Coded Aperture Mask. The collimated FOV of each detector module is $4.6^{\circ} \times 4.6^{\circ}$. The collimators and the coded mask become progressively transparent above 100 keV and CZTI acts as an open detector. It has a spectral resolution of ~ 6% at 100 keV and a time resolution of 20 μ s.

2.1.2.6 Neutron Star Interior Composition Explorer (NICER)

NICER is one of the newest additions to the army of X-ray astronomy satellites committed to explore the high-energy universe. It aims to provide high precision measurements of the masses and radii of neutron stars which will constrain the equations of state of the neutron star's interior. It was launched on 3 June 2017 and operates as a payload of the International Space Station. *NICER* achieves its objective with fast timing and spectroscopic measurements complemented by low background and high throughput. It has one primary science instrument, namely, the X-ray Timing Instrument (XTI; Gendreau et al., 2016)

The XTI is an array of 56 X-ray concentrator optics (XRC) with silicon drift detectors (SDD) at the focal plane. The XRCs collect photons from a large FOV $(30'' \times 30'')$. The SDDs operate in the 0.2 - 12 keV range and are read out at an unprecedented time resolution of < 300 ns. Because of its high effective area of ~ 2000 cm²at 1.5 keV, its energy resolution is comparable with the focusing optics instruments like XMM Newton and Chandra (85 eV at 1 keV and 137 keV at 6 keV).

2.1.3 Mt Abu Infrared Observatory (MIRO)

The Mount Abu Infrared Observatory (*MIRO*), managed by Physical Research Laboratory, Ahmedabad, houses a 1.2m f/13 telescope with Cassegrain focus. It is located near the Guru Shikhar peak of the Aravalli range of hills in the state of Rajasthan. With an altitude of ~ 1680 m and seeing of ~ 1.2', *MIRO* allows 150 - 200 observing nights per year. Out of the many back end instruments in operation, two were used in this work - 1) Near Infrared Camera/Spectrograph (NICS; Anandarao et al., 2008), and 2) Optical CCD. The optical filters (B,V,R,I) are in Johnson-Cousins photometric system and the NIR (J,H,Ks) filters are in MKO system.

2.2 Spectral Analysis

2.2.1 The rationale

The observed spectrum of a source is obtained in terms of instrumental quantities, i.e., as photon counts (C) as a function of instrument channel (I). This count spectrum is governed by the transfer function of the entire telescope and detector which needs to be decoded. However, what we are interested in is the intrinsic source spectrum (S), i.e., count rate per energy bin. The actual spectrum is related to the observed spectrum as follows:

$$C(I) = \int S(E) R(I, E) dE \quad , \qquad (2.1)$$

where R(I, E) is the response matrix of the instrument. R(I, E) is a product of the redistribution matrix (RMF - Redistribution Matrix File) and the instrument effective area (ARF - Auxiliary Response File). The RMF is a matrix that encodes the probability that a photon with energy E has to be detected in the channel I. The seemingly simple task now is to invert the equation and obtain S(E) for different values C(I). Unfortunately, it turns out that equation 2.1 is not invertible because of the cross-talk between different energy intervals in the RMF. Besides, any attempt to invert the equation will be unstable to changes in C(I) and non-unique. This dilemma leads us to an alternative known as "forward-folding approach". Under this scheme, a model with a number of free parameters is assumed to mimic the actual source. This
model is convoluted with the instrumental response to output a spectrum in the same units as the observed spectrum. The folded model and the observed spectrum are then compared and the degree of agreement between the two is judged by calculating a goodness-of-fit statistics. The parameters of the model are then varied to obtain a desirable fit statistic. After securing the best fit, confidence intervals are calculated for the best-fit parameters. The most common statistic, and the one used in this thesis, is χ^2 which is defined as:

$$\chi^2 = \sum \frac{(C(I) - C_p(I))^2}{\sigma(I)^2} \quad , \tag{2.2}$$

where $C_p(I)$ is the predicted count rate from the model and $\sigma(I)$ is the error for each channel and is estimated as $\sqrt{C(I)}$. χ^2 statistics requires that the counts (background subtracted) in each spectral channel is approximated by a gaussian distribution. The rule-of-thumb while fitting is to ensure that the "reduced χ^2 " (χ^2_{ν} , where ν is the number of degrees of freedom and is obtained by subtracting the number of free parameters from the number of channels) approximately equals one. As will often happen, more than one model can fit a data well, especially when the data is poor. In such a scenario, the correct model is chosen by comparing the physical relevance of the best-fit parameters.

2.2.2 Data reduction

After the observation is done, the data are stored in a flexible image transport system (FITS; Pence et al., 2010) format as an "event" file. It is named so because it saves the information of each interaction of the detector, an event, with photons or charged particles. The primary information that are stored in an event file are the photon (or particle) interaction time, the position of the interaction (X and Y coordinates for a CCD and layers for a proportional counter), the pulse-invariant channel (energy information), and the count rate. Along with these, many other auxiliary information are also stored. Most of the times, the raw event file (the so-called Level 1) is unusable and needs to be reprocessed to generate a cleaned and filtered event file (the so-called Level 2). The filtering criteria varies from instrument to instrument, but mostly it involves the removal of the obvious sources of spurious signals, such as those originating due to bad (hot or flickering) pixels, undershoot and overshot of the discriminators, afterglows etc. The information about these issues are stored in the Calibration Database (CALDB *). The analysis pipelines of most of the observatories also provide enough flexibility to the users to customize the reduction process as per need. Once the cleaned event file is created, the next task is to extract science products, i.e., spectra, lightcurves and images. While some observatories like RXTE and AstroSat (LAXPC) have their own extractors, others like NICER and Swift are reduced using the common FTOOL xselect [†] for extraction of the science products. The details of the analysis procedure for different instruments used in the thesis will be discussed in the respective chapters.

Once the spectrum is extracted, the next job is to find a suitable model that mimics the source and fit (Section 2.2.1). The fitting is carried out using packages such as **xspec**, **Sherpa**, **ISIS**, etc. These are basically looping engines that vary the model parameters with an aim of reducing the fit statistics (e.g., equation 2.2). In this thesis, **xspec** is used for fitting both the energy and power spectra. One advantage of **xspec** is that it has a huge repository of empirical and physical models. In the next subsection, the properties of some of these models used in the thesis are discussed.

2.2.3 Spectral models

As discussed in Section 1.4.1, the X-ray spectrum of a black-hole binary typically consists of three components - a thermal blackbody, a power law for Comptonization, and a reflection component. Figure 2.1 shows the typical shapes of the three models. Several models have been developed over the years trying to compute the spectrum of one or more of these components. In this section, the models used in the thesis will be discussed in detail.

2.2.3.1 Empirical models

Before moving to physical modeling, it is always useful to first fit the spectrum with empirical models to examine the general properties. Sometimes, results from empirical model fitting can also give valuable information about the source. Some of the common xspec models used in this work are diskbb, powerlaw, and gaussian to

 $[*]https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_intro.html$

[†]https://heasarc.gsfc.nasa.gov/ftools/xselect/



Figure 2.1: The three principal components of the X-ray spectrum for a black-hole binary. The blue, red, and green curves represent the thermal disk, Comptonization, and reflected components respectively. The black curve shows the total spectrum. (Figure courtesy: Gilfanov, 2010)

account for the thermal emission from an accretion disk, power-law emission due to inverse Comptonization, and emission lines. Out of the three, the **diskbb** model is the one which is motivated by physical processes occurring in the thin accretion disk. Developed by Mitsuda et al. (1984), it is one of the earliest accretion disk models inspired by the Shakura & Sunyaev (1973)'s thin disk prescription and is still widely used. **diskbb** is basically a multi-temperature blackbody model based on Planck's law. The disk is divided into small annular segments and blackbody emission from each of these segments is added up to give the total flux. The inner most annulus has the highest temperature and primarily dominates the X-ray spectrum. The temperature profile varies as $T(R) \propto R^{-3/4}$, where R is the radius of the annulus. The model has only the inner-disk temperature (T_{in}) and the norm as a free parameter. The norm, which is defined as $(r_{in}/D_{10})^2 \cos \theta$, can be used to predict the inner-disk radius using the correction factor spelled out by Kubota et al. (1998) for a given value of distance $(D_{10}, in units of 10 \text{ kpc})$ and inclination angle (θ).

2.2.3.2 Thermal disk models

diskpn (Gierliński et al., 1999) is an extension of the diskbb model with an improved temperature distribution near the black hole. As mentioned above, diskbb assumes an asymptotic temperature profile which makes T_{in} achieve higher values as the disk moves closer to the black hole ($R \lesssim 6R_g$, where R_g is the gravitational radius). The fact that the disk truncates at some distance from the black hole implies that the innermost boundary of the disk will not experience any torque. Therefore, the temperature, and hence the emission, will sharply fall from a point, with maximum temperature (T_{max}) , which is slightly farther from the actual inner boundary of the disk. Such a temperature profile is more physical, especially for soft state spectra when the disk is believed to truncate at the ISCO. diskpn attains such a profile by incorporating a pseudo-Newtonian potential calculated by Paczyńsky & Wiita (1980). Apart from T_{max} , diskpn has the inner radius of the disk (R_{in}) as a free parameter. Here, the norm is defined as $M^2 \cos \theta / (D^2 \times \beta^4)$ where M is the black-hole mass (in units of solar mass), D is distance in kpc, and β is the spectral hardening factor defined as the ratio of color and effective temperature. One more advantage of diskpn is that the mass accretion rate can be calculated using T_{max} (Gierliński et al., 1999). The Compton upscattered photons can back scatter and irradiate the disk and consequently changing its temperature profile substantially. This effect becomes important during the hard states when the ratio of Compton to unirradiated disk luminosity becomes \gg 1. The model diskir (Gierliński et al., 2008) incorporates this and parameterizes the illuminated radiation by the fraction of irradiation f_{in} and the radius of Compton illuminated disk r_{irr} . The Compton tail can also irradiate the outer disk which makes the reprocessed emission dominate in ultraviolet or optical wave bands. To facilitate multi-wavelength spectral fits for the irradiated accretion disk, diskir includes f_{out} , the fraction of bolometric flux that thermalises in the outer disk, and r_{out} , the outer disk radius, as free parameters (Gierliński et al., 2009). An even more advanced model for thermal disk emission is kerrbb. kerrbb is a general relativistic model for a thin and stable accretion disk around a kerr black hole. It includes many second order relativistic effects such as frame-dragging, gravitational redshift, Doppler boost, and bending of light. It also includes effects of self-irradiation and allows non-zero values

for the torque at the inner boundary of the disk. kerrbb has many free parameters such as black-hole mass, distance, spin, inclination, and mass accretion rate. It allows different values for the spectral hardening factor and has flags for including effects of self-irradiation, limb darkening, and torque at the inner boundary. Over the years kerrbb has been used to estimate the values of some system parameters for a known value, or range, of other parameters. It has been one of the primary tools for estimating the spin parameter using continuum fitting method (Kulkarni et al., 2011; Reis et al., 2011; Gou et al., 2011; Steiner et al., 2011). Similarly, Parker et al. (2016) estimated the mass of the black hole in GX 339–4 using kerrbb where the spin and inclination were estimated from reflection spectroscopy.

2.2.3.3 Comptonization models

nthComp (Zdziarski et al., 1996; Życki et al., 1999) is one of the common models for thermal Comptonization. The cutoff at higher energy is parameterized by the electron temperature (kT_e) . It is sharper than an exponential cutoff of the cutoffpl model. At the lower energy also the Comptonized spectrum experiences a rollover which is driven by the seed photon energy. Between these two rollovers the shape of the spectrum is decided by the electron temperature and the scattering optical depth which is approximated by an asymptotic power law with index Γ . A more advanced version of thermal Comptonization model is ThComp (Niedźwiecki et al., 2019). It calculates the spectrum by Comptonization of sinusoidally distributed seed photons from a spherical cloud of thermal electrons. ThComp can Comptonize both hard and soft seed photons as it is a convolution model. It describes both downscattering and upscattering and agrees more with Comptonized Monte Carlo spectra than nthComp (Zdziarski et al., 2020).

2.2.3.4 Reflection models

The relxill reflection model (García et al., 2014; Dauser et al., 2014) is a combination of the advanced code xillver (García & Kallman, 2010; García et al., 2011, 2013) and the relativistic line-emission kernel relline (Dauser et al., 2010, 2013). It incorporates the angular dependence of reflection with radius of the accretion disk and allows a

proper treatment of ionization balance by including the recent photoionization data (Kallman & Bautista, 2001). relxill allows two basic geometries for the calculation of emissivity - (1) extended corona (relxill) and (2) lampost corona (relxillp). In the extended-corona flavour the emissivity follows a broken power law, while for the lampost geometry the corona is assumed to be a point-like source over the rotation axis of the black hole and the emissivity is calculated from the coronal height (h) which is a free parameter in the model. The model can calculate both the reflected spectrum and the illuminating continuum. The user has the freedom to opt for both or only consider the reflection spectrum from **relxill** and use a separate component for the illumination. Two types of illuminating continua have been included - (1) a power law with exponential cut-off and (2) nthComp -type thermal Comptonization (implemented with a suffix Cp). The later, being a more physical description of the illumination, has been found to provide substantial improvement to the fits. The reflection fraction in relxill is defined as the ratio of the coronal flux that is reflected from the disk to the flux that directly reaches the observer. For a lamppost with small height the reflection fraction will be high due to the gravitational bending of light near the black hole (Miniutti & Fabian, 2004). The reflected continuum not only depends on the emissivity profile but also on the ionization state, disk density and iron abundance of the accretion disk. However, these parameters have been found to be degenerate and hence should be interpreted with caution (Tomsick et al., 2018; Jiang et al., 2019). Apart from the parameters that define the shape of the reflected continuum, relxill also estimates the spin and inclination by fitting the relativistically smeared fluorescent Fe line (Ludlam et al., 2015; Rout et al., 2020). It must be noted that this model is in continuous developmental stage and gets updated often with more advanced features. One should also be aware that several assumptions have been made in the relxill family of models which are not physical in nature. For instance, the disk density is assumed to be independent of height, the abundance of elements other than iron is fixed to solar values, and the irradiation angle is kept constant at 45° .

Besides these, a few other important effects have also not been taken into account which have been later found to affect the spectroscopy (Niedźwiecki et al., 2016). For a small height ($h \leq 5 R_g$) of the source in a lamppost model and steep emissivity profiles, gravitational redshift is neglected. This leads to the underestimation of the cutoff energy in the Comptonization spectrum and also affects the shape of the reflected spectrum. The returning (reflected) radiation due to light-bending effect from near the black hole can also irradiate the disk. Such a second-order effect can significantly change the reflected spectrum for $h \lesssim 3$. Compton scattering in the xillver code is treated in a non-relativistic way and hence the reflected flux at higher energies ($\gtrsim 20 \text{ keV}$) is incorrect, especially for small h and steep radial profile (Zdziarski & Gierliński, 2004). These limitations in the relxill model were corrected in a newer reflection model reflkerr (Niedźwiecki et al., 2019). Here, the incident spectrum is calculated using the compps model (Poutanen & Svensson, 1996) which agrees well with the simulations compared to the nthComp model incorporated in relxill. reflkerr includes the primary source on both sides of the disk which is important for calculation of the reflected spectrum for a truncated disk (Niedźwiecki & Zdziarski, 2018). The parameters for reflkerr are mostly similar to relxill with a few differences. The photon index is replaced by optical depth τ_y and there is flag for choosing a geometry for the Comptonizing source. There is also an option to include or exclude contribution from the bottom of the lamp.

2.3 Temporal Analysis

The study of the rapid time variability of binaries is primarily done in the Fourier space. The simple reason is that the interesting features, such as QPOs, occur at very high frequencies and with low fractional amplitudes compared to the Poisson noise and, therefore, they can not be directly detected in the time series. Only very low frequency oscillations are sometimes studied in the time domain (e.g., Stiele et al., 2016). The requirement for Fourier analysis is uninterrupted high time resolution data of considerably long segments whose length exceeds the characteristic time scales of the PDS features. The details of the Fourier techniques are presented in van der Klis (1989).

For constructing a power spectrum, the following steps are taken. The time series, x(t), is divided into a number of contiguous segments of equal length. Each of these segment is Fourier transformed using the Fast Fourier Transform algorithm (FFT)and converted to the frequency domain $(x_i(t) => X_i(\nu))$. The lowest frequency



Figure 2.2: The four steps followed during calculation of power spectrum. Courtesy: Stefano Rapisarada

 (ν_{min}) and the frequency resolution $(\delta\nu)$ are determined by the length of each segment (T), i.e., $\delta\nu = 1/T = \nu_{min}$. Accordingly, the highest detectable frequency, also known as the Nyquist frequency (ν_{Ny}) , is governed by the time resolution of the data δt , i.e., $\nu_{Ny} = 1/2\delta t$. In the field of signal processing, this condition is called as Nyquist-Shannon sampling theorem. The consequence of this is that for studying low and high frequency variability we need long segments and high time resolution data, respectively. The power is computed as the squared modulus of the Fourier amplitudes, i.e., $P_i(\nu) = |X_i(\nu)|^2 = X_i^*(\nu)X_i(\nu)$. This power is then Leahy normalized by dividing a factor $2/X_i\nu_0$ (Leahy et al., 1983), where ν_0 equals the number of photons in $x_i(t)$ and is called the zero-frequency component. The Leahy normalized power spectra of all the segments are then averaged to form a single power spectrum $P(\nu)$ whose Poisson noise level is approximately 2. The relative error of the power is given by $\sigma_P/P = 1/\sqrt{n_p n_f}$ where n_p and n_f are the numbers of the power spectra and frequency bins averaged, respectively, and the product $n_p n_f$ is large enough. Finally, the Poisson noise subtracted and Leahy

normalized average power spectrum is normalized to give the fractional root-meansquare (rms) amplitude by dividing the power by mean count rate (van der Klis, 1997; Vaughan et al., 2003). With this normalization, the fractional rms of the lightcurve can be computed by integrating the power spectrum over all the frequencies. A typical power spectrum, shown in Figure 1.3, consists of different features. The peaked features are the QPOs and the broadband features spread over several decades in frequency are the noise. The power spectrum of black-hole binaries can be fitted by a combination of Lorentzians (Nowak, 2000; Belloni et al., 2002).

Chapter 3

Multi-wavelength view of the galactic black-hole binary GRS 1716–249

3.1 Introduction

During outburst, an LMXB (low mass X-ray binary) brightens by several orders of magnitude in the entire electromagnetic spectrum. While the origins of radio and X-ray emission are better understood, the mid-energy emission in ultra-violet (UV), optical, and infrared (IR) poses a certain level of ambiguity as there are multiple sources for their emissions (Done et al., 2007; van Paradijs & McClintock, 1995; Falcke & Biermann, 1996; Charles & Coe, 2006). The emission from outer accretion disk occurs in longer wavelengths compared to X-rays and is further escalated by irradiation by X-rays from the inner disk and/or back scattered photons from the corona (Hameury, 2020). The strength of this irradiation depends on the geometry of the corona and scale height of the outer disk (Cunningham, 1976; van Paradijs & McClintock, 1994). The companion star, which in case of LMXBs is a late type M, K, or G class star, peaks in optical or IR (OIR) wavelengths. This emission from the companion is also enhanced by irradiation of X-rays from the accretion disk by a few to several percentage. Synchrotron emission from relativistic jets can also dominate the OIR flux (Corbel & Fender, 2002; Russell et al., 2006). In fact, the crucial break frequency dividing the

optically thick and thin portion is believed to lie in the OIR bands which can help in quantifying the total energy content of a jet (Russell et al., 2013). However, this break frequency is observed only in a very few sources with good significance (Coriat et al., 2009).

Deciphering the correct emission mechanism behind UV, optical, and IR emission remains challenging. Many techniques have been developed over the years to ascertain their true origin. Emissions from jet are known to show rapid variability in short time scales whereas those from disk or irradiated disk remain stable (Gandhi et al., 2008). High cadence observations in OIR bands can shed some light on the mechanism involved in its emission (Curran & Chaty, 2013; Kosenkov et al., 2020). The study of correlations between contemporaneous OIR and X-ray emission can also help in picking the dominant mechanism (Russell et al., 2006; Bernardini et al., 2016). Fitting a simultaneous broadband spectral energy distribution (SED) spanning radio to X-rays is also a well-established method. Furthermore, there are several models which attempt to explain the low frequency radiation by Synchrotron emission from a hot plasma above the disk (Veledina et al., 2013). In these models, the hard X-ray emission is produced by thermal Comptonization of soft Synchrotron photons. Optical excess is also thought to be produced from magnetic reconnections in flares on the disk (Merloni et al., 2000) or from gravitational energy release near the circularization radius (Campana & Stella, 2000). The problem, however, remains that of degeneracy wherein multiple models are able to satisfactorily explain the emissions whereas the available data are unable to discriminate between various competing models. Here we attempt to discern the origins of the near infrared (NIR), optical, and UV emissions observed during outburst of a black-hole binary GRS 1716–249 by evaluating the broadband SED.

GRS 1716-249 (aka GRO J1719-24 and Nova Oph 1993; hereafter, to be referred as GRS1716) went into outburst on 18 December 2016 after more than 20 years of quiescence (Negoro et al., 2016). During its discovery outburst in 1993, GRS1716 was measured to be located at a distance of $2.4 \pm 0.4 \, kpc$ along with harboring a K type (or late) companion in a 14.7 hr orbit (della Valle et al., 1994). The lower limit on black hole mass was estimated to be $4.9 \, M_{\odot}$ (Masetti et al., 1996). During 2016, GRS1716 underwent a "failed" outburst wherein it did not transition into high/soft or soft-intermediate state although it tried, on three occasions, to transition into a canonical soft state (Bassi et al., 2019). These softening episodes were marked by increase in the photon index and inner-disk temperature along with a decrease in the inner-disk radius. Bassi et al. (2019) suggest that during these soft phases either the disk reached the inner-most stable orbit or the Corona momentarily condensed to form an inner mini disk. The source also lied in the outlier branch of radio/X-ray correlation plot with $L_R \propto L_X^{1.4}$ *. Bharali et al. (2019) found minimal to no disk truncation along with detecting type C quasi periodic oscillations whose frequency increased with time. Jiang et al. (2020) also concluded similarly about the inner disk radius along with providing constraints on the disk density. With joint *Swift* and *NuSTAR* spectroscopy, Tao et al. (2019) constrained the spin and inclination of the source. The spin was constrained to a high value with $a \ge 0.92$ and inclination was estimated to lie within $40^{\circ} - 50^{\circ}$.

GRS1716 was also observed by AstroSat as a Target of Opportunity on three epochs - 1) 15 Feb 2017 (57799), 2) 6 Apr 2017 (57849), and 3) 13 Jul 2017 (57947). It was also observed from Mount Abu Infrared Observatory during March to May 2017 for 24 nights in optical and NIR bands. We present the joint spectral analyses of all three instruments of AstroSat along with a multi-wavelength SED study to find the origin of NIR/optical/UV emission. The UV data were observed from Swift/UVOT (Ultraviolet and optical Telescope). We have also utilised radio data from the Australian Large Baseline Array in the SED. The observation logs for this work are noted in Table 3.1. All the observations are further marked alongside the full MAXI lightcurve in Figure 3.1.

3.2 Observations and Data Reduction

3.2.1 AstroSat

SXT (Singh et al., 2016, 2017) data were analysed with the standard analysis software and other auxiliary tools developed by the Payloads Operations Center (POC^{\dagger}). sxtpipeline module was run to generate orbit-wise Level 2 event files. This ex-

 L_R and L_X refer to radio and X-ray luminosity respectively.

[†]www.tifr.res.in/~astrosat_sxt



Figure 3.1: MAXI on-demand lightcurve of GRS1716 in $2 - 20 \, keV$ band (black circles Matsuoka et al., 2009). The blue vertical bars mark the three epochs of *AstroSat* observations. UVOT observations in all six bands are depicted with violet bars. Optical (B,V,R,I) and NIR (J,H,Ks) observations from Mt. Abu are represented with red and green vertical bars.

traction takes care of most of the elementary data cleaning and good-time interval (GTI) selection. The event files for every orbit were then merged using the script **sxtevtmergerj1**. Final products were generated using the FTool **xselect** after incorporating custom GTIs to remove flaring regions and drop outs from the lightcurve. SXT spectra are known to be affected by pile up for rates above ~ $40 \ counts/s$ (or 200 mCrab) in Photon Counting (PC) mode. The count rates for GRS1716 during the first two epochs were ~ $42 \ and ~ 59 \ counts/s$ respectively. In order to verify the presence of pile up, annular regions with outer radius fixed at 12' and inner radius varying from 1' upwards were used to generate spectra. Each of these spectra was fitted with an absorbed multi-color disk and power-law model and then the variation of photon index studied. The spectra were found to be piled up and thus annular regions with inner radii of 1' and 2.5' were selected for source extraction for epoch 1 and 2 respectively. The epoch 3 spectrum, with a count rate of ~ $28 \ counts/s$, was not piled up and hence, a circular region of 15' radius was opted. To incorporate the changes in the effective area due to the annular region and vignetting caused by the off-axis positioning of the

Bands	Observatory	Energy/Wavelength	Date
X-ray	Astrosat	1-120keV	15 Ferbruary, 06 April, 13 July
UV	Swift	1928, 2246, 2600 Å	28 January - 13 August
Optical	Swift	3465, 4392, 5468 Å	31 January - 20 October
Optical	MIRO	4353, 5477, 6349, 8797 Å	22 March - 28 May
NIR	MIRO	1.25, 1.64, 2.15 μm	17 April - 25 May
Radio	LBA	8.4GHz	22 April

Table 3.1: List of all observations used in this work. The wavelengths in UV, optical and NIR bands corresponds to the filters in respective instruments. All observations were made in the year 2017. The data for the radio observation was reported by Bassi et al. (2019)

PSF (Point Spread Function), the default ARF (Auxiliary Response File) was scaled using the script sxtARFModule. The response matrix and the background spectra were provided by the POC. The spectra were grouped to have a minimum 30 counts per energy bin and a systematic error of 2% was added.

The analysis of LAXPC (Yadav et al., 2016b,a; Agrawal et al., 2017) data were carried out using the Format A - LAXPCsoftware_Aug4 - package[‡]. LAXPC30 module was affected by gas leakage resulting in continuous gain instability (Antia et al., 2017). Hence, only LAXPC10 and LAXPC20 were chosen for spectral analysis in this work. All the layers of both the LAXPCs were opted to maximise the signal as there were more than 15% of counts in the bottom four layers. Level 2 event files were generated using the tool laxpc_make_event which was followed by the usage of laxpc_make_spectra and laxpc_make_backspectra for source and background spectral extractions. The channels in the spectra were grouped by a factor of 5 and a systematic error of 2% was added.

The reduction of CZTI (Vadawale et al., 2016; Bhalerao et al., 2017) level 1 files to level 2 and final products were carried out using the tool cztpipeline (Version 2.1). Spectrum from only Quadrant 0 was used for analysis as the other quadrants are affected by higher systematics. The spectra were grouped to have a minimum of 30 counts per energy bin and no systematic error was added.

[‡]http://astrosat-ssc.iucaa.in/

3.2.2 Swift /UVOT

GRS1716 was observed several times during the outburst with UVOT onboard *Swift* satellite (Breeveld et al., 2011). Photometry for all the filters (W2, M2, W1, U, B, V) was done using the tool **uvotsource**. A circular region of 5" radius was considered for source while a source-free aperture of 20" radius was chosen for background extraction. The U, B, and V magnitudes of UVOT were converted to Johnson system using the conversion factors described by Poole et al. (2008). The flux conversions were also done using the zero-point values for Vega flux given by Poole et al. (2008). The lightcurves with all six UVOT filters are depicted in Figure 3.2.



Figure 3.2: Lightcurves in UV and optical bands using Swift/UVOT. The top three panels display the lightcurves in UV filters (W2, M2, W1) while the bottom three show the optical lightcurves (U, V, B). The blue dots in V and B bands represent the same filters as observed from *MIRO*.

3.2.3 Mount Abu Infrared Observatory (PRL)

Four campaigns of observations were undertaken spanning 17 March to 28 May 2017 starting from a mid-plateau region to the first quarter of outburst decay of GRS1716 (Joshi et al., 2017). Standard aperture photometry was carried out for optical and NIR



Figure 3.3: Optical and NIR lightcurve of GRS1716 as observed from *MIRO*. From top to bottom, the black points represent the optical filters of B, V, R, I respectively (also labelled on the plots). Similarly, the red points represent the NIR bands of J, H, and Ks respectively.

observations using the IRAF package. NIR observations were acquired in 5 dithered positions separated by $\sim 30''$. These frames were median combined to produce a skyframe which was subtracted from individual raw frames. Individual frames of the raw images for each day was subjected to bias subtraction for optical observations. Variable pixel response was corrected by the standard procedure of flat-field correction for both optical and NIR observations. The instrumental magnitudes of 3 to 4 field stars were then compared with corresponding apparent magnitudes from the standard catalogues viz. SDSS and 2MASS for optical and NIR, respectively, to find a zero point. The R and I band magnitudes of the comparison stars were in Sloan filters. The differences in Sloan and Johnson-Cousins filters were taken into account using transformation equations calculated by Jordi et al. (2006). Similarly, the 2MASS magnitudes of the comparison stars were converted to MKO system[§]. The errors in the transformation equations were propagated in quadrature while calculating the errors in the obtained magnitudes. This zero-point factor was, in turn, considered to calculate the apparent magnitude and standard deviation of the source. The Vega flux for magnitude to flux conversion for all 7 filters were taken from Bessell et al. (1998). The optical and NIR lightcurves with MIRO are shown in Figure 3.3.



Figure 3.4: AstroSat spectra of all three epochs and instruments. From top to bottom - Epoch 1: 15 February 2017 (black), Epoch 2: 06 April 2017 (red), and Epoch 3: 13 July 2017 (blue). The spectrum LAXPC20 is represented by a lighter shade on all three days.

3.3 Analyses and Results

3.3.1 Joint AstroSat spectral fitting

Spectral analysis was carried out by jointly fitting SXT, LAXPC10, LAXPC20, and CZTI using xspec (Arnaud, 1996). The energy ranges of SXT and LAXPC spectra were restricted to $1 - 7 \, keV$ and $5 - 60 \, keV$ respectively so as to avoid higher systematic errors outside these ranges. CZTI spectrum was fitted in the full range of

https://sites.astro.caltech.edu/jmc/2mass/v3/transformations/



Figure 3.5: The top panel displays the residuals of the *AstroSat* spectra with diskir model assuming no irradiation in the inner disk for all three epochs. The bottom panel displays residuals after including irradiation. The color coding is the same as in Figure 3.4. Dots, up-triangles, down-triangles, and squares are used to represent SXT, LAXPC10, LAXPC20, and CZTI respectively.

 $30-120 \, keV$. Thus, the combination of the three instruments resulted in a contiguous and wide energy coverage from 1 to 120 keV. For SXT, an additional gain correction was added using the command gain fit in xspec. The best fit offset was found to be $\sim 40 \, eV$, for a unit slope, which improved the fits significantly[¶]. To adjust for the cross-calibration discrepancy among the different instruments, a constant was multiplied to the model. It was fixed to unity for LAXPC10 and was left free to vary for the rest of the instruments. The average value of the best-fit constant factor for SXT and CZTI varied around $\approx 21\%$ of LAXPC10's factor whereas LAXPC20 varied between $\approx 5\%$. These are within the expected uncertainties in the effective areas of the three instruments.

The AstroSat spectrum was fitted with an absorbed multi-temperature accretion disk - TBabs*(diskbb+nthComp) - for all three epochs. The abundance for ISM absorption in TBabs was set to Wilms et al. (2000). The fit for all epochs were statistically good with a χ^2_{ν} of 1.07, 1.03, and 1.04 for 740, 598, and 569 degrees of freedom respectively. The hydrogen column density (N_H) was constrained to ~ $0.7 \times 10^{22} \, cm^{-2}$, varying by 0.1 across the three epochs. The inner disk temperature and photon index were constrained to ~ $0.3 \, keV$ and ~ 1.7 respectively. The spectrum for all three

[¶]https://www.tifr.res.in/~astrosat_sxt/instrument.html

epochs is depicted in Figure 3.4 and the residuals of the above fit are shown in the top panel of Figure 3.5. Despite good statistics, the residuals seem to be of somewhat wavy nature indicating the presence of reprocessed coronal emission from the disk. Although reflection is a common candidate for reprocessing, we did not find telltale features like broad Fe line or Compton hump in the residuals.

Nevertheless, we checked for the presence of reflection in the spectra by adding a relativistic reflection component - relxillCp - to the existing model. The photon index and cutoff energy in relxillCp were tied to the corresponding parameters in nthComp. The emissivity index was fixed to the Newtonian value and the Fe abundance was set to that of the Sun. The spin parameter was fixed to 0.998 and the inner-disk radius was left free to vary. The possible values of inclination vary between $30^{\circ} - 50^{\circ}$ as reported by various authors (Bharali et al., 2019; Tao et al., 2019). Since inclination could not be constrained, we fixed it to a rough average of 40° . Rest of the parameters were left to float. There was only a marginal improvement in fit compared to the previous model with $\Delta \chi^2$ of 7.7, 10.4, and 24.1 per degree of freedom (dof) for epochs 1, 2, and 3 respectively. The inner radius could not be strongly constrained but hinted towards a possible disk truncation. Fixing spin to intermediate and Schwarschild values like a = 0.7, 0.3 & 0 also did not have any effect. The cutoff energy was only weakly constrained in the first epoch at $74.2^{+52.8}_{-14.3}$. For the other two cases, it pegged at the maximum limit and could not be constrained. This is in contrast to the values obtained by Bassi et al. (2019) who strongly constrained kT_e to ~ 48 and ~ 52 keV for the first two epochs, and weakly at $\sim 74 \, keV$ for the third. This is probably due to competition of the Compton hump to fit the curvature around $40 - 50 \, keV$ which resulted in the cutoff energy being unconstrained.

In the hard state of black-hole binaries, thermalization of Comptonized photons in the inner disk can also substantially contribute to the disk emission (Gierliński et al., 2008). To test this, the spectrum was fitted with the **diskir** model (Gierliński et al., 2008). **diskir** is a hybrid of both blackbody and Comptonization components. It parameterizes irradiation by two additional components - 1) Fraction of Compton tail that is thermalized (f_{in}), and 2) Radius of Compton illuminated disk (r_{irr}); along with calculating the ratio of luminosities in Compton tail and unilluminated disk (L_c/L_d). It also has two more parameters for effects of irradiation at the outer disk. These parameters were frozen to nominal values as they would not affect X-ray emission and would be considered in the next exercise where broadband SED fitting is undertaken. First, irradiation was turned off by freezing f_{in} to 0. The best-fit parameters and fit statistics were almost identical to the previous fits with TBabs*(diskbb+nthComp). The values of L_c/L_d were constrained around 5 indicating strong reprocessing which would also affect the thermal disk emission (Gierliński et al., 2008). To include this effect, f_{in} was fixed to 0.1 and r_{irr} was left free to vary while fitting. For epochs 2 and 3, the fits improved significantly while for epoch 1 it deteriorated a bit. f_{in} , for epoch 1, was found to be smaller by roughly a factor of 3. r_{irr} was constrained to $\sim 1.01 R_{in}$ (where R_{in} is the inner-disk radius). The improvement in fit after including irradiation was verified by F-Test, wherein the probability that this advancement would be random was found to be less than 10^{-15} for all three epochs. The best-fit parameters are listed in Table 3.2 and the residuals are represented in bottom panel of Figure 3.5. There is a clear improvement in the fit after including irradiation. Fits with disk irradiation were also statistically better compared to reflection model with $\Delta \chi^2$ decreasing as 32.2, 11.6, and 26.1 per dof for the three epochs. Thus, the data favors the case for disk irradiation and does not require any reflection component. In reality, however, the spectrum could have contribution from both reflection and irradiation. However, deciphering the exact fraction of contribution from each of the two would be extremely difficult given the modest resolutions of SXT and LAXPC.

3.3.2 Broadband Spectral Energy distribution

Although there were many observations of GRS1716 in the low energy bands, there were not any strictly simultaneous with *AstroSat* observations. It was only during the second epoch (06 April) of *AstroSat* when a number of observations with *MIRO* and UVOT were in temporal proximity with it. The closest were the NIR observations which were made on 7 April while the optical measurements were made a few days later on 11 April. Similarly, the UV observations in W1, U, B, and V bands were scattered within a few days of 6 April. Moreover, around the date of the X-ray observation, the optical and UV flux did not vary significantly allowing multi-waveband spectroscopy (Figures 3.3 and 3.2). The other two UV bands of UVOT (M2 and W2) were much



Figure 3.6: SED of GRS1716 after fitting with TBabs*diskir to the quasi-simultaneous observations on epoch 2. The X-ray spectrum, in steelblue color, is unfolded and rebinned by a factor of 4 for clarity. The SXT, LAXPC10, LAXPC20, and CZTI are represented by dots, up-triangles, down-triangles, and squares respectively. In lower energies, the NIR spectrum is represented with red circles, optical points with green diamonds, and UV points with violet stars. The black dashed line represents the best-fit model.

farther away in time from the X-ray observation and also suffered from heavy extinction leading to huge uncertainty in flux measurement. Therefore, they were not included in the SED.

As hinted in section 3.3.1, the model diskir also calculates the effect of irradiation in the outer disk where the emission is predominantly in UV, optical, and NIR bands (Gierliński et al., 2008). This is parameterized as f_{out} and R_{out} which represents the fraction of total flux thermalizing the outer disk and the outer-disk radius respectively. The NIR, optical, and UV magnitudes were converted to flux in physical units and then incorporated into PHA files, one each for *MIRO* and UVOT. Diagonal response matrices were created such that the convolved model would be in the same unit as the spectra. All spectra were loaded into xspec and fitted simultaneously with the model TBabs*redden*diskir. Since *MIRO* and UVOT spectra were not corrected for interstellar absorption, the xspec routine redden was employed to calculate extinction

(Cardelli et al., 1989). It has one free parameter, the color excess (E_{B-V}) , and it was left to float. N_H and E_{B-V} were fixed to 0 for UV/optical/NIR and X-ray spectrum, respectively, to avoid inter-mixing of the effects. E_{B-V} was constrained to 0.75 ± 0.04 and N_H was constrained to $0.70 \pm 0.04 \times 10^{22} \, cm^{-2}$ making the ratio $E_{E-B}/N_H \sim$ $1.1 \times 10^{-22} \, cm^2 \, mag$. This ratio is fully consistent with the recent findings of Lenz et al. (2017). The cumulative line of sight galactic reddening is ~ 0.93 (Schlafly & Finkbeiner, 2011) and our result is also consistent with this limit. The best-fit value of f_{out} was 0.04 ± 0.01 while R_{out} was constrained to ~ $10^{5.5}R_{in}$. Although the irradiated disk model explained the optical and UV bands well, it failed to account for the excess in the NIR emission (see Figure 3.6). To verify whether the NIR excess could be due to intrinsic absorption we multiplied another reddening component to the model. We fixed one E_{B-V} to the best-fit value of 0.75 and let the other to float. The extra reddening component could not explain the NIR excess and was weakly constrained to a small value of ~ 0.05.

Date	kT_{in}	Г	kT_{e}	L_c/L_d	f_{in}	r_{irr}	norm
(MJD)	(keV)	_	(keV)	-c/ -u	Juu	(R_{in})	$(\times 10^{3})$
57799	0.47 ± 0.02	1.60 ± 0.01	46^{+7}_{-5}	8.2 ± 0.6	0.03*	1.012 ± 0.002	$2.26^{+0.79}_{-0.49}$
57849	0.44 ± 0.01	1.68 ± 0.01	22 ± 1	2.54 ± 0.04	0.1^{\star}	1.011 ± 0.001	$5.80^{+0.04}_{-0.03}$
57947	0.48 ± 0.01	1.65 ± 0.01	23^{+1}_{-2}	$2.73^{+0.05}_{-0.14}$	0.1^{\star}	1.010 ± 0.001	$1.87^{+0.03}_{-0.01}$

Table 3.2: Best-fit parameters of the joint X-ray fit with SXT, LAXPC, and CZTI using TBabs*diskir model.

3.4 Discussion

GRS1716 exhibited "failed" outburst and never transitioned to the canonical soft state (Bassi *et al*). This was also suggested by the broadband rms variability of the source in the 3 – 30 keV band. For epoch 1, the variability was $\approx 24\%$ whereas for epochs 2 & 3 the variability remained around 20%. During the three AstroSat observations, spanned across ~ 5 months, GRS1716 remained in a power-law dominant state with the luminosity ratio (L_c/L_d) remaining > 2. The spectrum of the source was significantly affected by irradiation of the back scattered Compton flux in the inner disk (Gierliński et al., 2008). For hard states of black-hole binaries, the fraction of the thermalizing flux (f_{in}) is about 0.1 (Poutanen et al., 1997). This fraction is a function of the geometry



Figure 3.7: Left panel shows the 2MASS image of the source during quiescence phase. The purple crossbar marks the source position. The right panel shows the H band image of the same field of view as observed with NICS instrument at *MIRO* during the outburst. Inside the purple circe, a bright object is clearly seen.

of the electron cloud and angle-averaged albedo of the thin disk. While epochs 2 and 3 confirmed the expected value of 0.1, f_{in} for the first epoch was constrained to 0.03. This suggests a possible change in geometry, and hence covering fraction, of the overlying electron cloud. The complete outburst of GRS1716 is marked by 3 small softening episodes, also characterized by increase in flux. The epoch 2 AstroSat observation (MJD 57849) was done 5 days before the second peak (MJD 57854). The effect of this softening was reflected in the spectral fits wherein, there was an increase in the disk flux and decrease in the luminosity ratio (Table 3.2).

We monitored GRS1716 in the optical and NIR bands from *MIRO* during mid-March to May 2017. The optical lightcurve (Figure 3.3) remained constant throughout the observations while the NIR lightcurve was marked by a drop in flux (1 - 2 magnitudes) around MJD 57850. The UVOT lightcurve (Figure 3.2), which spanned a longer duration, displayed constant flux in all bands up to MJD 57900 and a gradual decrease in the UV bands thereafter. Using quasi-simultaneous X-ray, UV, optical and NIR spectra we carried out a broadband spectral study to decipher the origin of the low energy emission using an irradiated disk model. The irradiated disk perfectly explained the optical and UV flux while slightly underestimating the NIR spectrum (Figure 3.6). Without irradiation, the model underpredicted the flux by almost 3 orders of magnitude in all the bands. From the best-fit norm of **diskir** (4181^{+1451}_{-887}), the inner-disk radius was calculated to be ~ 22 km, which was consistent with radii obtained by Bassi et al. (2019). The best-fit value of f_{out} was found to be 0.03 ± 0.01 and that of R_{out} was constrained to ~ 6.27×10^6 km. This R_{out} is slightly larger than the Roche lobe radius of ~ 1.56×10^6 km estimated from the reported orbital parameters and assuming a $10 M_{\odot}$ black hole and 45° disk inclination^{||}. Considering the uncertainties involved in the above calculation, we can infer that the outer disk has to be as big as the Roche lobe in order to describe the UV/optical spectrum. Trying to increase R_{out} to account for the NIR spectrum would make the disk unrealistically large and also overestimate the optical spectrum.

A natural alternative for the this excess is emission from a secondary star. We searched for the images of the source in all-sky surveys to quantify the flux during quiescence which would be predominantly from the companion. However, the 2MASS H-band image of the field does not have any object at the position of GRS1716 (Figure 3.7). The H-band image from MIRO, on the other hand, shows a bright object at the source position. Hence, the NIR brightening which the source had undergone during the outburst is not due to the secondary star. It is also possible for the emissions from the binary to be absorbed and re-emitted in the IR regime from a dust envelope/cloud covering the binary. Taranova & Shenavrin (2001) reported such a scenario where the X-ray binary XTE J1118+480 showed excess in mid-IR regime which could be explained by a 900 K circumstellar dust envelope. To test this hypothesis, we added the bbodyrad model to the SED only in the UV/optical/NIR region. We fixed the temperature to 900 K and fitted for the norm. The best-fit radius of the cloud was found to be $\sim 3.3 \times 10^8 \, km$. The cloud, if present, could as well be hotter and smaller in size or cooler and larger. Without observations in longer wavelengths, it is difficult to constraint any of these properties robustly. Although the primary source of heating of a bright dust cloud is disk emission during an outburst, it can also be moderately excited by emission from the secondary star. The object was, however, not detected in the mid-IR bands of the WISE (Wide-field Infrared Survey Explorer) catalogue observed during the 2010-11 epoch. Moreover, the source was also not detected in NIR, or even optical bands, after we resumed observations post Monsoon during Sep-

[∥]The Roche lobe radius distance of the inner Lagrangian point tousing the primary object (black hole) was estimated the following tool: http://www.orbitsimulator.com/formulas/LagrangePointFinder.html

Oct 2017. During these months the source had decayed substantially in X-rays but was still bright in UV (see UVOT lightcurves in Figure 3.2) This suggests that the NIR and optical brightening was exclusively tied to the X-ray activity. The possibility of a NIR emitting dust cloud that engulfs the entire system is, therefore, highly speculative.

The other most viable candidate for the NIR excess is Synchrotron emission from a compact jet. As reported by Bassi et al. (2019), GRS1716 was detected in radio wavebands throughout the outburst by ATCA, LBA, and VLA from 9 February 2017 till 13 August 2017 (see their Table 3). The closest radio observation to our SED was made on 22 April using LBA. The flux in the 8.4 GHz band, with a bandwidth of 64 MHz, was reported to be $1.13 \pm 0.11 \, mJy$. The observation before 22 April was made about two months earlier, on 9 February, during which the flux was $1.28 \pm 0.15 \, mJy$. This means the flux would not have changed much during the intervening period. The correlation between radio and X-ray luminosities provide an useful tool to study the emission properties of black-hole binaries. These are known to follow two distinct power-law relations in the log-log space. The radio-loud systems follow a relation $L_R \propto L_X^{1.4}$ whereas the radio-quiet systems (the so-called "outliers") follow $L_R \propto L_x^{0.6}$ (Corbel et al., 2013). Using the radio luminosity from LBA in the 8.4 GHz band $(L_R \approx 6.5 \times 10^{28} \, erg \, s^{-1})$ and the X-ray luminosity in the $1 - 10 \, keV$ band from AstroSat $(L_X \approx 4.5 \times 10^{36} \, erg \, s^{-1})$ we obtained a radio/X-ray luminosity relation of $L_R \propto L_X^{1.45}$. Here, we have assumed a distance of 2.4 kpc and a proportionality constant of 1.85 (Corbel et al., 2013). Thus, GRS1716 adds to the pool of sources in the "outlier" branch of the radio/X-ray plane, consistent with the findings of Bassi et al. (2019). To have a cursory idea of the full radio to X-ray SED, we also add the 22 April radio observation in the SED (Figure 3.8). Unfortunately, with the data available with us, it is not possible to identify the exact position of the break frequency. We tried fitting the radio to NIR spectrum with a broken power law but could not constrain the parameters, especially the break frequency. An approximate spectral index of the radio spectrum is +0.5, obtained by fixing the spectral break at the Ks band of the NIR spectrum. Such highly inverted optically thick part of the radio spectrum has been seen earlier for a few sources such as MAXI J1836–194 (Russell et al., 2014), XTE J1118+480 (Fender et al., 2001), etc. Although standard jet models, as that of Blandford & Königl (1979), assuming a conical geometry predict a shallower slope,



Figure 3.8: Complete SED of GRS1716 along with the 22 April radio observation with LBA. The X-ray spectrum is rebinned by a factor of 4 for clarity. The X-ray, UV, optical, and NIR spectra are the same as in Figure 3.6. The radio observation is marked with a black open triangle. The grey dotted line joining the radio and Ks band is just for representation and not a fitted model.

steeper spectrum can be expected for a rapidly flaring jet geometry (Dinçer et al., 2018).

Chapter 4

Spectral and timing evolution of MAXI J1631–479 during the 2018-19 outburst with *NICER*

4.1 Introduction

The outburst of a BHB (black-hole binary) is characterized by various states depending on the spectral and temporal properties (Chapter 1.4.2). These states can be identified by locating the source in the hysteresis tracks of the HID (Hardness-Intensity Diagram) and the RID (RMS-Intensity Diagram). The HRD (Hardness-rms Diagram) also serves as a useful tool in this regard. During an outburst, a BHB rises from quiescence in the LHS when the accretion disk is truncated at a large distance and thermal viscous instability kicks in (Lasota, 2001). This phase is marked by the right-hand vertical track in the HID where hardness is the highest. From here the hardness decreases as the contribution of the thermal disk starts to dominate the spectrum. This is believed to happen as the inner radius of the accretion disk moves inward, driven by an increase in accretion rate (Done et al., 2007). This track is marked by a passage of the source to the HSS through the HIMS and SIMS. The source reaches its highest luminosity and the softest state. From here the luminosity starts to decrease as the material of the disk is either dumped into the black hole or ejected out via winds and jets. With decrease in luminosity the source moves from HSS back to the LHS via the same intermediate



Figure 4.1: Top row: MAXI lightcurve in the 2 - 10 keV range. Second row: NICER lightcurve in the same energy range. Third row: Time evolution of hardness with NICER. Fourth row: Time evolution of broadband fractional rms measured with NICER. The red and black colors, in this and the other figures, represent HSS and HIMS respectively. The grey dots in the MAXI lightcurve are the points not observed by NICER.

states. Occasionally, the source also undertakes excursions to the intermediate and some anomalous states (Belloni & Motta, 2016). The detailed spectral and timing properties of the source is explained in Chapter 1.4.2.

QPOs are interesting features on the PDS of a BHB. The time scales associated with them indicate towards their possible origin from very close to the black hole. Hence, they serve as useful tools to study matter in strong gravity. Even though QPOs have been studied extensively, the reason behind their origin is still debated (Chapter 1.3.2). Using correlations between spectral and timing properties as a tool we explore the possible origin of a newly discovered BHB MAXI J1631–479 (hereafter J1631).

J1631 is a newly discovered galactic X-ray transient which hosts a rapidly spinning massive black hole at its center (Xu et al., 2020). During the HSS, J1631 exhibits outflow of matter in the form of ultra-fast disk winds. It also shows radio flaring during state transitions and a radio/X-ray luminosity pattern typical of BHBs



Figure 4.2: Hardness-intensity diagrams with MAXI (left panel) and NICER right panel). The grey points in the MAXI HID are those that do not have a corresponding point in NICER. The initial points in the MAXI HID are marked with dark grey squares to distinguish from the final points. The data points are not corrected for interstellar absorption.

(Monageng et al., 2021). Fiocchi et al. (2020) and Rout & Vadawale (2021) have reported on the presence of hybrid plasma in the *INTEGRAL* and *NuSTAR* spectra respectively. In this work we carry out a comprehensive spectral and timing analysis of the X-ray transient J1631 using data from *NICER*. We endeavour to understand the phenomenology of state transition and the associated time variability, especially the rms spectra and low-frequency QPOs.

4.2 Observation and Analysis

4.2.1 Data Reduction

J1631 went into outburst on 21 December 2018 and was first detected with MAXI/GSC. After an ambiguity due to its proximity with the pulsar AX J1631.9–475, located within the MAXI error circle, it was later confirmed to be a new X-ray transient using ~ 14 ks data from NuSTAR on 28 December (Miyasaka et al., 2018). Due to Sun-angle constraints, the peak of the outburst was missed by NICER as well as most other Xray satellites. From 2019 January 15 onward J1631 was observed with NICER, almost daily, with exposures ranging from a few hundred seconds to a few thousand seconds till 2019 July 4. All the analysis in this work were done using HEASoft-v6.25. Analysis of the X-ray Timing Instrument (XTI; Gendreau et al., 2012) data was carried out using NICERDAS-v5.0. After generating the event files using nicer12, the higher level products were generated with the ftool xselect. Several observations in the beginning were affected by flaring events. These were removed by setting COR_SAX > 6. The intervals with count rate greater than 1 counts s⁻¹ in 13 - 15 keV range were also rejected as they are affected by background flares. The background spectra for each observation were generated using nibackgen3C50-v5. Each *NICER* observation has several data segments based on the ISS orbit. If the count rate in the individual segments differed significantly (i.e., ≥ 400 counts s⁻¹), they were analysed separately. After 2019 March 20, the background starts to dominate beyond 8 keV and spectral analysis was carried out in the range of 0.5-8 keV. Further, from April 22 the background was dominant even below 8 keV. Thus, in this paper we only present the results till 2019 April 21. This amounts to a total of 88 observations spanned between 2019 January 15 (OBSID: 1200500101) to 2019 April 21 (OBSID: 2200500131).

4.2.2 Timing Analysis

Time-series analysis was done using the GHATS package *. NICER data were rebinned by a factor of 10^4 , which brought down its time resolution to 400 μ s, corresponding to a Nyquist frequency of 1250 Hz. PDS in the energy range of 0.5 - 10 keV were constructed for a time series consisting of 65536 time bins. Each series was, thus, ~ 26.21 s long and led to a minimum frequency of ~ 0.04 Hz. All PDS in a segment were then averaged and rebinned logarithmically. We have verified that the source shows very little variability for frequencies below 0.04 Hz and the choice of a longer time series would result in decrease in their number which would lead to poor statistics for the averaged PDS. The average power in the 100 - 1250 Hz, where the source showed no intrinsic variability, was subtracted from the Leahy normalized PDS which were subsequently converted to squared fractional rms (Belloni & Hasinger, 1990). The power spectral analysis was done with raw counts without subtracting the background. The PDS during the HIMS were then fitted by a multi-Lorentzian model (Belloni et al.,

^{*}http://www.brera.inaf.it/utenti/belloni/GHATS_Package/Home.html

2002). Depending on the shape and number of QPOs, the PDS required about 2 to 5 Lorentzians. The multi-Lorentzian model provided a satisfactory fit for all the PDS. During the HSS, the PDS required only a single power law to be fitted reasonably.

To construct rms spectra, the above method was repeated for the following energy bands: E1:0.2 - 0.8, E2:0.8 - 1.0, E3:1.0 - 2.0, E4:2.0 - 6.0, and E5:6.0 - 12.0keV. These intervals were selected so as to ensure that each of the energy bands receive roughly similar throughput. The fractional rms in the 0.1 - 50 Hz range was calculated by integrating the total variability from the best-fit multi-Lorentzian model. The rms was then plotted as a function of the above defined energy bands.

4.2.3 Spectral Analysis

Spectral analysis was carried out using xspec-v12.10.1 (Arnaud, 1996). The background spectrum for each observation was generated using the tool nibackgen3C50. In order to avoid over-sampling the spectra were rebinned by a factor of 3 and ensured that each spectral bin had a minimum of 30 counts. A systematic error of 1 per cent was added to all the channels. The two main components of a black-hole binary spectrum are a multi-color blackbody (Matsuoka et al., 2009) and a thermal Comptonization component (Zdziarski et al., 1996; Życki et al., 1999). Therefore, we fitted the 0.5 - 10 keV NICER spectra with the xspec model - TBabs*(diskbb+nthcomp). The solar abundances in TBabs was set according to Wilms et al. (2000) and the crosssections were taken from Verner et al. (1996). Residuals around ~ 2 keV revealed complex features which are caused due to calibration uncertainty at the Si and Au edges. We added two gaussians at ~ 1.7 and ~ 2.2 keV. Another bump at ~ 1.2 keV was also apparent, which was also due to calibration uncertainty at the low energy tails and became visible owing to the high absorption suffered by the source. The best fit hydrogen column density (N_H) was found to be ~ 6 × 10²² cm⁻², albeit, with some variability primarily because of degeneracy with diskbb norm. The average of all best fit N_H was found to be $6.34 \times 10^{22} \, cm^{-2}$. In most observations during the bright phase of the outburst, an emission feature was apparent at the Fe K α range of 6-7 keV. So, another gaussian was added to each spectrum. The strength of this line varied across the observations. In some occasions the line energy pegged at 6.4



Figure 4.3: RMS - Intensity diagram (RID). The source begins from low variability soft states and transitions to intermediate variability in the HIMS. Finally, it moves back to the low variability soft state till the last observation.

keV suggesting that the gaussian is, perhaps, not the best model for a relativistically skewed line. However, a more sophisticated reflection spectroscopy was not the plan of this paper and hence we did not pursue it. During the HSS, on 2019 January 16, the residuals indicated a dip at ~ 7.2 keV. A negative gaussian was added to the model to account for the dip. The best fitting line energy was ~ 7.4 keV with an FWHM of ~ 0.1 keV. These features are an indication of absorption by blue-shifted H- or He-like Fe ions originating from an equatorial disk wind and have also been detected by Xu et al. (2020).

Although a reasonably good fit was obtained using the above procedure, the instrumental gaussians seemed to over fit the continuum. There was also a clear zigzag pattern in the residuals between 1-2.5 keV. Therefore, we re-fitted all the spectra in the range of 2.5-10 keV avoiding the instrumental features. The best-fit parameters and fluxes were very similar to the previous case, the average N_H being 6.44×10^{22} cm⁻². This suggests that both ranges could be used for studying the spectral properties but, we chose the later range of 2.5 - 10 keV in this work. To avoid the effect of the correlation between N_H and diskbb norm on the parameters, N_H was fixed to the average value of 6.44×10^{22} for all observations.

4.3 Results

4.3.1 Outburst evolution

The *MAXI* lightcurve of J1631 is shown in the top panel of the Figure 4.1. The peak of the outburst is on 2019 January 07, following which the flux continuously decayed. As mentioned before, *NICER* started observing from 2019 January 15. *NICER* lightcurve and hardness ratio curve are displayed in the second and third panels of Figure 4.1. *NICER* started observing the source when it was in the HSS (shown with red colour). On 2019 January 24 J1631 transitioned into a harder state which was marked by a drop in count rate by about $\sim 1000 \ counts/s$ and an increase in hardness. The transition is even more clearly seen in the increase of the broadband rms from about 2 per cent to 7 per cent as shown in the bottom panel of Figure 4.1. From a timing and spectral study, we find that the source transitioned into the HIMS and remained there till 2019 March 03 (shown in black circles in the figure). Following this date, a long data gap ensued and when the source was re-observed it had transitioned back to the HSS.

The left panel of Figure 4.2 shows the HID using MAXI lightcurve. The outburst began in a hard state with the hardness ratio being ~ 1 till 2018 December 31. By 2019 January 07, the source had reached the peak and was in a soft state (hardness ratio ~ 0.5). As the decay began, J1631 remained in the HSS till January 24 when it transitioned to the HIMS (shown with black points). The excursion to HIMS lasted for a little more than a month following which the source transitioned back to HSS. During the decaying HSS, the hardness was stable around 0.2 while the flux decreased by an order of magnitude. Finally, the source transitioned to the LHS at very low count rates. The *NICER* HID (plotted in the right panel of Figure 4.2) is more clear, but is sparse given that the observations did not cover the entire outburst. *NICER* began the observations on January 15 when J1631 was in the HSS and continued through the transition to the HIMS. The HIMS observations were abruptly halted on March 3 and when the observations resumed the source was already in the HSS. A peculiar feature of the *NICER* HID is that during the prolonged excursion to the HIMS the count rate decreased by a large factor from ~ 5500 counts/s to ~ 2000 counts/s giving it a vertical shape. Generally, these excursions occur for shorter periods and at a similar flux level.



Figure 4.4: From left to right: *NICER* PDS observed on 2019 January 17, January 27, and February 11.



Figure 4.5: From top to bottom: Variation of QPO frequency, quality factor and QPO rms for all observations in the HIMS

4.3.2 Timing properties

The state classification for J1631 is confirmed by studying the time variability (see Figure 4.3). The HSS was marked by very low variability (~ 1 per cent broadband rms), while rms in the HIMS was in the range of 8 - 10 per cent. Apart from the broadband rms, all the PDS during the HIMS were characterized by a flat-top noise and a Type-C


Figure 4.6: Characteristic rms spectra spaced across the entire outburst. From panels (a) to (i): 2019 January 20, January 22, January 26, February 2, February 13, February 17, February 21, March 1, March 20

QPO whose centroid frequency roughly coincided with the break frequency of the red noise. Figure 4.4 shows three characteristic PDS spaced across the outburst. The PDS during the HSS (2019 January 17) shows 0.38 ± 0.05 per cent variability and contains significant power upto only ~ 0.3 Hz. All the PDS during the HSS have a similar power distribution and were fitted by a power law model. The second and third panels display PDS in the HIMS measured on 2019 January 27 and February 11 respectively. The right-hand panel shows the only PDS which has a sub-harmonic QPO. The sub-harmonic and second harmonic QPOs have a frequency of 2.19 ± 0.03 and 8.95 ± 0.04 Hz which are well-placed compared to the fundamental QPO at 4.45 ± 0.01 Hz. Most of the other PDS only have the second harmonic and some PDS do not even have any

harmonic component.

The middle panel shows the PDS which displays a QPO-like feature below the fundamental frequency at a non-harmonic ratio. While the fundamental and the second harmonic are at 5.72 ± 0.02 Hz and 11.54 ± 0.10 Hz respectively, this non-harmonic feature is detected at a frequency of 4.09 ± 0.08 Hz and has a quality factor of 4.06. Although these properties qualify it to be considered as a QPO, we remark that the addition of that Lorentzian component accounts for the extra power around 4 Hz, but no clear peak is visible in the PDS, making the identification as a 4 Hz QPO uncertain.

The time evolution of the fundamental QPO and its properties, during the HIMS, is shown in Figure 4.5. The QPO frequency laid, mostly, within 4-7 Hz going beyond 8 Hz on two occasions. The quality factor varied between 2 and 10 throughout the observations. The QPO rms showed a declining trend, starting from 4-5 per cent during the beginning of HIMS and reaching 2 - 3 per cent towards the end.

Nine representative rms spectra in the broadband frequency range of 0.1 - 50 Hz are displayed in Figure 4.6. The *NICER* energy range was divided into 5 energy bands (as spelled in Section 4.2.2) and the rms was calculated by fitting the PDS in each of these bands. The rms of almost none of the energy bands could be constrained during the HSS. It was only during 2019 January 22 (Panel b) that the rms of the last two bands were constrained. Since all other spectra in the HSS only have upper limits, it would be difficult to infer much from them. The rms spectra in the HIMS were characterized by a hard shape with the rms rising from to E3 to E5. Here also the first two bands could not be constrained for most of the observations, possibly owing to low statistics. However, in a few occasions, as shown in Panels (d), (e), (f), and (g), one or both of the E1 and E2 bands were constrained. If these were to represent the entire ensemble, it could be inferred that the rms in the first two bands (E1 and E2) would be slightly higher than E3 with the entire spectrum having a concave shape.

4.3.3 Spectral properties

As mentioned in Section 4.2.3, the spectral fitting was done with the model TBabs*(diskbb + nthComp + gaussian). The seed photon temperature in nthComp was tied to the inner-disk temperature in diskbb. The inp_type parameter was fixed to 1, thus, as-



Figure 4.7: Top panel: Two characteristic spectra representing HSS (red, 2019 January 18) and HIMS (black, 2019 February 28), along with individual model components. The dotted line represents the thermal disk component and the dashed line represents the thermal Comptonization component. The gaussians for Fe line are plotted with dot-dashed lines. The bottom two panels show the best fit residuals.

suming a disk blackbody for seed photons. None of the observations could constrain the electron temperature due to the relatively soft response of *NICER*, thus it was fixed to 1000 keV. Figure 4.7 shows two characteristic spectra representing the two spectral states that the source was in. The time evolution of the primary components is shown in Figure 4.8. The top panel shows the evolution of the unabsorbed flux and the subsequent two panels display the evolution of photon index (Γ) and inner-disk temperature (T_{in}). The first three observations were completely disk dominated and did not require the Comptonization component. The total unabsorbed flux during these three days and the following seven days, while the source was in the HSS, is ~ 1.2×10^{-7} erg s⁻¹ cm⁻² in 0.5 - 10 keV range. From 2019 January 24 onwards, when the source transitioned to the HIMS, the flux started decaying gradually till the end of observations. The contribution of the disk and Comptonization components to the total flux is marked with orange and green points respectively. It is interesting to note that, although the state transition from HSS to HIMS took place on January 24, the Comptonization component started dominating the total flux five days before that from January 19. When the observations resumed on 2019 March 18 the contribution of the individual components to the total flux had flipped, with the disk dominating the total flux, which is consistent with the state transitioning back to HSS. While in the initial HSS, the photon index varied between 4-7 and during the HIMS it remained stable around 3. During the third phase of observations, when the source was back in HSS, Γ had increased slightly but mostly remained unconstrained. One possible reason for this might be that the background had started dominating the high energy tail of the spectrum and starting from January 20, the spectra were fitted in the 2.5-8keV. Thus, for the final 20 soft state observations, Γ was fixed to the last constrained best-fit value of 4.39 (OBSID: 2200500110). The best-fit inner-disk temperature also displays a declining trend during the HSS. It starts from ~ 1.1 keV on the first observation and decreases to ~ 0.8 keV on January 24. During the entire HIMS, T_{in} varied between 0.5 - 0.7 keV. Then, again during the second HSS it increased to ~ 0.8 keV and decreased gradually to 0.7 keV till the end of the observations.

4.4 Discussion

We present a detailed spectral and temporal analysis of J1631 during its discovery outburst in 2018-19 with quasi-daily monitoring data from *NICER*. *NICER* observed J1631 for a little more than three months from 2019 January 15 to 2019 April 21. By the time *NICER* commenced observation the source was already in HSS. Hence, the initial LHS and the subsequent intermediate states were missed by *NICER*. This initial transition from the LHS to the HSS was so fast that it was also missed by *MAXI*. The left panel of Figure 4.2 displays the full outburst HID using *MAXI* lightcurve and the right panel displays the *NICER* HID (also see Fiocchi et al., 2020; Monageng et al., 2021). J1631 is discovered in the LHS with the hardness lying between 1 - 2 (*MAXI* HID) and reaches the peak at a lower hardness ratio of ~ 0.5. During this rising phase the source would have transitioned to the HSS. However, the transition is missed by *NICER* and by the time it commences observations the source is already



Figure 4.8: Top panel: Time evolution of unabsorbed flux along with the two primary contributors. Middle panel: Evolution of photon index. After January 20, the index was fixed to 4.39 as it could not be constrained. Bottom panel: Variation of inner-disk temperature. In the last two panels, the red and black colors represent HSS and HIMS respectively.

in the HSS. On January 24, the source transitioned to HIMS and remained there for about two months when observations were interrupted resulting in a data gap. When observations resumed on March 18, the source had again transitioned back to the HSS. Till the end of *NICER* observations, the source remained in the HSS. The RID, in Figure 4.3, tracks the state transitions quite clearly. During the HSS the broad band variability remained around 1 per cent. The transition to the HIMS was marked by an increase in the variability to a range of 7 - 10 per cent. As the source moved out of HIMS, the variability further decreased to the 1 per cent level.

Figure 4.8 shows the evolution of the primary spectral parameters during the outburst. During the initial HSS, the photon index (Γ) laid between 3–7 and the inner disk temperature (T_{in}) ranged from 0.7 – 1.1 keV. The HIMS was then characterized by a stable Γ at ~ 3 and a T_{in} that remained within 0.5 – 0.7 keV. After transitioning back to HSS, at a lower luminosity, T_{in} started from 0.8 keV and gradually decreased to 0.7 keV. The power-law index, on the other hand, could not be well constrained and was fixed to 4.39. The individual flux contribution to the total flux showed a disk dominance during the HSS and a power law dominance during the HIMS. One



Figure 4.9: Broadband (0.1 - 50 Hz) rms as a function of QPO frequency.

peculiarity being that the power-law flux started dominating 5 days before the timing properties indicate a state transition. With a limited energy range, primarily covering the soft X-rays, *NICER* is not well suited to constrain the power-law component. This effect becomes more serious for J1631 as the thermal disk covers a major portion of the spectrum. This could be a possible reason behind the observed anomaly in the individual flux contributions.

The study of temporal properties serve as a better tool for understanding state transitions. The track of the source in the RID, for example, clearly distinguishes the states. The shape and properties of the PDS are also well defined according to the spectral states. During the HSS, they have a power-law shape with very little variability (Figure 4.4). Being dominated by the unmodulated thermal disk component, this is expected from soft state PDSs. During the HIMS, the PDS have a flat top red noise with a moderate variability ~ 10 per cent. There PDS are also usually accompanied by Type-C QPOs superposed on the broadband noise.

4.4.1 QPO identification and origin

LFQPOs have been classified into three distinct types based on various properties of the PDS (Casella et al., 2004, 2005). Although the QPO frequency and quality factor of the three types have considerable overlap, a somewhat clear distinction arises upon



Figure 4.10: Variation of QPO frequency with total unabsorbed flux in 0.5 - 10 keV.

comparing the shape and variability of the underlying noise component. Figure 4.9 displays the relation between the frequency of the primary QPO and the broadband rms. The anti-correlation clearly observed in this plot indicates that the QPOs are all Type-C in nature. Type-C QPOs show a complex dependence with disk and power-law flux depending on the hardness (Motta et al., 2011). The frequency is correlated with disk flux and anti-correlated with power-law flux laying out well defined paths in the flux-frequency plane. But, when the data are separated by hardness, the anti-correlation of the frequency with power-law flux becomes weak for soft phases and disappears for hard states. Type-C QPOs in J1631 are detected only in the HIMS spanning a narrow range in hardness. Besides, the total flux during this phase is completely dominated by power law (Figure 4.8). Therefore, the total flux does not show any strong correlation with the QPO frequency (Figure 4.10) consistent with the findings of Motta et al. (2011).

Several models have been proposed to explain the origin of the LFQPOs. These are broadly classified into two categories based on the nature of origin of the QPOs, i.e., geometrical and intrinsic variability. The geometrical models of QPOs based on the Lense-Thirring precession of the inner hot flow have advanced considerably. Motta et al. (2015) and van den Eijnden et al. (2017) have demonstrated the inclination dependence of Type-C QPOs. Type-B and A QPOs, however, are not dependent on inclination and thus could have a different origin (García et al., 2021). Ingram et al. (2009) and Ingram & Done (2011) have shown that the QPO frequency is strongly anti-correlated with the outer radius of the hot flow, which is nothing but the truncation radius between the thin and thick disk. This means that the innerdisk temperature, which is also anti-correlated to the inner-disk radius assuming that the accretion rate does not vary much during the HIMS (see top panel of Figure 4.8), should be positively correlated with QPO frequency. The correlation of QPO frequency and rms with inner disk temperature is shown in Figure 4.11. The frequency shows a positive correlation with temperature supporting the predictions of the Lense-Thirring precession model. Since the intrinsic disk emission has little variability and QPOs originate from the hot flow, the increase in disk contribution should lead to a decrease in the rms (Sobolewska & Życki, 2006; Axelsson et al., 2014). Figure 4.11 shows such an anti-correlation between QPO rms and T_{in} , although it is weak compared to the previous case. The Spearman's rank correlation coefficient for the two parameters is ~ -0.35 with a p-value of ≈ 0.0099 indicating less than 1 per cent chance of being created by random noise. Kalamkar et al. (2015) have shown that this type of correlations are typical of BHBs in HIMS and not seen in other states. It should be noted that the decrease in count rate during the HIMS could possibly result in a corresponding decrease in mass accretion rate. However, this relation is not straightforward as the count rate also depends on the inner radius. The width of the Fe line, fitted by a gaussian, can be used as a proxy for the inner radius. Disks closer the black hole will experience stronger gravitational potential resulting in a broader Fe line while disks truncated at a larger distance will result in narrower Fe lines (Fabian et al., 2000), but also see Miller et al. (2006b) and Reis et al. (2010). We verified that T_{in} is inversely correlated to the best-fit width of the Fe line and hence also the inner radius of the accretion disk.

4.4.2 rms spectra

The study of fractional rms spectra is an important tool to help distinguishing the contribution of the individual processes and the origin of variability. Gierliński & Zdziarski



Figure 4.11: Variation of QPO frequency (left) and rms (right) as a function of innerdisk temperature.

(2005) had studied the shape of the rms spectra for various spectral states and deciphered the relative contributions of the various components to the total variability (see also Belloni et al., 2011, for a similar description with a slightly different state classification scheme). While flat rms spectra indicate variability in the normalization of the Comptonization component, hard and inverted spectra would require the variation of spectral shape along with normalisation (Gierliński & Zdziarski, 2005). The rms spectra of J1631 is displayed in Figure 4.6. During the HSS, almost all the energy bands have very little variability and the amplitude could not be constrained. This is not surprising considering that even the energy integrated PDS (see Figure 4.4) during the HSS had almost no power. The rms spectra during the HIMS have a hard shape that is characteristic of a late state HIMS which is about to transition to the HSS (Belloni et al., 2011). As mentioned above, this shape would arise because of variability in the Compton tail along with normalization of the Compton spectrum. The first two energy bands (E1 and E2) during the HIMS could not be constrained for most of the observations. Some of the best case scenarios are shown in Figure 4.6, particularly in Panels (d), (e), (f), and (g). Since we only have upper limits for the first two energy bands, the true shape is uncertain. It could either be flat as expected for the very high state (VHS) cases studied by Gierliński & Zdziarski (2005), or could have an inverted shape with a soft excess. One clear example of this kind of spectrum is shown in Panel

(d). Panels (e) and (g) could also fall in this category, but we can not be certain. While the minima in the E3 (or sometimes E2) energy band can be understood as a dominant contribution from the unmodulated thermal disk, the excess in the E1 and E2 bands is puzzling.

Chapter 5

The 2016-17 state transitions of Cygnus X–1 observed with AstroSat

5.1 Introduction

HMXBs (High mass X-ray binaries) hosting a black hole, being persistent sources, serve as excellent laboratories to study the accretion process. To this end, the bright prototypical black hole Cyg X–1 has been studied numerous times. Although, the study of state classifications began with Cyg X–1, it became increasingly clear later on that the vast majority of black-hole binaries belong to a separate category (namely, LMXBs) which show a different behaviour on HID (Chapter 1.4.2). While LMXBs trace a'q'-shaped hysteresis track on the HID, HMXBs do not show any hysteresis. Cyg X–1, in particular, spends most of its life in a hard state and sometimes undergo transition to a softer state through a series of intermediate states. It is found that Cyg X–1 has never transitioned to the canonical soft state (Wilms et al., 2006). The transitions mostly happen at similar luminosity levels and hence hysteresis effect is not observed (Grinberg et al., 2013). The PDS (power density spectra) of Cyg X–1 are also known to be different compared to the LMXBs. The hard and intermediate state PDS of LMXBs consist of a zero-centered Lorentzian often accompanied by a QPO (quasi periodic oscillation) and its harmonics, or a peaked noise. The difference between them

Date	OBSID
2016 November 28	900000834
2016 December 16	900000890
2017 March 20	9000001094
2017 March 31	9000001122
2017 April 17	9000001180
2017 May 08	9000001210
2017 May 30	9000001258
2017 June 15	9000001304
2017 July 05	9000001358
2017 July 05	9000001360
2017 July 29	9000001414
2017 August 17	9000001470

Table 5.1: List of all the observations used in this work. In rest of the chapter, only the last four digits of the ObsID will be used.

is only a reduction in the rms. For Cyg X–1, however, the PDS are fitted by two to four Lorentzians and no QPOs are ever detected (Pottschmidt et al., 2003; Axelsson et al., 2005). In soft states, both LMXBs and Cyg X–1 display a power-law shaped PDS.

It is generally believed that a similar accretion environment drives the somewhat different phenomenology for the two kinds of sources. Thus, studying the outburst dynamics in Cyg X–1 can provide useful insights into the accretion process around black holes, in general. Moreover, it is also important to infer the real reasons behind the subtle differences in the phenomenology of LMXBs and HMXBs.

In this work, we have analysed twelve *AstroSat* observations of Cyg X–1 made between 28 Nov 2016 and 17 Aug 2017. We carried out spectral and timing analysis to trace the source properties during the state transitions. We attempt to understand the reasons behind state transitions and also try to identify the origin of the power spectral components. In section 5.2 we describe the details of data reduction and analysis. In section 5.3 we present the results of the spectral and timing analysis. Lastly, in section 5.4 we conclude by discussing the implications of our results.



Figure 5.1: Top panel: MAXI on-demand lightcurve of Cyg X–1 in 2 - 20 keV band. Middle panel: Hardness ratio with MAXI data, defined as the ratio of count rate in 4 - 10 keV and 2 - 4 keV. Bottom panel: BAT lightcurve in 15 - 50 keV. The blue bars in the top panel represent the epochs for the twelve *AstroSat* observations used in this work.



Figure 5.2: Two representative spectra

5.2 Data Reduction and Analysis

5.2.1 Spectral analysis

The reduction of *AstroSat* data were carried out using the standard procedure. The details of the analysis for SXT and LAXPC are explained in Chapter 3.2.1. During the hard state, i.e., the first two observations, SXT data were not piled up and hence

circular source extraction regions with 15' radii were used. Following the third observation, the effects of pile-up became apparent and an annular region had to be selected for spectrum extraction. From the third (ObsID: 1094) to the tenth (ObsID: 1360) observation, an inner radius of 3' was used. The last two observations required a larger inner radius of 5' for extraction. The outer radii for all the annular extraction regions were opted to be 15'. As an additional test, the photon indices of the spectra with each extraction region in the 4 - 8 keV band were compared to the photon index measured with LAXPC spectrum in the same band. In all the selected regions, the photon indices were consistent between SXT and LAXPC.

Spectral analysis was carried out by jointly fitting SXT, LAXPC10, and LAXPC20 in xspec (Arnaud, 1996). The energy ranges of SXT and LAXPC spectra were restricted to 1 - 7 keV and 4 - 80 keV respectively. Thus, the combination of the three instruments resulted in a contiguous and wide energy coverage from 1 to 80 keV. For SXT, an additional gain correction was done using the command gain fit in xspec. The average best-fit offset was found to be ~ 40 eV, for a unit slope, which improved the fits significantly^{*}. To adjust for the cross-calibration discrepancy among the different instruments, a constant was multiplied to the model. It was fixed to unity for LAXPC10 and was left free to vary for rest of the instruments. The spectra were grouped to have a minimum of 30 counts per energy bin and a systematic error or 3% was added. The model for fitting the joint spectrum consists of three components (see sections 1.4 and 2.2 for details) along with TBabs, that accounts for absorption due to neutral hydrogen. The thermal disk was accounted by diskbb, the thermal Comptonization by nthComp, and the reflection part was fitted by relxillCp . relxillCp assumes a Coronal geometery with a broken power law-type emissivity profile and the illumination continuum calculated with nthComp . The relativistic broadening of the fluorescent Fe line is calculated using relline which incorporates the spin (a), inclination (i), and inner-disk radius (R_{in}) as free parameters. The ionized reflection is produced with xillver and includes the ionization parameter $(\log \xi)$ and Fe abundance $(A_{Fe}$ in solar units) as free parameters. The ratio of flux in the reflected component to that in the primary source (i.e., the reflection fraction $refl_frac$) is also kept as a free parameter. The final model in xspec

^{*}https://www.tifr.res.in/~astrosat_sxt/instrument.html

is constant*TBabs*(diskbb+nthComp+relxillCp). The seed photon temperature in nthComp was tied to the inner-disk temperature (T_{in}) in diskbb. The spin of the black hole was fixed to 0.998 (Zhao et al., 2021) and the inclination was fixed to 30° (Duro et al., 2016). The inner radius of the disk was allowed to vary freely. The photon index (Γ) and electron temperature (kTe) of relxillCp was tied to the respective parameters in nthComp. Since nthComp accounted for thermal Comptonization, the refl_frac parameter in relxillCp was frozen at -1. The emissivity index was fixed to the Newtonian limit of 3 for all radii. All the three components of the model were significantly required for all the observations and the fits were statistically good with χ^2_{ν} lying below 1 (Figure 5.3). Across the observations, the neutral hydrogen column density (N_H) varied between ~ 0.3 - 1 × 10²² cm⁻². N_H is known to be degenerate with the norm of diskbb component. Thus, for the final fits, we fixed N_H to the average value of 0.45×10^{22} cm⁻². All the fits, except the second one, were good and allowed for a more secular investigation on the thermal disk parameters. The second observation, with ObsID 0890, could not be constrained by fixing N_H to the average value. This observation was made during a hard state when contribution from the thermal disk would be negligible. Even after excluding the disk component from the model, the fits would not converge. Finally, the best fit was arrived at only after leaving N_H free to vary in which case it constrained to a higher value of $\sim 1.06 \times 10^{22}$ cm⁻². In case of Cyg X–1, stellar winds from the massive companion are known to result in a variable column density (Miškovičová et al., 2016). It is possible that a clump of gas may have come in the line of sight leading to a stronger absorption. In any case, the caveat opted by us owing to the requirement of higher absorption does not have any impact as the disk contribution during the hard state, when the observation was made, is negligible. The spectrum along with the individual model components and the residuals for two representative observations for the hard (0834) and soft state (1470) are depicted in Figure 5.2. The change in contribution of the model components across the two states is clear from the figure. The evolution of the best-fit spectral parameters is further shown in Figure 5.3.



Figure 5.3: Evolution of best fit parameters from spectral fit. The top two planels show the evolution of the best-fit inner-disk temperature and photon index. The third panel contains the total unabsorbed flux in 0.1 - 100 keV range in erg s⁻¹ cm⁻². The bottom panel shows the reduced χ^2 values for the fits.

5.2.2 Timing analysis

Rapid time variability was studied using the LAXPC instrument (Chapter 2.1.2.5) in the broad energy band of 3 - 80 keV. The analysis was done using the IDL-based GHATS software[†]. Cyg X–1 is known to show variability over a large range of frequencies spanning almost five orders of magnitude (Pottschmidt et al., 2003). We also opted to study all the features of the PDS. To meet that end, the LAXPC data were binned by a factor of 100 corresponding to a Nyquist frequency of sim500 Hz. The data were then divided into segments with 262144 bins each corresponding to a length of sim262.14 s. The minimum frequency attainable, as well as the frequency resolution, was thus 3.81 mHz. The PDS was then constructed by Fourier transforming the lightcurves of each segment and then averaging over all segments. The long exposures of AstroSat allowed sufficient number of segments to be averaged, thus resulting in good statistics. At this stage the normalization is set according to Leahy et al. (1983). The Poisson noise, i.e., the average power in the 100 - 500 Hz range where there is no intrinsic source variability, was then subtracted from the PDS and converted to fractional rms (Belloni & Hasinger, 1990). The PDS was then fitted by a combination of **lorentz**

[†]http://www.brera.inaf.it/utenti/belloni/GHATS_Package/Home.html

and cutoffpl (Axelsson et al., 2005). The first two observations (ObsIDs - 0834 and 0890) required four lorentz components similar to that obtained by Pottschmidt et al. (2003) for hard state. Following the next observation (1094), the first lorentz was replaced by a cutoffpl with an exception for ObsID 1210 when the lorentz came back. As the source evolved, the cutoffpl became more and more dominant with the last observation (1470) consisting mostly of a cutoffpl with a very weak and broad lorentz. Four representative power spectra, corresponding to ObsIDs 0834, 1180, 1414, and 1470 are shown in Figure 5.4. The best-fit parameters are listed in table 5.2. The Lorentzians are numbered 1 to 4 from left to right, i.e., from lowest centroid frequency to the highest. The first Lorentzian is replaced by a cut-off power law from the third observation on wards, except the sixth observation (1210). The numbering of the Lorentzians is done in comparison to the four components of the first two observations. So, even if the first component from the third observation on wards is a cutoffpl the second component is numbered lorentz 2 despite it being the first lorentz in the model. This is done so that the evolution of the Lorentzians can be studied easily. Similarly, for the last observation the only Lorentzian component is named lorentz 3 as its frequency matched with those of lorentz 3 from previous observations (but see 5.3.

5.3 Results

Figure 5.1 shows the lightcurves of Cyg X–1 using MAXI and Swift /BAT in the first and third panels, respectively, spanning a period that we have opted for this work. The MAXI lightcurve shows a gradual increase in flux from about 1 to 4 photons s⁻¹ cm⁻² from MJD 57710 to MJD 57980. However, the BAT lightcurve does not evolve in tandem with its MAXI counterpart. The BAT count rate remains stable at about 0.2 counts s⁻¹from almost the entire period and only starts to decay after MJD 57940. The second panel shows the evolution of hardness ratio, defined as ratio of MAXI flux in 4 - 10 keV and 2 - 4 keV. The hardness gradually decreases from ~ 1.0 to ~ 0.25 during the entire period. The fact that the MAXI lightcurve (2 - 20 keV) increases and hardness ratio decreases during MJD 57700 to MJD 57940, while the BAT lightcurve (in 15 - 50 keV range) remains stable, suggests that there is an increase in soft X-ray



Figure 5.4: PDS for four representative cases.

flux (2 - 4 keV) with the hard-X-ray output remaining unchanged.

The inference that the soft X-ray flux increases during the observations is also apparent from spectral fits. The evolution of the best-fitting T_{in} , Γ , and inner-disk radius (R_{in}) are shown in Figure 5.3. T_{in} increases from ~ 0.1 keV for ObsID 0834 to ~ 0.5 keV for last ObsID 1470. Similarly, Γ also evolves from ~ 1.4 to ~ 2.1. However, as has been observed earlier (Wilms et al., 2006), the source does not venture into the canonical LMXB states. From 0834 to 1470, the disk contribution to the total unabsorbed flux increases from ~ 11.4% to ~ 52.9% and the contribution of the Compton flux decreases from ~ 48% to ~ 19.7%. All observations between these two have fluxes within these limits. It is noteworthy that none of these shall qualify for being categorized into the canonical hard or soft states (Wilms et al., 2006). It is also important to note that a significant fraction of the total unabsorbed flux is accounted by the reflection component. Between the two extreme observations, the fraction of total flux by the reflection component decreased from ~ 40.6% to ~ 27.4%. The bestfit ionization parameter was constrained to higher values at about 10⁴ erg s cm⁻¹. The Fe abundance was also found to be super solar, with it pegging at the maximum value of 10 times the solar value during the fits. The 95% lower limit was found to be ~ 9 times the solar value for all observations. Although super-solar abundances have been reported earlier, Tomsick et al. (2018) have systematically studied contemporary *Suzaku* and *NuSTAR* data to conclude that such values are an artefact arising due to the low disk density (10¹⁵ cm⁻³) assumed in the **relxill** models that is more apt for AGN. Using variable disk density models, they have shown that Fe abundance for Cyg X–1 could be solar with the disk density constraining to much higher values ($\sim 10^{20}$ cm⁻³).

The PDS is a useful tool that reflects the inner dynamics of the accretion process quite well. As seen from Figure 5.4, throughout the study period Cyg X-1varied considerably. During the first two observations, identified with the hard state, the power spectra were decomposed into four Lorentzians (named lorentz 1, 2, 3, & 4). **lorentz** 1 is practically zero-centered and it is this component which vanishes during the intermediate states where it is replaced by a cut-off power law. The spectral index of the cut-off power law remains $\lesssim 1$ for all observations where it is present. lorentz 2 & 3 have average centroid frequencies of ~ 0.53 Hz and ~ 3.61 Hz respectively. lorentz 3 is the most peaked feature of the PDS. lorentz 4 is the broadest and the highest frequency component with an average centroid frequency of ~ 26.67 Hz and width of ~ 45.48 Hz. The centroid frequency and width of the only Lorentzian in the last observation (1470) makes its identification difficult. Its frequency (~ 6 Hz) is similar to those of lorentz 3 while its width (~ 22 Hz) is similar to those of lorentz 4 (see table 5.2). It is too slow for lorentz 4 and too broad for lorentz 3. We have arbitrarily put it under lorentz 3, but it is possible that the third and fourth Lorentzians, detected in the previous observations, have merged to give a single broad feature.

	norm	$0.22_{ m 0.01}^{ m 0.01}$	$0.20_{0.00}^{0.01}$	$0.42_{0.01}^{0.01}$	$0.05_{0.00}^{0.01}$	$0.41_{0.02}^{0.03}$	$0.37_{0.02}^{0.04}$	$0.07_{\scriptstyle 0.01}^{\scriptstyle 0.01}$	$0.04_{\scriptstyle 0.01}^{\scriptstyle 0.01}$	$0.06_{\scriptstyle 0.01}^{\scriptstyle 0.06}$	$0.41_{ m 0.03}^{ m 0.02}$	I	ı	sisted
lorentz 4	Width	$37.44_{1.90}^{1.91}$	$42.86_{1.95}^{3.01}$	$74.97^{2.38}_{2.15}$	$26.29_{3.21}^{8.90}$	$80.27_{3.98}^{4.28}$	$86.46_{5.34}^{6.78}$	$26.70^{7.94}_{5.06}$	$26.69_{6.96}^{9.29}$	$27.03^{22.73}_{5.74}$	$71.57_{1.93}^{3.33}$	I	ı	ObsIDs con
	LineE	$21.31_{\scriptstyle 0.60}^{\scriptstyle 0.61}$	$26.43_{0.73}^{0.74}$	$24.12_{1.27}^{1.26}$	$44.78_{1.05}^{1.07}$	$13.05_{6.92}^{4.52}$	$11.59_{3.39}^{3.14}$	$41.55_{0.88}^{0.87}$	$41.88_{1.69}^{1.64}$	$39.35_{1.27}^{1.27}$	$29.27^{1.99}_{2.19}$	ı	ı	sk-marked (
	norm	$1.92_{0.03}^{0.02}$	$1.62_{0.04}^{0.04}$	$2.19_{0.01}^{0.01}$	$1.39_{0.01}^{0.01}$	$2.03_{0.05}^{0.05}$	$1.57_{0.02}^{0.02}$	$1.71_{0.02}^{0.02}$	$2.19_{0.04}^{0.03}$	$1.96_{0.05}^{0.05}$	$1.64_{0.09}^{0.11}$	$0.69_{0.02}^{0.03}$	$0.99_{0.01}^{0.07}$	the asteris
lorentz 3	Width	$7.23_{ m 0.05}^{ m 0.06}$	$9.00_{-0.07}^{0.07}$	$6.19_{0.04}^{0.04}$	$5.63_{0.04}^{0.05}$	$5.76_{0.10}^{0.08}$	$6.59_{0.06}^{0.06}$	$6.05_{0.05}^{0.05}$	$4.89_{0.04}^{0.04}$	$5.05_{0.06}^{0.05}$	$4.03_{0.11}^{0.09}$	$8.22_{0.19}^{0.19}$	$21.91\substack{0.32\\2.16}$	model for
	LineE	$2.36_{0.05}^{0.05}$	$3.05_{0.05}^{0.04}$	$2.57_{0.03}^{0.03}$	$4.67_{0.02}^{0.02}$	$2.86_{0.07}^{0.07}$	$4.78_{0.03}^{0.03}$	$3.52_{0.04}^{0.03}$	$1.83^{0.06}_{0.04}$	$2.06_{0.07}^{0.04}$	$1.87_{0.03}^{0.06}$	$7.68_{0.11}^{0.10}$	$6.11_{0.01}^{0.29}$	atz.The
	norm	$2.23_{0.19}^{0.19}$	$1.96_{0.08}^{0.09}$	$2.25_{0.02}^{0.02}$	$1.71_{0.02}^{0.02}$	$1.79_{0.16}^{0.06}$	$1.50_{0.02}^{0.01}$	$1.67_{0.03}^{0.02}$	$1.70_{0.05}^{0.06}$	$1.70_{0.05}^{0.03}$	$1.56_{0.04}^{0.03}$	$1.99_{0.03}^{0.03}$	ı	and lore
lorentz 2	Width	$1.26_{0.02}^{0.05}$	$1.42_{0.02}^{0.03}$	$0.88_{\scriptstyle 0.01}^{\scriptstyle 0.01}$	$1.41_{0.02}^{0.02}$	$0.91_{0.03}^{0.03}$	$1.61_{ m 0.03}^{ m 0.03}$	$1.12_{0.02}^{0.02}$	$0.69_{0.02}^{0.03}$	$0.74_{0.02}^{0.02}$	$0.63_{0.02}^{0.02}$	$3.72_{0.08}^{0.08}$	ı	cutoffpl .orentz .
	LineE	$0.45_{0.03}^{0.05}$	$0.72_{0.02}^{0.01}$	$0.32_{\scriptstyle 0.01}^{\scriptstyle 0.01}$	$0.57_{0.01}^{0.01}$	$0.38_{0.02}^{0.02}$	$0.62_{\scriptstyle 0.01}^{\scriptstyle 0.01}$	$0.46_{\scriptstyle 0.01}^{\scriptstyle 0.01}$	$0.30_{\scriptstyle 0.01}^{\scriptstyle 0.01}$	$0.27_{0.01}^{0.01}$	$0.27_{0.01}^{0.01}$	$1.51_{ m 0.03}^{ m 0.03}$	ı	ation of a nent is a 1
*	norm	$4.01_{0.09}^{0.14}$	$3.26_{0.05}^{0.02}$	$2.37_{0.22}^{0.23}$	$0.10\substack{0.00\\0.00}$	$0.39_{0.09}^{0.12}$	$0.27_{0.01}^{0.01}$	$0.09_{0.00}^{0.00}$	$0.14_{ m 0.01}^{ m 0.01}$	$0.12\substack{0.01\\0.01}$	$0.34_{0.03}^{0.03}$	$0.08_{0.00}^{0.00}$	$0.50_{0.01}^{0.01}$	g a combir st compor
cutoffpl /lorentz 1	Ecut/Width	$0.21_{\scriptstyle 0.01}^{\scriptstyle 0.01}$	$0.29_{0.01}^{0.01}$	$0.03_{0.01}^{0.00}$	$124.28^{12.26}_{8.93}$	$0.51_{0.23}^{0.20}$	$0.05_{0.00}^{0.00}$	> 356.60	$123.02^{15.11}_{13.30}$	$94.76_{13.78}^{5.06}$	$12.09_{1.04}^{1.34}$	> 165.78	$12.38^{2.81}_{2.16}$	rameters using ents, so the fire
	PhInd/LineE	$0.03_{ m 0.01}^{ m 0.01}$	< 0.005	$0.09_{0.02}^{0.02}$	$0.85_{0.01}^{0.01}$	$0.57_{0.05}^{0.06}$	< 0.01	$0.91_{\scriptstyle 0.01}^{\scriptstyle 0.00}$	$0.96_{0.01}^{0.01}$	$0.84_{0.01}^{0.01}$	$0.72_{0.02}^{0.01}$	$0.95_{0.01}^{0.01}$	$1.02_{ m 0.01}^{ m 0.01}$	The best fit pa rentz compone
ObsID		0834^{*}	•0890	1094	1122	1180	1210^{*}	1258	1304	1358	1360	1414	1470	Table 5.2: of four 1 0

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5.4 Discussion

5.4.1 The state transition

In this work we have analysed twelve observations of Cyg X-1 with data from the AstroSat observatory spanning a period of about ten months in 2016-17. During this period, the source transited from a power law-dominated hard state to a disk-dominated soft state through a series of intermediate states. The exact physical mechanism driving these state transitions is still debatable. While some believe that the change in state is due to change in the properties of the corona (Miller et al., 2006a,b; Rykoff et al., 2007), others believe that the state transitions are effected by truncation of the inner disk (Gierliński et al., 2008; García et al., 2015). Recently, Kara et al. (2019) have shown that the transition in the bright LMXB MAXI J1820+070 takes place due to contraction of the corona. For Cyg X–1, the evolution of the best-fit inner radius shows that the disk moves from $\sim 3 \times R_{ISCO}$ in the initial observations (hard state) to $\sim 1 \times R_{ISCO}$ in the last two observations. Upon fixing R_{in} to ISCO, the fits are only slightly worse but still acceptable given that we use a high systematic error of 3%. Perhaps, the AstroSat spectrum is insensitive to R_{in} . The lightcurves and hardness evolution shown in Figure 5.1 suggest that the transition in Cyg X-1 essentially takes place due to an increase in the soft X-ray flux (2 - 4 keV) while the hard X-ray flux remains constant (apparent from the stable BAT count rate). The inner-disk temperature also increases from ~ 0.1 keV to ~ 0.5 keV. These properties can be easily explained by considering that the inner radius of the disk was truncated during the hard state and starts to move in during the transition up to the ISCO. The alternative explanation, that the disk remains stable at ISCO throughout and the increase in T_{in} happens due to an increase in the mass accretion rate, also can not be completely ruled out. However, the process by which such a rise in accretion rate takes place without corresponding change in inner radius is hitherto unknown.

5.4.2 Identification of Lorentzians

The power spectra of Cyg X–1 is markedly different from those seen in LMXBs. During the canonical hard state, an LMXB PDS exhibits a flat top noise (fitted by a zero-



Figure 5.5: Left: Correlation between centroid frequencies of lorentz 3 and lorentz 2. Right: Variation of centroid frequencies of lorentz 2 and lorentz 3 with the photon index.

centered lonrentzian) which is sometimes accompanied by a QPO or a peaked noise (Belloni & Motta, 2016). The PDS of Cyg X–1 in the hard state, on the other hand, is decomposed into four distinct Lorentzians as seen in Figure 5.4 (also see Pottschmidt et al., 2003). During the intermediate state, the HIMS in particular, the shape of the PDS of an LMXB is similar to those found in the hard state, but with reduced rms (from 30% to 10%). In case of Cyg X–1 the zero-centered Lorentzian is replaced by a cut-off power law. Axelsson et al. (2005) analysed all the RXTE observations of Cyg X–1 and detected the same behaviour during transitions. However, due to a smaller frequency range (0.01 - 25 Hz) they do not measure all the components. In soft states, both types of sources exhibit a power-law shape with the rms for Cyg X-1 ($\sim 20\%$) being quite higher compared to LMXBs (< 5%). One distinctive feature in the PDS of Cyg X-1 is the non-appearance of QPOs in any of the states. LMXBs, on the other hand, are known to show the peaked oscillations of different types depending on the states (Casella et al., 2004; Belloni & Motta, 2016), the origin of which still remains debatable (Belloni, 2010; Ingram & Motta, 2019). Over the recent years, there has been increasing evidence in favour of the models which describe QPOs (especially Type-C) as a consequence of Lense-Thirring precession of the inner disk due to a misalignment between the spin axis and the orbit of the binary (Ingram et al., 2009; Ingram & Done, 2011; Motta et al., 2015). Sources such as SAX 1819–2525 (Maccarone, 2002), XTE J1550–564 (Steiner & McClintock, 2012), H1743–322 (Ingram et al., 2017), etc show misalignment from about 5° to over 50° . Although misalignment between the

binary and spin axis can take place due to natal kicks during supernova explosion (Fragos et al., 2010), there must be sources where there is no misalignment and hence do not show Type-C QPOs. Several sources, for example XTE J1652–453 (Hiemstra et al., 2011), LMC X-3 (Boyd et al., 2000), 1E 1740.7–2942 (Smith et al., 1997), etc, do not show Type-C QPOs. However, it is difficult to ascertain that these sources have misaligned spin and orbital axes. Probably, Cyg X-1 falls in this category and there is also evidence that it felt no natal kick (Mirabel, 2017). Although there are no QPOs in Cyg X–1 (defined tentatively as peaks with quality factor > 2), its PDS can be decomposed into a few Lorentzians, some of which are quite peaked during the intermediate states. The origin of these broad features still remains uncertain and it is interesting to see if any of these features are analogous to the components found in LMXBs. Figure 5.5 (right plot) shows the dependence of centroid frequencies of the second and third lorentzians with the photon index. Here, one can see that **lorentz** 3 shows a positive correlation with photon index similar to Type-C QPOs in LMXBs (Vignarca et al., 2003; Shaposhnikov & Titarchuk, 2007; Stiele et al., 2013), whereas, lorentz 2 frequency does not show any dependence on photon index. This suggests that lorentz 3 is analogical to Type-C QPOs. The positive correlation can be explained under the truncated disk geometry of the Corona where state transition is effected by the movement of inner edge of the disk (Stiele et al., 2013). The left plot in Figure 5.5 shows the correlation between the centroid frequencies of lorentz 2 & 3. The positive correlation between the two is also reported previously by Axelsson et al. (2005). Since our data is sparse, especially in the hard state, we can not trace the change in the slope through the transition. We do not attempt to constrain the slope, but, qualitatively the positive correlation can be understood as a consequence of relativistic precession of a blob of gas around the black hole where the two frequencies are the precession and nodal frequencies (Stella & Vietri, 1998; Axelsson et al., 2005). The fractional rms of the Lorentzians are plotted against the inner-disk temperature in Figure 5.6. While the rms for lorentz 2 and lorentz 4 do not show any correlation with T_{in} , the rms for lorentz 3 display a negative, although weak, correlation. The correlation further improves if we exclude the left-most two points which belong to the hard state when the inner-disk is truncated at a larger radius. Such negative correlations can be explained under the ambit of geometrical models for QPOs (Rout

et al., 2021). It may be possible that the inner disk becomes momentarily misaligned due to radiation warping (Pringle, 1996; Ingram & Motta, 2019) which results in the peaks. We note that these properties are only suggestive in nature and more research is required for concluding definitively about the power spectral properties and spectral transition in Cyg X–1. Understanding the radiative properties of the peaks should throw some light about its origin. Recently, it has been shown that Comptonization is able explain the lag and rms spectra of all kinds of QPOs (Type-B, Type-C and kiloHertz QPOs in neutron stars) Karpouzas et al. (2020); García et al. (2021). It would be interesting to see if the peaks in the power spectra of Cyg X–1 are being explained by the same Comptonization model. We plan to study the same in the future.



Figure 5.6: Correlation between inner-disk temperature and fractional rms of individual components of the PDS

Chapter 6

X-ray spectroscopy of MAXI J1631–479: Implication for a massive black hole

6.1 Introduction

X-rays emitted from the inner-most regions of the accretion disk are affected by the fundamental parameters of the black hole, such as mass and spin. By carefully analyzing the X-ray spectrum during softest states, when the disk is believed to reach ISCO (inner-most stable circular orbit), the values of these two parameters can be obtained. Along with fitting the continuum, spin can also be obtained by accurately modeling the fluorescent Fe K α line in the reflection spectrum. The measurement of spin is the subject matter of the next chapter (7). In this chapter, we attempt to constrain the mass of the black hole in MAXI J1631–479 (hereafter, J1631) by fitting the soft X-ray continuum.

The distribution of masses for black holes found in a variety of sources can help in constraining the stellar and binary evolution theories. Of particular interest is the dichotomy which has started to appear in the masses of black holes discovered in X-ray binaries and from merger events using gravitational waves. While the former is restricted to a lower range of values (5 - 15 M_{\odot} , Wiktorowicz et al., 2014), the later is spread over a broader and larger range (20 - 70 M_{\odot} , Abbott et al., 2019). This apparent polarity has prompted researchers to understand the phenomenon by attributing different formation channels to the two systems, with the former evolving from isolated binaries of field stars while the later forming primarily via dynamical interaction in star clusters (Perna et al., 2019). With about 12 detection using gravitational waves and about 20 confirmed mass estimates in XRBs, the sample space at this moment is too sparse to arrive at a definitive conclusion on the existence of a dichotomy.

The conventional method for measuring black-hole mass hosted in XRBs involves radial velocity measurement of emission lines obtained from the companion star. Apart from this method, the mass of a black hole can also be constrained using X-ray emission from inner most regions of the accretion disk during high/soft state. The soft X-ray flux ($\sim 0.1 - 3 \, keV$) is a function of mass along with distance, spin, and inclination (Zhang et al., 1997). A robust estimate of the spin and inclination (from reflection spectroscopy) can provide a relation between mass and distance (Parker et al., 2016). A limit on the distance can consequently provide a limit on mass. We use this technique to constrain the mass for a newly discovered XRB MAXI J1631–479.

J1631 was detected as a bright hard X-ray transient with MAXI/GSC on 2018 December 21 at 04:33 UTC. The outburst was marked by a fast rise in luminosity till 2019 January 07 followed by an exponential decay, a pattern which is typical of BHBs. Fiocchi et al. (2020) reported results on the INTEGRAL/IBIS spectrum suggesting possible emission from a hybrid plasma. Xu et al. (2020) studied the variation of reflection features using NuSTAR as the source transitioned from a disk-dominated state to a power law-dominated state. Rout et al. (2021) studied the spectral and timing evolution of the source using NICER. In this work, we analysed the joint Swift/XRTand NuSTAR spectrum to estimate the mass along with providing new limits on the spin and inclination.

The rest of the paper is organised as follows. In section 2 we explain the methods of data reduction and spectral analysis of both XRT and joint XRT/NuSTAR. We have divided section 3 into two parts wherein we discuss the results on the estimation of the spin and inclination and measurement of mass. Finally, in section 4 we summarize the important results.



Figure 6.1: Spectra and residuals of the first four XRT observations made on 2019 January 16, 17, 18, and 19. Each of these observations were fitted by an absorbed disk model (TBabs*diskbb). The top panel displays the unfolded spectrum for each observation with similarly colored residuals in the subsequent 4 panels. The residuals are plotted chronologically from top to bottom.

6.2 Data Reduction and Analysis

6.2.1 Swift/XRT

J1631 was monitored by the *Swift* observatory (Burrows et al., 2005) from 2019 January 16 on wards till 2019 June 4 when the source almost went to quiescence. Since we are interested only in the soft states and Rout et al. (2021) showed that the source hardens later on we analysed only the first 8 XRT spectra observed between 2019 January 16 to 30 that traced the soft to hard transition of the source. Out of the 8 spectra, we simultaneously fitted the first 4 for the mass measurement and used the January 17 and 30 spectra to jointly fit with *NuSTAR*. Standard data reduction procedure was employed as explained in the analysis threads *. Pile-up and bright source corrections were carried out as delineated by Romano et al. (2006) and Motta et al. (2017).

Spectral analysis was carried out using the typical combination of a multicolor blackbody model diskbb (Mitsuda et al., 1984) and a thermal Comptonization model ThComp (Niedźwiecki et al., 2019; Zdziarski et al., 2020) along with the neutral absorption component TBabs. It was found that during the first four observations, from 2019 January 16 to 19, the spectrum could be perfectly fitted only with an absorbed disk component (Figure 6.1). From January 20 on wards Comptonization became necessary which was evident from an excess at higher energies in the residuals as well a significant improvement in the fit statistics. The best-fit parameters for all 8 observations are noted in Table 6.1. The neutral hydrogen column density was high ($\sim 6 \times 10^{22} \text{ cm}^{-2}$) making J1631 one of the highly absorbed BHBs in the galaxy.

Date	$N_{H} (\times 10^{22})$	kT_{in}	norm $(\times 10^3)$	Γ	f_{sc}	Flux (×10 ⁻⁷)
	cm^{-2}	keV	(diskbb)			$\rm erg~s^{-1}~cm^{-2}$
2019 Jan 16	5.58 ± 0.05	1.21 ± 0.01	3.35 ± 0.11			1.36
2019 Jan 17	5.54 ± 0.05	1.19 ± 0.01	3.78 ± 0.13			1.41
2019 Jan 18	6.32 ± 0.10	1.25 ± 0.01	2.58 ± 0.14			1.18
2019 Jan 19	6.05 ± 0.08	1.25 ± 0.01	2.82 ± 0.13			1.28
2019 Jan 20	7.22 ± 0.15	$1.09^{+0.03}_{-0.10}$	$4.16_{-0.47}^{2.23}$	< 4.06	$0.035^{+0.639}_{-0.005}$	1.15
2019 Jan 26	$6.34_{-0.12}^{0.08}$	1.09 ± 0.04	$3.52^{+1.02}_{-0.45}$	< 1.78	$0.12_{-0.01}^{+0.32}$	1.12
2019 Jan 29	$5.97\substack{+0.09\\-0.12}$	1.16 ± 0.04	$2.36_{-0.29}^{+0.45}$	< 2.03	$0.08\substack{+0.28\\-0.01}$	0.90
2019 Jan 30	$5.17_{-0.07}^{+0.04}$	$1.22_{-0.08}^{+0.04}$	$1.20_{-0.13}^{+0.36}$	< 2.17	$0.13_{-0.01}^{0.54}$	0.60

Table 6.1: Best-fit parameters for the first eight Swift/XRT observations. The errors represent 1σ statistical uncertainty. The unabsorbed flux in the 7th column is calculated in the 0.7 - 10 keV range.

6.2.2 Joint Swift/XRT and NuSTAR analysis

Modeling the reflection spectrum, especially the fluorescent Fe-K α line, allows the spin and inner-disk inclination to be determined independently. *NuSTAR*, with a broad energy band and high spectral resolution is ideal for such a study (Harrison et al., 2013). The analysis of *NuSTAR* was carried out using the (NUSTARDAS) following the standard procedure [†]. Of the four *NuSTAR* observations, the January 17 and 30 observations were made quasi-simultaneously with *Swift*/XRT. Since the combined energy

^{*}https://www.swift.ac.uk/analysis/xrt/

[†]https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/

band (0.7 - 78 keV) would better constrain the thermal disk and reflected emission, we present the results of only these two NuSTAR data. The January 17 data was further divided into two parts as there is an increase in flux and hardness in the second half of the observation (see Figure 6.2). The joint spectra were fitted with a model consisting of a multi-color blackbody (diskbb) and a reflection component of the reflkerr family (Niedźwiecki et al., 2019). We used the flavour reflkerrD_lp which assumes a lamppost geometry along with variable disk density. The effect of allowing higher density is important since thermal re-emission from the disk could be in the range of a few keV which can lead to incorrect modeling of the continuum and hence wrong estimates of spin and inclination (García et al., 2016; Jiang et al., 2019; Zdziarski et al., 2020). The scaling parameter of reflection, rel_refl, was fixed to one ensuring a physical lamp-post normalization. The geometry parameter was fixed to zero that calculates the escape probability for a spherical corona. Finally, emission from bottom of the lamp was neglected before fitting. A negative gaussian model was added to account for a blue shifted H-like Fe XXVI absorption line. Both the January 17 spectra showed an excess in the high energies, > 40 keV, which was fitted by a low-cut powerlaw with the cutoff energy fixed to 50 keV. Fitting with such a model combination is quite tricky because the excess power law and the Compton tail from the reflected emission will compete with each other. This makes constraining either of the components difficult. Therefore, once a reasonable fit was achieved the excess power law index and norm were frozen while fitting the reflected emission and vice versa. Because of such a caveat we refrain from drawing any strong conclusion from the power-law component of these fits. However, we have verified that the addition of the power-law component does not considerably affect other best-fit parameters such as spin and inclination. It is evident that this hard X-ray excess is most likely due to non-thermal Comptonization (Fiocchi et al., 2020). The other possibility, i.e., hard X-ray synchrotron emission from jets, is quite unlikely as the jet is known to be quenched during the high/soft states (Fender & Belloni, 2004). The final model setup in xspec was constant*TBabs*(diskbb + reflkerrD_lp + gaussian + expabs*powerlaw). The best-fit parameters for both these model combinations are mentioned in Table 6.2



Figure 6.2: NuSTAR lightcurve and hardness ratio for the January 17 observation. The hardness ratio is defined as the ratio of count rate in 10-78 keV to that in 3-10 keV. The two parts represent two different levels of count rate and hardness and thus, the spectral analysis was done separately for each part. Here, we only show the lightcurve for FPMA.

6.3 Results and Discussion

J1631 is a highly absorbed source with the average neutral hydrogen column density (N_H) lying above 6×10^{22} cm⁻². The observation on January 17 was in a disk dominated state while that on January 30 was dominated by power-law component. Despite leaving disk density as a free parameter, it was constrained to a rather low value of $\sim 10^{16}$ g cm⁻³. The Fe abundance, however, could not be well constrained across epochs. The absorption line at $\sim 7 \, keV$ represents resonance absorption by H-like Fe XXVI ions which is blue shifted as the absorbing material, i.e., disk winds, flows towards the observer. As per the best fit line energies, the wind velocity during the January 17 and 30 observation were $\approx 0.06c$ and $\approx 0.04c$ respectively. Such ultra fast winds, although common among Active Galactic Nuclei, is not new to black hole systems and has been detected only in high inclination binaries like IGR 17091–3624 (King et al., 2012) and GRS 1915+105 (Zoghbi et al., 2016). We note that the absorption lines are quite broad with FWHM of about 0.3 keV. It could be possible that these features represent an absorption complex with contribution from multiple species, instead of one ion, which could not be resolved with NuSTAR. In such a case, the identification

Parameters	17 January (P1)	17 January (P2)	30 January
N _H (×10 ²² cm ⁻²)	6.43 ± 0.01	6.65 ± 0.02	5.36 ± 0.01
kT_{in} (keV)	1.028 ± 0.001	1.080 ± 0.001	1.084 ± 0.002
norm _{diskbb}	4586 ± 3	3360^{+36}_{-14}	1148^{+7}_{-63}
h (\mathbf{R}_g)	2.096 ± 0.003	$2.69^{+0.08}_{-0.01}$	$26.67^{+0.31}_{-0.57}$
a	0.987 ± 0.001	0.972 ± 0.001	
Incl (degrees)	$69.82_{-0.04}^{+0.03}$	$61.00_{-0.13}^{+0.20}$	$67.35_{-0.29}^{+0.03}$
$\mathbf{R}_{in} (r_{isco})$			$3.61_{-0.34}^{+0.11}$
$ au_y$	$0.21^{+0.01}_{-0.04}$	< 0.05	0.71 ± 0.04
A_{Fe}	> 9.94	$4.53_{-0.22}^{+0.04}$	0.56 ± 0.01
kTe	$49.1_{-0.1}^{+6.5}$	$143.5_{-0.2}^{+4.0}$	68.8 ± 0.1
$\log \xi$	1.67 ± 0.01	3.49 ± 0.02	3.19 ± 0.01
log N	$16.13^{+0.11}_{-0.06}$	15.54 ± 0.01	16.28 ± 0.02
norm	$4.94_{-2.73}^{+0.02}$	$7.25_{-0.28}^{+0.03}$	3.57 ± 0.01
LineE	7.47 ± 0.02	7.39 ± 0.01	7.28 ± 0.01
Sigma	0.46 ± 0.02	0.33 ± 0.01	0.29 ± 0.01
$\operatorname{norm}_{gaussian} (\times 10^{-3})$	$-5.71^{+0.25}_{-0.22}$	$-10.73_{-0.45}^{+0.26}$	$-7.18^{+0.53}_{-0.25}$
LowECut	50^{\star}	50^{\star}	
Г	1.75 ± 0.01	$1.61_{-0.04}^{+0.02}$	
norm _{powerlaw}	0.123 ± 0.005	0.148 ± 0.005	
Flux _{0.7-10keV} (×10 ⁻⁸)	$5.\overline{67}$	5.78	4.28
Flux _{10-78keV} (×10 ⁻⁸)	0.10	0.30	1.09
$\chi^2 (dof)$	$26\overline{46.11}$ (1847)	3276.36(2354)	3806.88(3221)

Table 6.2: Best-fit parameters from the joint Swift/XRT-NuSTAR spectral fit. The model is defined as TBabs*(diskbb + reflkerrD_lp + gauss + expabs*powerlaw). The extra low-cut power law is not required for the January 30 spectrum. The asterisk represents the values where the parameter was fixed while fitting. The errors represent 1σ confidence range. The unabsorbed fluxes listed are in the units of erg s⁻¹ cm⁻². All symbols have the usual meaning.

of the ion may be wrong and the inferred wind velocity different.

6.3.1 Estimates of the spin and inclination

The accurate estimation of spin and inclination is highly sensitive to the modeling of the underlying continuum. Our analysis of joint XRT and *NuSTAR* spectra shows that both spin and inclination are high. The inclination was 69° and 61° for parts 1 & 2 of January 17 observation whereas for the January 30 observation, it was ~ 67°. Accordingly, the spin was ~ 0.99 and ~ 0.97 for the two parts of January 17. The high spin is consistent with Xu et al. (2020) who reported a > 0.94. However, they obtained a lower value for inclination of $29 \pm 1^{\circ}$. There are considerable differences between the

approach of Xu et al and that of ours. Xu et al model the primary reflection component using a compound model relconv_lp*refbhb. While refbhb might provide a better physical description of reflection due to disk atmosphere during soft states, it also makes some simplifications that can affect the continuum shape. For example, it assumes a single-temperature blackbody for the emission from the accretion disk which is less accurate compared to the more physical multi-temperature model (Reis et al., 2008). The Fe abundance was fixed to the solar value by Xu et al while fitting. Although, it was not constrained from our fits, the best-fit values hinted towards super-solar abundance. This is in spite of using a reflection model which allowed the disk density to float (Tomsick et al., 2018). We also notice that the column density (N_H) reported by Xu et al is low. During the fits, they left N_H free to vary and arrived at a best-fit value of 3.3×10^{22} cm⁻². With XRT spectrum, whose range (0.7-10 keV) allows for a better control over N_H , we obtained a higher range of 5 - 7 × 10²² cm⁻² (see Table 6.1). Rout et al. (2021) have also reported a higher N_H at ~ 6.4×10^{22} cm⁻² from the analysis of NICER data. We tried fixing the N_H to 3.3×10^{22} in the XRT spectra, but did not find an acceptable fit $(\chi^2_{\nu} \approx 6)$. Thus, we suspect that the low N_H could have played a role in improper modeling of the continuum leading to a low inclination for Xu et al. We further note that apart from fitting the Fe-K α line, a higher inclination is also independently supported by the detection of ultra-fast winds (Ponti et al., 2012; Boirin et al., 2005). The possibility of a nearly face-on disk with relativistic winds is even a more exotic scenario. Thus, we conclude that the most likely range of the inclination is 61° - 69° and the spin is 0.97 - 0.99.

6.3.2 Constraining black-hole mass

With firm estimates of the spin and inclination it is possible to constrain the mass if distance to the source is known. The first four *XRT* spectra were found to be completely disk dominated and were simultaneously fitted with an absorbed general-relativistic accretion disk model (TBabs*kerrbb Li et al., 2005). All the system parameters that do not change across the observations like spin, inclination, mass, and distance were tied up. This left only the mass accretion rate as untied parameter across the four observations. The spin and inclination were fixed to a combination of extreme values



Figure 6.3: The spectra along with individual model components for the three cases studied. The first two columns display the two parts of the January 17 observation and the third column displays the January 30 observation. Green, blue and red colors are used for XRT, FPMA, and FPMB respectively. The fitting is done using the model M1 as described in Table 6.2. The second row depict the residuals without the gaussian and expabs*powerlaw components. This clearly reveals strong features at the Fe XXVI energy of ~ 7.1 keV for all three cases and excess beyond 40 keV for the two January 17 spectra. The third row shows the residuals with the complete model setup. The identification of individual model components in the top panel is to be done with following aid: Solid-diskbb, Dashed-nthComp, Dotdashed-reflkerrD_lp, Dotted-power law. The black solid line represents the total model.

from the joint fits and the distance was fixed to a value ranging from 2 - 8 kpc all the while fitting for the mass. The flags for including the effects of limb darkening was turned on and that for the effects of self-irradiation was also turned on. It was assumed that there would be zero torque in the inner boundary of the accretion disk. The spectral hardening factor (κ) was fixed at 1.7 (Shimura & Takahara, 1995). For each combination of inclination, spin, and distance the mass accretion rate and mass were fitted. All the fits were statistically good with the χ^2_{ν} lying close to 1. The result of this exercise is shown in Figure 6.4. The green line represents the low spin - low inclination pair (a = 0.97, $i = 61^{\circ}$) and the blue line represents the high spin - high inclination pair (a = 0.99, $i = 69^{\circ}$). The shaded region along the lines represent 1- σ statistical error for mass. The other combinations, i.e., high spin - low inclination and low spin - high inclination, give intermediate values for the mass. These lines suggest that the black hole is quite massive. Even at a very low distance of 3 kpc the mass is in excess of 10 M_{\odot} .

In order to validate this method and the obtained result of high mass we analysed another BHB 4U 1630–47 which has close resemblance to J1631 in many aspects. It is also a rapidly spinning high inclination binary showing clear presence of disk winds (Tomsick et al., 1998; Pahari et al., 2018) and located in a direction very close to J1631. Seifina et al. (2014) have deduced the mass to be ~ 10 M_{\odot} based on the correlation between photon index, low-frequency quasi-period oscillations and mass accretion rate. During the 2016 outburst, 4U 1630–47 remained pre-dominantly in disk-dominated high-soft state for most part, with the hardness only increasing slightly towards the end. The source was monitored with Swift starting from 30 August till 21 October and then resumed on January 2017. Just like J1631, we analysed the first four XRT spectra observed on 30 August and 5, 6, and 7 September during which it was in high/soft state. The same procedure, as opted for J1631, was followed to find the relation between mass and distance. The result of this exercise is overlaid on Figure 6.4 (grey line). Despite similar values of spin and inclination for both the sources, the mass ranges are clearly separated. 4U 1630–47 occupies the typical range of 3 - 10 M_{\odot} for the entire distance range. Even if we consider the full extent of inclination, the mass range would be significantly different in the two cases. The estimated mass of 10 M_{\odot} (Seifina et al., 2014) for 4U 1630–47 concurs roughly with the galactic-center distance of 8 – 10 kpc. At that typical distance, J1631 will have a mass of about 40 M_{\odot} . These results suggest that J1631 hosts a massive black hole compared to other such galactic systems.

A reasonable limit on the distance could now give a possible range for the mass. In order to have some estimate of the distance, we use the optical observations of the source. If the optical flux is assumed to be originating from the accretion disk, then by comparing the observed flux with the expected flux some estimate on the distance can be obtained. Several attempts were made to detect the source during the outburst (Kong, 2019; Shin et al., 2019). However, as reported by Kong (2019) a certain level of ambiguity exists in detecting the source at the exact location. For a star closest to the source position Kong reported a magnitude of 19.36 ± 0.06 in the SDSS-r band on 10 February 2019. 18 days before this, Shin et al. (2019) reported a slightly brighter object with 19.1 magnitude at the source location. This object may or may not be the optical counterpart of J1631. But, the optical counterpart cannot be brighter than that, as otherwise it would have been certainly detected. Thus, to remain on the conservative side, we considered that the reported magnitude represents the source.

We carried out a Monte Carlo simulation to infer the limits on distance. The optical flux originating from an XRB during outburst is a combination of emission from the irradiated outer accretion disk and the secondary star. For a low mass late type Secondary, the disk flux during a typical outburst is about 2 to 5 orders of magnitude brighter than the secondary companion rendering its contribution to the total flux negligible. The disk flux was calculated by approximating a multi-temperature blackbody in the geometry of an irradiated thin accretion disk (Frank et al., 2002). The innerdisk temperature $(0.91 \pm 0.09 \text{ keV})$ was sampled from a gaussian distribution of best-fit parameters obtained by fitting the XRT spectrum observed on the same day as the optical measurement by Kong (2019), with diskbb. Other parameters like mass (3 -60 M_{\odot}), outer-disk radius (6 × 10⁴ - 10⁵ R_q), distance (1.5 - 10. kpc), inner disk radius $(1.24 - 2.5 R_q)$, and inclination $(60^\circ - 70^\circ)$ were drawn randomly from a wide uniform distribution. An essential element of this calculation, which basically constrains the distance, is extinction by interstellar dust. To incorporate this, the 3D extinction map by Marshall et al. (2006) was used. Since this map is in infra-red band (K_s -filter), it was converted into SDSS-r band extinction using the conversion factors given by Mathis (1990) and the extinction law calculated by Cardelli et al. (1989). Finally, the expected magnitude was compared to the observed magnitude by Kong (2019) for 10^6 iterations.

Whenever the expected flux lied within the observed flux range (i.e., 19.3 - 19.42 magnitude) the corresponding distance was selected. At the end of this simulation, 5111 distance values were selected. Then we used these distances to fit for mass using the same simultaneous XRT fitting method as undertaken earlier. But instead of fixing spin and inclination, we generated a random distribution with spin varying from 0.97 to 0.99 and inclination ranging from $61^{\circ} - 69^{\circ}$. Each iteration results in a possible mass



Figure 6.4: The green and blue oblique lines represent the mass - distance relation obtained by simultaneously fitting four soft state XRT spectra for different combinations of spin and inclination mentioned in the legend. The red-yellow 2D histogram represents the probability distribution of mass and distance with the assumption that the observed optical flux originates from the actual counterpart. The gray (dot-dashed) line at the bottom are for another BHB 4U 1630–47 with a = 0.90 and $i = 65^{\circ}$, also obtained by fitting XRT spectra. The shaded region along the lines represent 1- σ statistical uncertainty on best-fit mass.

value and a 2D histogram of 5111 mass values is plotted in Figure 6.4 with red-yellow points representing the probability of occurrence. From this histogram, it is apparent that the most probable mass is ~ $30 M_{\odot}$ corresponding to a distance of ≈ 6 kpc. The confidence limit is set by marking the distance bin for which at most 99% of the points were rejected, i.e., when the expected magnitude were less than the observed magnitude. This ensured that the 99% confidence lower limit of the distance is 3.7 kpc which corresponds to a mass of 18 M_{\odot} . We note that the assumption of considering the observed optical flux to be emitted from the source ensures that the distance is lowest for any combination of other parameters. If this is not true, then the distance would be much larger resulting in a higher mass. This exercise suggests a possible distance range of 4 - 7 kpc and consequently a likely mass range of 20 M_{\odot} - 40 M_{\odot} . BHBs are mostly populated around the central parsec of the galactic centre which is about 8 kpc away (Generozov et al., 2018). If this were true for J1631, its mass would most likely be 50 M_{\odot} making it the most massive galactic black hole to be hosted in X-ray binaries. It should be noted that the value of the likely mass or the mass range
is dependent on the crude distance estimate. However, the massive nature of the black hole is well established from X-ray fitting of the accretion spectrum itself. Thus, this black hole is among the heaviest stellar-mass black holes in the galaxy, even if it is as close as 3 kpc.

Chapter 7

A retrograde spin of the black hole in MAXI J1659–152

7.1 Introduction

The spin of a black hole can be measured by two techniques - the continuum fitting method (Zhang et al., 1997, CF), and Fe-line spectroscopy (Fabian et al., 1989). Both methods infer the value of spin indirectly by measuring the inner radius of the accretion disk, which is assumed to extend down to the ISCO (innermost stable circular orbit). In the CF method, the inner radius is estimated by fitting the thermal disk continuum with a general relativistic disk model (Gierliński et al., 2001; McClintock et al., 2006; Shafee et al., 2006). Geometrical parameters of the system like black-hole mass, distance, and inclination and the spectral hardening factor must be known a priori for the CF method to work. Reflection spectroscopy consists of modeling the spectrum originating from the reflection of the back-scattered coronal emission from the inner disk. Two important features of this spectrum are the fluorescent Fe-K α emission between 6.4 to 6.97 keV and a Compton hump peaking at around 30 keV. The red-ward extent of the line profile, that gets skewed by gravitational redshift, essentially gives the inner radius of the disk and hence the spin (Iwasawa et al., 1996; Miller et al., 2002, 2004), while the blue wing of the line essentially gives a measure of the inclination (Miller et al., 2018). There have also been attempts to constrain the black-hole spin using quasi periodic oscillations (QPO). The relativistic precession model (RPM; Stella & Vietri,



Figure 7.1: J1659 lightcurve in the 2-10 keV band with MAXI/GSC (Matsuoka et al., 2009). The colored vertical bars represent the epochs of the XMM-Newton and RXTE observations.

1998; Ingram & Motta, 2014) associates various QPO frequencies with the orbital and precession frequencies of the accretion disk. Motta et al. (2014) and Šrámková et al. (2015) have applied this method to arrive at an estimate of the spin. However, these measurements remain few in number and enshrouded by uncertainty owing to there dependence on the models used. Dovčiak et al. (2008) showed that the polarisation angle and degree, expressed as a function of thermal energy, varies with spin and can be used as a method for spin determination, although it is yet to be applied.

While the spin of a stellar mass black hole is reminiscent of the natal kick during a supernova explosion, the angular momentum of the accretion disk is determined by the binary orbit. Although, accretion would tend to align both the spin and the disk angular momentum through torques, that generally does not happen in LMXBs. This is because the mass required to be gained by the black hole to alter the spin significantly can not be supplied by a low-mass companion during the binary evolution (King & Kolb, 1999; McClintock et al., 2006). Thus, the spin is most likely natal and should be randomly distributed among the black-hole population. However, on observational grounds, most of the sources that have robust spin measurement shows positive spin (McClintock et al., 2014; Reynolds, 2014). It is only recently that a few systems with negative, or being consistent with negative, spin have come up (Morningstar et al., 2014; Reis et al., 2013; Rao & Vadawale, 2012). Here, we present a case where the binary system MAXI J1659–152 hosts a negative spin black hole for almost the entire parameter space.

7.2 Observation and Data Reduction

MAXI J1659-152 (henceforth termed as J1659) went into outburst on 2010 September 25, and was detected by Swift/BAT at 08:05 UTC on that day. Soon after the initial detection, Swift and RXTE were used to monitor the source continuously revealing many important properties of the source (Yamaoka et al., 2012; Kennea et al., 2011; Kalamkar et al., 2011). Three days into the outburst J1659 was observed with XMM-Newton with a single pointing of \sim 50 ks exposure. The availability of simultaneous XMM-Newton and RXTE data enables us to try both the continuum fitting and reflection spectroscopy to measure the spin of the black hole.

The complete outburst lightcurve of J1659 is shown in Figure 7.1. The source reached its maximum luminosity on MJD 55477 during a flare and the thermal peak on MJD 55489 (Kalamkar et al., 2011). J1659 was observed in timing mode with XMM-Newton (Jansen et al., 2001) on September 27 at UTC 16:15:27. For our analysis, only the pn-CCD of the European Photon Imaging Camera was used (Strüder et al., 2001). We used the recent version of SAS (17.0.0) and followed the instructions given in the data analysis threads *. Standard procedure for pile-up correction was undertaken by excising central 5 rows of the PSF and comparing the grade ratios from the output of the SAS tool epatplot.

It was found that the background was contaminated by source counts because of its brightness and the relatively extended PSF of the EPIC-pn CCD. The flux difference between the background corrected and uncorrected spectrum was found to be $\sim 3.7\%$. It was verified using phenomenological models that the inclusion or exclusion of background did not have any significant impact on the model parameters. Hence, the analysis was carried out with the background extracted from the tail of the PSF. The data were grouped to have a minimum of 25 counts per bin to facilitate chi-square statistics and a systematic error of 1.5% was added. It is quite customary to encounter absorption features of instrumental origin in the EPIC-PN (timing mode) spectrum at \sim 1.8 and \sim 2.3 keV corresponding to Si-K and Au-M edges respectively (Wang et al.,

^{*}https://www.cosmos.esa.int/web/xmm-newton/sas-threads

2019; Papitto et al., 2009). To keep the model simple, we ignored the range of 1.5 - 2.5 keV from the spectrum instead of adding two absorption components which, we verified, would not have improved our results significantly.

J1659 was observed with RXTE (Swank, 2006) on several occasions across the outburst. One observation with Obs. ID 95358-01-02-00 starting on 28 September 2010 at 00:58:24 partially overlapped with the XMM-Newton observation for a duration of ~20 ks. Standard screening and filtering criteria were used to analyze the data of the Proportional Counter Array (PCA, Jahoda et al., 2006). Only the top layer of PCU2 was used for the analysis. A bright model for the background as provided in the PCA Digest page[†] was used to produce the background spectrum. The exposure of both the source and background spectra were corrected for dead time effects and a systematic error of 0.5% was added. Since the observation was during the rising phase of the outburst (Figure 7.1) only the overlapping period of PN and PCA data, with an exposure of ~20 ks, was used to avoid any spectral change. Upon using the full range of PCA, large residuals were observed in the 4 - 10 keV range. Such features are due to energy dependent cross-calibration uncertainty between PN and PCA and were previously reported by Kolehmainen et al. (2014) and Hiemstra et al. (2011), among others. Thus, we use the PCA in the 10-40 keV range.

7.3 Analysis and Results

We fitted the data in XSPEC- v12.10.1 with a combination of models to describe the broad-band spectrum of J1659. The best fitting parameters for each of the models considered are listed in table 7.3 and the residuals of the fits are shown in Figure 7.2. To allow for the possible energy-independent cross-calibration uncertainties a multiplicative factor, constant, was added to the model. This parameter was frozen at 1 for EPIC-pn and left free to vary for PCA. The photo-electric absorption in the inter-stellar medium, was accounted by multiplying a phabs component to all the models.

We first fitted the Comptonization model nthComp (Zdziarski et al., 1996) but the fit was unacceptable with $\chi^2_{\nu} = 12.27$ for 186 degrees of freedom (dof). The fit was

[†]https://heasarc.gsfc.nasa.gov/docs/xte/pca_news.html



Figure 7.2: Top panel: The unfolded spectrum of J1659 along with the individual model components. The cyan, green, and black curves represent, respectively, the thermal-disk, power law and reflection components (Model 3 below). Residuals for the following models from second to fourth panel: Model 1 - const*phabs* (diskbb + nthComp); Model 2 - const*phabs (gaussian + diskbb + nthComp); Model 3 - const*phabs*(diskpn + nthComp + relxillCp). The lighter-shade residuals in the bottom two panels were obtained by fixing the normalization of Gaussian and relxillCp to zero respectively.



Figure 7.3: Results of the monte-carlo simulations to test the significance of the Fe emission line in J1659. The left panel shows a comparison of the norms obtained from simulations (blue histogram) to that obtained from the data (red line). The first bin (left most) in the histogram reaches up-to 500000, and has been clipped at 40000 for clarity. The six plots in the right show the distribution of the parameters that went into the simulation.

repeated with a blackbody-like model to account for the thermal (disk) component of the spectrum. Adding a diskbb model (Mitsuda et al., 1984) gave a better fit than before, with $\chi^2/d.o.f. = 244.60/185$. However, the second panel of Figure 7.2) show positive residuals at ~ 7 keV, which are most likely due the Fe-K α emission. To incorporate this feature, a Gaussian component was added to the model that improved the fit significantly (see Figure 7.2, second panel) along with keeping most of the other parameters within 90% confidence of the previous fit, and yielding a $\chi^2_{\nu} = 0.76$ for 182 d.o.f. The best-fit parameters for both these models are given in table 7.3. The F-test probability for the Gaussian being present by chance was 3.93×10^{-22} . However, the F-test is not always appropriate for verifying the significance of line models (Protassov et al., 2002). Thus, a Monte-Carlo simulation was carried out for the same. In this regard, the best-fit continuum model, without the line, was used to simulate a series of 10^6 spectra by incorporating the uncertainties in the continuum parameters from the previous fit. Then these spectra were fitted with a model including a Gaussian component with the line energy and width fixed to the respective best-fit values from Model 2 and its norm compared with the best fit norm. We never found a case in which the norm was equal or larger than the one in Model 2, hence we conclude that the probability for the spectrum to fit the line component by chance is less than 10^{-6} . The results of this exercise are plotted in Figure 7.3.

A broad Fe line is a strong signature of reflection from regions close to the black hole, the broadening being essentially caused by gravitational redshift and Doppler effects (Fabian et al., 2000). This motivated us to use the state-of-the-art reflection code of the relxill family so as to constrain the spin of the black hole (Dauser et al., 2014; García et al., 2014). The flavor that was opted, i.e., relxillCp, assumes a coronal geometry with a broken power law emissivity which was fixed to 3 for the entire disk. We replaced the thermal disk component, diskbb, with diskpn (Gierliński et al., 1999) which, differently from the former, assumes zero torque at the inner boundary and the process-dependent parameters are separated from the geometrical parameters, the later making up the norm of this component. The seed photon temperature in nthComp was tied to maximum disk temperature of diskpn. The photon index and electron temperature were tied across nthComp and relxillCp. Similarly, the innerdisk radius was tied across diskpn and relxillCp. The binary inclination for J1659 is constrained between 65° - 80° owing to the detection of dips in the lightcurve and non detection of eclipses (Kuulkers et al., 2013). However, it is possible for the inner disk to have a different inclination due to the Bardeen-Peterson effect (Nealon et al., 2015). Thus we relaxed this limit and let the inclination vary between 30° - 85°. The best-fit parameters are listed in the third column of table 7.3 under Model 3. The fit was excellent ($\chi^2_{\nu} \sim 1$) but the value of the spin parameter pegged at the negative extreme of -0.998 and could not be constrained. An upper limit on R_{in} was found to be ~ 16 R_g at 95% confidence, indicating that the inner disk radius is close to the ISCO. The significance of the **relxillCp** component was verified by an F-test, the probability of which came out to be 9.49×10^{-10} . **diskpn**, being a non-relativistic model, assumes zero spin, and hence, can not be used in a model that measures spin directly. The rationale for using it will be discussed in the next section.

Being a general relativistic disk model, kerrbb is appropriate to characterize the thermal component of the spectrum (Li et al., 2005). Hence, diskpn was replaced by kerrbb for further analysis. Since the system has a relatively high inclination, the effects of limb darkening were included in the model calculation. The effect of selfirradiation, however, was ignored and a zero torque was assumed at the inner boundary. The spectral hardening factor was fixed at the canonical value of 1.7 (Shimura & Takahara, 1995). The spin parameter was tied across kerrbb and relxillCp and kept free. This has the advantage of undoing any effect of pile-up that would have remained in the spectrum in-spite of removing the central rows. As concluded by Miller et al. (2010), the presence of pile-up in a spectrum would artificially lead to a low spin value upon using reflection spectroscopy and a high spin value upon using continuum fitting method. Hence, tying up the spin from both models would reduce the effect.

After fitting, it was observed that the data cannot constrain all the free parameters, including the spin. In order to freeze the geometrical parameters, prior knowledge on them is required which is derived from the literature. The distance to J1659 is 4.5 - 8.5 kpc (Homan et al., 2013). This range encompasses the prediction from several other observations (Yamaoka et al., 2012; Kennea et al., 2011). Similarly, the mass of the black hole is 3 - 10 M_{\odot} (Yamaoka et al., 2012)). As described in the previous section, the inclination was allowed to vary between 30° to 85°. Then, a scheme was devised in which the entire parameter space was systematically explored, fixing the

Model components	Parameters	Model 1	Model 2	Model 3
phabs	$nH (cm^{-2})$	0.22 ± 0.01	0.21 ± 0.01	$0.22^{+0.02}_{-0.01}$
gaussian	LineE (keV)		6.78^{\star}	
	Sigma (keV)		$1.54_{-0.32}^{+0.50}$	
	norm $(\times 10^{-2})$		$1.14_{-0.36}^{+0.75}$	
diskbb	$kT_{in} (keV)$	0.39 ± 0.01	$0.40_{-0.01}^{+0.02}$	
	norm $(\times 10^3)$	$7.61^{+1.20}_{-1.01}$	$5.91^{+1.15}_{-1.04}$	
diskpn	kT_{max} (keV)			$0.40^{+0.02}_{-0.01}$
	R_{in} (R_g)			$10.65^{+5.25}$
	norm $(\times 10^{-2})$			$9.09^{+0.99}_{-6.53}$
$\operatorname{nthComp}$	Γ	1.87 ± 0.01	1.93 ± 0.02	1.90 ± 0.02
	$kT_{e} (keV)$	$10.44_{-0.46}^{+0.52}$	$12.94^{+1.41}_{-1.06}$	$11.01^{+0.53}_{-0.62}$
	norm	0.82 ± 0.03	0.83 ± 0.04	$0.79^{+0.04}_{-0.02}$
relxillCp	a			-0.998^{\star}
	Incl (degrees)			$85_{-1.06}$
	$\log \xi$			$2.98^{+0.10}_{-0.24}$
	$A_{\rm Fe}$			$10.0_{-1.25}$
	norm $(\times 10^{-4})$			$3.26^{+1.30}_{-0.08}$
$\chi^2 \; (\mathrm{dof})$		244.59(185)	139.26(182)	173.27(179)
$\chi^2_{ u}$		1.32	0.76	0.97

Table 7.1: Best fit parameters of models as defined in Figure 7.2.

geometry parameters to a set of values encompassed within the acceptable range. The grid consisted of the following values: $M = (4, 6, 8, 10) M_{\odot}$ and D = (4.5, 6.5, 8.5) kpc. After that, the spin was also fixed to a set of 8 equi-spaced values ranging from -0.998 to 0.4. For each of these 216 combinations, the data were fitted for mass accretion rate, \dot{M} . Meaningful values of \dot{M} would give us a constrain on the spin.

In the above analysis, the spin was constrained partly through the Fe line, and partly through the continuum. In order to constrain the spin only with the continuum, relxillCp was replaced by a Gaussian to account for the line. Now, it would only be the spin parameter, a, in kerrbb that constrains the spin. The black-hole mass and distance were fixed to the grid of values as defined above. Then, the same exercise was repeated by fitting for \dot{M} keeping the spin fixed to a set of values.

The results of the above two exercises are represented in Figure 7.4. Each colored line on the plots represents the combination of distance and black-hole mass that gave a good fit (i.e., $\chi^2_{\nu} \leq 2$). The four colors denote the four masses chosen. Those combinations of the parameters which did not return a statistically acceptable fit were ignored and are not included in the plots. As is expected, \dot{M} decreases monotonically

with increasing spin. This is so, because in kerrbb the inner radius of the accretion disk is assumed to be at the ISCO. So, with increasing spin (i.e., lowering the inner radius), the accretion rate has to decrease to keep the flux constant.

It has been a standard practice to restrict spin measurements to the soft state when the inner accretion disk is presumably at the ISCO. However, it has been shown that the disk extends down to the ISCO even in the hard state if the source is substantially luminous, and robust estimates of that spin have also been given in the hard state (García et al., 2015; Miller et al., 2015). A theoretical limit of 0.08% of \dot{M}_{edd} on accretion rate, which translates in to ~ 0.008 L_{edd} assuming an efficiency of 0.1, was given by Esin et al. (1997) below which the disk would be truncated. Similarly, Reynolds & Miller (2013) and Reis et al. (2010) have studied several XRBs to enunciate observational limits of 0.001 L_{edd} and 0.0015 L_{edd} respectively. The luminosity of J1659 lied between 0.019 - 0.067 of the Eddington value for a 10 M_{\odot} black hole. This range is entirely above both the theoretical and observational limits provided and hence it is possible that no significant truncation of the accretion disk has taken place.

7.4 Discussion

We carried out a broad-band spectral analysis, using simultaneous XMM-Newton and RXTE data to estimate the spin of the black hole in J1659. We detected a broad Fe line with high significance, which was verified by Monte-Carlo simulation. This allowed us to use reflection spectroscopy along with the continuum fitting method. Due to uncertainties on the geometrical parameters, we employed a novel technique to scan the entire parameter space and represent the accretion rate as a function of spin. Figure 7.4 shows that for reasonable estimates of the mass accretion rate, most of the system parameters unambiguously yield a negative spin. A large fraction of the best-fit parameters also reveal a fascinating and unprecedented consequence of extreme retrograde motion (a = -1) for a stellar-mass black hole. These results were ratified by both reflection spectroscopy and continuum fitting method.

Depending on the accretion rate, which is usually quite difficult to ascertain, an upper limit on the spin can be arrived at. We explore different avenues to find a reasonable estimate of the accretion rate, given that a firm lower limit on \dot{M} would



Figure 7.4: Variation of M with a. Left figure represents the results using both CF and Fe line method; right figure represents results from only CF method. The different linestyles correspond to the distances and the colors of the lines represent the different black-hole masses. The horizontal lines in the figures represent different lower limits of the accretion rate, as explained in the text.

be useful in constraining the spin. One such limit can be deduced by considering the fact that the peak luminosity during major outbursts almost always exceeds 8% of the Eddington limit (L_{Edd}) and reaches about 50% on most occasions (Steiner et al., 2013). The peak phase of the outburst for J1659 lasted for about 25 days (Figure 7.1) where the flux hovered between 250 - 300 mCrab. The flux at the thermal peak, which occurred on MJD 55489 is close to that during our observation with a flux of ≈ 260 mCrab (Kalamkar et al., 2011). Since luminosity $L = F \times 4\pi D^2 \propto \dot{M}$ for radiatively efficient accretion (Frank et al., 2002), the accretion rate during our observation should be comparable to that during the peak. A lower limit of 8% on peak accretion rate constrains the spin to extreme negative values. The plateau phase of J1659 was also associated with a few flaring events which were, however, not associated with changes in the spectral hardness (Kalamkar et al., 2011). These flares pose an ambiguity in the choice of the outburst-peak. Nevertheless, even considering the strongest flare on MJD 55477 to represent the peak, the flux during our observation is only a factor of ~ 1.5 lower than at this peak. This leads to the accretion rate being ~ 5.3% of \dot{M}_{Edd} during our observation which also entirely restricts the spin to negative values.

Another limit comes from the norm of diskpn from the fit using Model 3. Using the formalism laid out by Gierliński et al. (Appendix A, 1999), the accretion rate can be expressed as a function of black-hole mass, maximum disk temperature, and inner-disk radius. The different \dot{M} values calculated using the best-fit values of the above parameters are represented in the Figure 7.4 through horizontal lines, the color of which corresponds to each black-hole mass chosen. Although **diskpn** is a non-GR model, assuming a static black hole, the accretion rates obtained from fits with this component are consistent with the ones from **kerrbb** having a significant overlap in the parameter space. This overlapping region also falls almost entirely in the negative spin domain, with an upper limit of ~ 0.2 for Fe-line method and ~ 0.4 for CF method. The fact that our fits favor a negative spin implies that the inner disk radius remains farther away than 6 R_g , thus justifying the use of **diskpn**.

To be fastidious enough, a much firmer limit on the black-hole spin in J1659 can be obtained by considering the fact that for the thin accretion disk to exist, the accretion rate has to be at least 2% of the Eddington limit (Narayan et al., 1998; Meyer et al., 2000). Below this limit, the accretion flow would be in the form of an ADAF, with the X-ray luminosity being too low. An \dot{M} of 0.02, in Eddington units, gives a higher and a more conservative upper limit, a prograde but moderately rotating black hole. Our analysis of J1659 (see also Kalamkar et al., 2011; Yamaoka et al., 2012), shows that this limit is most likely an overkill since a thermal disk component with a modest temperature of about 0.4 keV is indispensable for fitting the data.

Finally, we also test the possibility of a truncated prograde disk at the expense of other parameters. The spin was fixed to three values of 0, 0.3 and 0.9 while keeping the black-hole mass, distance and inclination unconstrained and free to vary. Since the geometrical parameters were left free, the statistics remained reasonably good and did not change drastically as in the earlier case ($\Delta \chi^2 \approx 13$ per d.o.f). Best-fit value of black-hole mass and inclination were slightly higher, but acceptable. However, the bestfit value of accretion rate attained much lower values of 0.18%, 0.09% & 0.004% of \dot{M}_{Edd} respectively. These values are too low, even for the formation of the thin accretion disk (Narayan et al., 1998). The distance and ionization parameters were also constrained to unphysically lower values. This shows that the data preferred a truncated prograde disk only for unphysical values of accretion rate, distance and ionization parameter. With this we demonstrate an unambiguous detection of retrograde spin for a stellar-mass black hole which is independent of the choice of the black-hole geometric parameters, and is concurrent across both Fe-line spectroscopy and continuum fitting method. This result further opens up the possibility that retrograde motion among black holes is a norm rather than exception.

Chapter 8

Summary and Future Work

8.1 Summary

The very definition of black holes makes their study extremely challenging by using electromagnetic waves as conventionally done for other astronomical objects. It is only through their impact on the matter within their gravitational influence that any reasonable understanding about them can be obtained. Accretion of matter onto black holes results in X-ray emission and such X-ray observations provide the best opportunity to study their properties. The only other possibility being the study of black hole mergers using gravitational waves, which is still a nascent field. As a corollary, black hole accretion systems also provide fertile conditions for understanding the complicated process of accretion.

In order to gain deeper insights into the accretion process we have studied black-hole X-ray binaries using X-ray spectroscopy and timing analysis as primary tools. We analyzed three LMXBs, namely GRS 1716–249, MAXI J1631–479, and MAXI J1659–152, using data from six X-ray observatories and one ground based infrared telescope. In our studies, we are able to perceive the geometry of the inner accretion by studying the properties of the QPOs. We have delineated the radiation emitting from inner accretion region. We have also constrained the two fundamental parameters of a black hole, i.e., spin and mass, for two systems - MAXI J1659–152 and MAXI J1631–479 which have far reaching consequences on the binary evolution and jet propagation theories. Below, the important results and their consequences from the work presented in the previous chapters are described.

Chapter 3 presents the results of a multi-wavelength spectral analysis of the galactic X-ray binary GRS 1716–249 using X-ray data from *AstroSat*, NIR/optical from *MIRO* and UV from *Swift*/UVOT. Broadband X-ray spectral analysis of all three epochs of *AstroSat* spectra show that the source was in a power-law dominant state. Irradiation of X-rays in the inner regions of the accretion disk significantly contributes to the soft X-ray flux of the source on all three epochs. Using multi-wavelength SED analysis, we found the optical and UV fluxes to originate from the irradiated outer accretion disk while part of the NIR emission is most likely emitted from a jet.

Chapter 4 presents a comprehensive spectral and timing study of the blackhole transient MAXI J1631–479 during its 2018-19 outburst using observations from the *NICER* observatory. The observations began while the source was in the HSS and after that the source moved to the HIMS for a couple of months. The transition back to the HSS was missed by *NICER* and the source continued to decay with decreasing hardness till the end of the outburst. The spectra could be fitted by a combination of a multi-color blackbody and a thermal Comptonization component. During the bright phases, a gaussian was required to account for the fluorescent Fe line. During the HSS, the variability was very low (~ 1%) and the PDS was a featureless power law. The PDS in the HIMS had a broadband noise component along with peaked noises and QPOs. All QPOs were of Type-C in nature. The frequency of the QPOs increase and the QPO rms decrease with increasing inner-disk temperature indicating a geometrical origin for the QPOs. This means that the inner accretion disk is misaligned with the orbital motion due to Bardeen-Peterson effect. This misalignment leads to a phase-related variation of the illumination of hard photons generating QPOs. The rms spectrum of J1631 in the HIMS is hard above 1 keV. The shape of the spectra below 1 keV is uncertain because the power in the first two bands could not be constrained. Some of the observations have more power in the lower energy bands. This effect is puzzling and not explained by merely varying the normalization and power-law slope of the Compton spectrum.

HMXBs are a class of their own. While the underlying process is the same as LMXBs, the phenomenology pertaining to state transitions is different. In particular, HMXBs do not show a hysteresis behavior in the HID during the outburst cycles and show any QPOs. To study these properties in detail, we investigated the prototypical black hole Cyg X - 1 with AstroSat data observed during the 2016-17 state transition in Chapter 5. Spectral and timing properties revealed that the source was in a hard state initially (during the first two observations) and then transitioned to a more softer state. During the transition the inner-disk temperature increased from $\sim 0.1 - 0.5$ keV and the photon index increased from ~ 1.4 to ~ 2.1 . The PDS shape also evolved with four Lorentzians in the hard state to one power law and three Lorentzians during intermediate state and finally requiring a power law and a broad Lorentzian during soft state. We suspect that the state transition occurs due to the inward movement of the disk. We also attempted to understand the nature of the PDS components. By studying the correlations as done in chapter 4 it was found that one of the Lorentzians (number 3) shows similar behavior as Type-C QPOs. Since Type-C QPOs likely have a geometric origin, it is possible that Cyg X-1 experiences a transient inner-disk warping leading to modulation of the lightcurve.

We further carried out a joint spectral analysis of the same source using Swift/XRT and NuSTAR (chapter 6). Broadband X-ray spectrum (0.7 - 78 keV) of both the epochs analyzed reveal strong reflection features. The January 17 observation is in a thermal disk dominant state and the January 30 observation is in an intermediate state. The analysis was done with the reflkerrD_lp reflection model. The height of the lamp post increased to $\sim 27 R_g$ from about 2 R_g across the epochs. The spin of the black hole is constrained to a high value of ~ 0.98 and the inclination is also high, lying between 61° - 69° . The density of the disk plasma is constrained to about 10^{16} g cm⁻³. We also estimated the possible mass of the black hole using the optical observations as an indicator for disk emission. The most probable mass of the black hole is $\sim 30 M_{\odot}$ with a 99% lower limit of 18 M_{\odot} and could be higher if the source is farther away. This is a conservative limit considering the assumption that the observed optical flux is actually emitted from the source. If true, J1631 would host the most massive stellar mass black hole in the galaxy. Therefore, we strongly recommend optical follow up of the secondary star during quiescence which can independently measure the blackhole mass. Being in a league hitherto only observed by GW detection, this result is at odds with recent studies that attempt to explain the apparent mass dichotomy to

be due to different formation channels (Perna et al., 2019). Current understanding of formation scenarios allows massive black holes only up to $\sim 25 M_{\odot}$ in Solar metallicity environments and heavier ones under considerably lower metallicity (Belczynski et al., 2010; Spera et al., 2015). J1631 could fall in the former regime allowing for a simpler evolutionary phase, or it could be much heavier requiring a more challenging scenario. The possibility that the progenitor of the black hole was a Population II or III star with poor metal content also cannot be ignored. It is worth noting here that, a massive stellar-mass black hole in the range expected of J1631 is observed in an extra-galactic object IC 10 X–1 (Silverman & Filippenko, 2008). In view of such discoveries, whether the mass dichotomy really exists or not is itself uncertain, and more such detection can only uncover the true nature of the galactic black-hole population.

Finally, in chapter 7 we have constrained the spin of the black hole in MAXI J1659–152 using broadband spectral analysis with simultaneous data from XMM Newton and RXTE. We detected a broad Fe line with high significance, which was verified by Monte-Carlo simulation. This allowed us to use reflection spectroscopy along with the continuum fitting method. Due to uncertainties on the geometrical parameters, we employed a novel technique to scan the entire parameter space and represent the accretion rate as a function of spin. For reasonable estimates of the mass accretion rate, most of the system parameters unambiguously yield a negative spin. A large fraction of the best-fit parameters also reveals a fascinating and unprecedented consequence of extreme retrograde motion (a = -1) for a stellar-mass black hole. These results were ratified by both reflection spectroscopy and continuum fitting method.

8.2 Future Work

Accretion around stellar-mass black holes provides valuable insights about the behavior of matter and space-time under strong gravitational potential. The X-ray phenomenology is both interesting and mysterious with many observed phenomena yet to be explained convincingly. In future, we would continue to explore the phenomenology of inner accretion environment. We would expand the parameter space from the usual energy and time (frequency) domain to polarization properties. The polarization properties of the X-rays are strongly modified by the general relativistic effects (Dovčiak et al., 2008; Li et al., 2009; Schnittman & Krolik, 2010). In particular, the polarization angle (PA) and polarization fraction (PF) vary significantly as a function of energy for different values of spin and inclination. Constraints on PA and PF can provide independent estimates on the spin and inclination of black holes. It can also help in narrowing down the geometry of the corona (Chauvin et al., 2018). Below, we list two projects that would be considered in the immediate future.

1. On the origin of the radiative properties of the peaked noises in Cyg X-1

The origin of the broad peaked components in the PDS of Cyg X–1 remains a mystery. Recently, it has been shown that the radiative properties of the QPOs, i.e., the rms and lag spectra, in LMXBs can be explained by fluctuation in the Comptonizing medium (Karpouzas et al., 2020; García et al., 2021). It would be interesting to verify if the peaked noises detected in Cyg X–1 also originate from these fluctuations. The Comptonization model can also constrain the size of the source. By studying the evolution of the same during state transitions, the physical mechanism of transition can be known. The evolution of the time lags, as a function of frequency, during the transition can also help in independently constraining the size of the corona (Kara et al., 2019). To this end, we shall study the variability properties of Cyg X–1 during the 2016-17 transition using data from LAXPC instrument.

2. Exploring the polarization signatures of BHBs in the context of POLIX

X-ray polarimetry is an hitherto unexplored field as most early missions ignored them owing to a high photon requirement compared to spectroscopy and imaging (Marin, 2018). However due to technological advancement, the last couple of decades has seen a revival of interest in X-ray polarimetry with approval of a few dedicated polarimetry missions, two of which are scheduled to launch by the end of 2021. One of them is the Indian small satellite mission, namely X-ray Polarimeter Satellite (XPoSat). XPoSat houses two science payloads - a soft-Xray spectrometer named XSPECT and a polarimeter named POLIX. POLIX is a Thomson scattering-based polarimeter which uses beryllium as a scatterer and proportional counters as detectors. It has a collimated field-of-view of $3^{\circ} \times 3^{\circ}$ and a collecting area of 640 cm². POLIX will operate in the energy band of 8 -

30 keV and will be sensitive to 2 - 3 % MDP (Minimum Detectable Polarization) in a 100 - 500 mCrab source for 1 Ms exposure (Rishin & et al., 2010). To reduce systematic effects, the satellite will be rotated along its viewing axis. Bright BHBs will be suitable targets for which the state dependent and energy resolved polarization measurements can be made.

According to Dovčiak et al. (2008); Schnittman & Krolik (2010), both thermal and Comptonized emissions can show significant polarization and can be used to estimate spin and inclination. This requires PF and PA measurements in several energy bands. POLIX operates in a low bandpass of 8 - 30 keV and offers low resolution as the detectors are proportional counters. This makes the analysis and interpretation of POLIX data challenging. Therefore, we plan to prepare an overall analysis framework for the actual POLIX observations of BHBs with realistic expectations. We shall also venture into modeling the polarization signatures so that by simultaneously fitting the PF and PA spectra physical parameters of the system, such as black-hole spin, mass, inclination, etc., can be estimated.

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