Probing accretion flow dynamics in X-ray binaries
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The process of accretion of matter in strong gravity is a very powerful and efficient mechanism to produce high-energy radiation. Soon after the discovery of the first celestial X-ray source (outside the Solar system) called Scorpius X-1 (Giacconi et al. 1962), the importance of accretion was realized; the strong X-ray emission was proposed to be due to accretion on to a neutron star (Shklovsky 1967). The technological advancement over the past few decades made it possible to send satellites to space dedicated to observing X-ray sources. This led to great scientific breakthroughs, such as the observation of the first system recognized to host a black hole (in the binary system Cygnus X-1; Webster & Murdin 1972), the existence of which is one of the extreme predictions of the theory of General Relativity. These systems provide an excellent laboratory for the testing of other predictions such as space-time curvature, bending of light by gravity, frame dragging, gravitational radiation, etc.

X-ray binaries offer excellent laboratories to gain insight into the behaviour of accreting matter under extreme gravity and density. In the vicinity of the compact object, the dynamical time-scales are less than a few milliseconds; the matter moves in orbits with very high velocities. The study of the emission from this matter provides an excellent probe to study not only the behaviour of matter under extreme conditions but also the compact object itself. This thesis is devoted to the study of the dynamics of the accretion flow around compact objects in X-ray binaries. In this chapter, I discuss the various phenomena commonly observed in these systems, our current knowledge and the challenges faced in understanding the accretion phenomena.
Compact objects - black holes (BH), neutron stars (NS) and white dwarfs represent the final stage of stellar evolution and are formed due to gravitational collapse. These are extremely dense objects and hence have strong gravitational fields. If the compact object is in a binary system with another star, under the right conditions it can consume matter from this companion star. The accreted matter gains gravitational potential energy, which can be eventually released mostly in the form of radiation. If all the energy gained is released in the form of radiation, then the emergent luminosity is $L_{\text{acc}} = \frac{GM\dot{M}}{R}$, where $\dot{M}$ is the accretion rate onto a compact object of mass $M$ and radius $R$ and $G$ is the Gravitational constant. The emitted radiation is mostly in the X-ray regime, and hence these binaries are called X-ray binaries.

X-ray binaries are classified based on the mass of the companion star: high ($\gtrsim 10 \, M_\odot$) and low ($\lesssim 1 \, M_\odot$) X-ray binaries. The mode in which each class achieves mass transfer is different. In high mass X-ray binaries, the massive companion has strong winds which can be captured by the compact object. In Low-Mass X-ray Binaries (LMXBs) the winds of the low-mass companion star are not significant. If the binary separation decreases or the size of the companion star increases, the gravitational pull of the compact object can remove the outer layers of the companion, in a process called Roche lobe overflow. Figure 1.1 shows a graphic illustration of a LMXB.

In this work, we study the NS and BH LMXBs in our Galaxy. There are hundreds of Galactic LMXBs that have been observed till date. These are typically old systems
1.2 Accretion flow

The matter accreted from the companion has to rid itself of most of the angular momentum in order to fall onto the compact object. The gas rotates in nearly Keplerian orbits at an angular velocity $\Omega_K = \sqrt{\frac{GM}{R^3}}$, slowly spiralling inwards as it loses energy (in the form of heat and radiation) and transfers the angular momentum outwards. The gas generally loses its energy faster than it loses angular momentum (unless the accretion time is shorter than the cooling time or the flow is radiatively inefficient). The flow is supported by pressure with the pressure scale height $H$ smaller than the radial extent of the flow $R$ ($H/R < 1$), and hence forms a disc structure (Pringle & Rees 1972). Due to the differential rotation of the matter, adjacent orbits interact viscously. The magnitude of this viscosity is important to characterise the behaviour of the accretion disc. The ‘viscosity mechanism’ which transports the angular momentum, is not fully understood and is an active area of research. Without the knowledge of the actual viscosity mechanism, Shakura & Sunyaev (1973) parametrized the viscosity $\nu$ as

$$\nu = \alpha c_s H$$  \hspace{1cm} (1.1)

where $c_s$ is the sound speed and $\alpha \leq 1$. $\alpha$ is a dimensionless parameter which isolates the uncertainties about the viscosity. There has been considerable progress in our understanding of X-ray binaries in the $\alpha$ prescription of the disc. It has been suggested that the angular momentum transport mechanism might have magnetic origin. Weak field lines anchoring in the differentially rotating disc get sheared and generate an instability, called the Magneto-Rotational Instability (Balbus & Hawley 1991).

The application of this disc model allows us to understand the transient behaviour of some of the LMXBs (Lasota 2001). The quiescence-outburst-quiescence behaviour can be understood as a ‘limit cycle’ oscillating between two states: during the quiescent state, the disc builds up matter till it eventually becomes hot enough to trigger a thermal instability. The thermal instability increases the mass accretion rate and triggers viscous instability causing the disc to be eaten away. A heat front propagates...
from this region through the disc, till the disc becomes fully ionized, and the source reaches the peak of the outburst. A cooling front propagates from the outer colder regions (when the temperature falls below the threshold) causing the gas to recombine and the source reaches quiescence. The viscosity and temperature are high during outburst and low during quiescence. The time scale on which the disc structure can change is the viscous time scale, which is the diffusion time scale of matter through the disc:

$$t_{\text{visc}} \sim \frac{R^2}{\nu}$$  \hspace{1cm} (1.2)

Most systems spend relatively shorter periods of time in outburst than between outbursts; outburst periods last from weeks to years but the quiescent periods can be longer.

The disc emission spectrum can be modelled by a quasi-blackbody component. It peaks at higher temperatures when the disc gets hotter. Observations reveal that in addition to this, the spectrum also shows the presence of a non-thermal power-law like component extending to energies of a few hundred keV, as opposed to the (soft) disc emission which peaks at a few keV. The high energy ‘hard’ emission has been attributed to the inverse Compton up-scattering of soft photons by an optically thin plasma of ‘hot’ electrons ($\sim 100$ keV). The structure and geometry of this hard emission region are topics of debate (discussed in Section 1.6).

The two components of the accretion flow are: the geometrically thin optically thick accretion disc, and the geometrically thick optically thin hard emission region. The energy spectra are dominated by these components in different strengths at different stages of the outburst. The total emission from these sources shows variability on time-scales from days (the outburst evolution) to milliseconds. The fast variability on the time scales of milliseconds arises from the innermost regions of the accretion flow. Hence, it can probe the behaviour of matter in the vicinity of the compact object. To study the spectra and variability in the LMXBs, they have been observed for decades with many current and previous X-ray missions. Below, I discuss the instruments and data analysis techniques we use to observe and study these sources, followed by a discussion on LMXB outburst behaviour and phenomenology.

### 1.3 Observational facilities

Although X-ray binaries can be observed at different wavelengths, the bulk of their emission is in X-rays. As X-rays are absorbed by the Earth’s atmosphere, detectors have to be sent to higher altitudes (few tens of km) for detecting it. This was achieved
in the past using balloons and sounding rockets. The advances in technology allow us to place detectors on board satellites which can go to even higher altitudes (few hundreds of km) and observe a broader range of X-rays. Some of the recent missions that have made significant contributions to the study of X-ray binaries are the Rossi X-ray Timing Explorer (RXTE) and Swift. These missions have provided regular monitoring observations of the outbursts of X-ray binaries over periods of days to years. The following sections discuss the instruments on board these satellites and their capabilities.

1.3.1 Rossi X-ray Timing Explorer

The Rossi X-ray Timing Explorer (RXTE; Bradt et al. 1993) was a mission dedicated to study X-ray sources, particularly their variability on short time scales. It was launched on December 30, 1995, and had a low-Earth circular orbit of altitude 580 km with an orbital period of 90 minutes. The mission was decommissioned on January 5, 2012. There were three instruments on board: the All Sky Monitor (ASM), the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE). Figure 1.2 shows a diagram of the spacecraft and its instruments.

The ASM (Levine et al. 1996) instrument consisted of three coded-aperture cam-
eras each with $6^\circ \times 90^\circ$ Field of View (FoV). It had a spatial resolution of $3' \times 15'$ and operated in the 1.5–12 keV range. It was designed to observe 80% of the sky every 90 minutes to monitor the activity of X-ray sources. The HEXTE (Gruber et al. 1996) consisted of two clusters of scintillation detectors. The FoV was $1^\circ$ full width half maximum (FWHM) and the detector was sensitive in a wide energy range of 15–250 keV.

The PCA (Zhang et al. 1993; Jahoda et al. 2006) was an array of five proportional counter units (PCUs) sensitive in the energy range of 2–60 keV with a total effective area of $\sim 6250 \text{ cm}^2$. The FoV of each PCU was $1^\circ$ (FWHM) which was defined by the collimator assembly on each PCU. The energy resolution was 18% at 6 keV. This instrument offered an excellent time resolution down to 1 $\mu$s. The capability to observe phenomena on short time scales has yielded important contributions to the study of variability. In this work we use data from this instrument.

### 1.3.2 Swift

The *Swift* mission (Gehrels et al. 2004) is a multi-wavelength observatory launched on November 20, 2004, and has a low-earth circular orbit of altitude 600 km and an orbital period of 90 minutes. Although it is dedicated to the study of gamma-ray bursts, it has made valuable contributions to the study of X-ray binaries. The instruments on board offer unprecedented simultaneous coverage from optical to gamma-ray energy bands: the Ultraviolet/Optical Telescope (UVOT), the X-ray Telescope (XRT) and the Burst Alert Telescope (BAT). Figure 1.3 shows the spacecraft with the three instruments. The UVOT (Roming et al. 2005) is a Ritchey-Chretien reflector telescope with photon counting detectors and is sensitive in the 170–650 nm wavelength range. The BAT (Barthelmy et al. 2005) is a coded aperture imaging instrument with a CdZnTe detector which operates in the 15–150 keV range.

The XRT (Burrows et al. 2005) is a grazing incidence JET-X Wolter I telescope which focuses the incoming X-rays onto a CCD detector. It operates in the 0.3–10 keV energy range with an effective area of 110 cm$^2$ and a spatial resolution of 18 arc seconds. The CCD is a three-phase frame-transfer device of an image area with $600 \times 602$ pixels ($23.6 \times 23.68$ sq.arc-min). The CCD can be operated either in the imaging mode or fast timing modes, depending on the requirement. In this work, we use the data obtained in the commonly used fast timing mode - the Windowed Timing (WT) mode which has a 1.766 ms time resolution. In this mode, only the central 200 columns of the CCD are read out. 10 pixels are binned along columns and hence the spatial information is lost in this dimension.
1.4 Observational Techniques

The most common techniques through which the emission from astronomical sources can be studied are: imaging, spectroscopy and timing. In this thesis, we study the X-ray timing and spectral properties of outbursts of several LMXBs. We study the evolution of power spectra, energy spectra and colours (ratios of count rates in different energy bands). As the contribution from the different components of the accretion flow changes along an outburst, all three characteristics evolve in a correlated fashion.

1.4.1 Timing analysis

The detectors provide information on the arrival time of the photons and their energy. As these instruments have high time resolution, from ms to μs, and the sources in their brightest stages have typical count rates $< 10^3$ ct/s, there may be less than 1 ct/time bin; the photon-counting noise (Poisson noise) is of similar magnitude as the signal strength. Hence, large amounts of data are necessary to detect the source signal against the noise. Fourier analysis has proven extremely useful for studying the variable emission. In this technique, the strength of the variability is studied in the frequency domain, by calculating a Fast Fourier Transform of segments of the
equidistantly binned light curve. The absolute value squared of the Fourier amplitude (the power) is expressed as a function of the corresponding frequency - this is called the power spectrum. The power spectra of multiple light curve segments are generally averaged (van der Klis 1989).

The highest frequency that can be observed is determined by the bin width (time resolution) $t_s$, and is called the Nyquist frequency given as $\nu_{Ny} = 1/2t_s$. The lowest frequency is determined by the length $T$ of the light curve segment used to generate the power spectrum, given as $\nu_{min} = 1/T$. The power spectrum is commonly expressed in two forms of normalization: Leahy (Leahy et al. 1983) and $rms$ (e.g., van der Klis 1995). In Leahy normalization, Poisson noise power has a value 2.0. The choice of this normalization comes from the fact that the (Poisson) noise power follows a $\chi^2$ distribution with 2 degrees of freedom (dof). In our applications, the signal at each frequency is given as $P = P_{noise} + P_{signal}$. Hence, the source signal power will add to the background value 2.0 and can be differentiated. The amplitude of the source signal can be expressed as a fraction of either the total count rate - source (S) + background sky (B), or only the source count rate. To express the amplitude as a fraction of total count rate, the Poisson level is subtracted from the Leahy power and then this power is divided by the total count rate (S+B). To express the amplitude as fraction of only the source count rate, it can be multiplied by a factor $(S+B)/S^2$. In this ‘$rms$ normalization’, the square root of the integral over the power spectrum is the $rms$ amplitude as a fraction of the source count rate.

The source signal can be periodic or aperiodic in nature. Figure 1.4 shows the signal in time and frequency domain. The sinusoidal signal, e.g., from a pulsar (top left panel) is strongly periodic and hence the power will be concentrated in an extremely narrow frequency range in the power spectrum (top right panel). If the signal is more irregular (bottom left panel), the power will be spread over a range of frequencies with different strengths in the power spectrum (bottom right panel). This is a typical power spectrum observed in LMXBs. In this thesis, I study the aperiodic variability. There are multiple ‘components’ observed in a power spectrum: broad-band components, and narrow peaked components called Quasi Periodic Oscillations (QPOs). Each component is characterized by its centroid frequency ($\nu_0$), width (FWHM) and strength.

The power spectrum can be fit using an empirical model composed of e.g., Lorentzians or Gaussians for narrow components, and (broken) power-laws for broad components. To fit the broad and narrow components with the same component for uniformity, we use the Lorentzian in the so-called $\nu_{max}$ representation of Belloni et al.
1.4 Observational Techniques

Figure 1.4: Signal in time domain and frequency domain

(2002b). It is parametrized by the characteristic frequency given as:

\[ \nu_{\text{max}} = \sqrt{\nu_0^2 + \left(\frac{\text{FWHM}}{2}\right)^2} = \nu_0 \sqrt{1 + \frac{1}{4Q^2}} \]  \hspace{1cm} (1.3)

where Q is the quality factor defined as \(\nu_0/\text{FWHM}\). The frequency \(\nu_{\text{max}}\) is that at which the component contributes most of its power per logarithmic frequency interval. A \(\chi^2\) fit statistic is used to determine the ‘best-fit’ model comprising of several Lorentzians, one for each component. In the source count rate \(\text{rms}\) normalization, the strength of the component can be expressed in fractional rms amplitude (%) which is the square root of the integrated power of the Lorentzian expressed in percent. For representation, the power spectra are commonly plotted in the \(\nu P_{\nu}\) i.e. frequency × power versus frequency representation. In this representation, the Lorentzian peaks at \(\nu_{\text{max}}\).
1.4.2 Spectral analysis

The energy spectra represent the energy distribution of the photons. To estimate the contribution from individual emission components, the spectrum is fit with different ‘models’, which provide the best approximations of the real physical models. It provides physical parameters such as disc temperature, disc radius, power-law index, size of the corona, etc. There are many models available in XSPEC (Arnaud 1996) for the disc emission (e.g., multi-temperature blackbody) and the power-law emission (e.g., simple power-law, Comptonization). The simplest model is a combination of: multi-temperature blackbody – a superposition of blackbodies each with its own temperature, and a power-law, arising from the Compton up-scattering of disc photons. Complexities arise when additional phenomena have to be taken into account such as: irradiation of the disc by the hard photons, general relativistic effects, reflection etc. Additional uncertainties are added by other parameters such as the inclination angle, distance to the source, which are unknown for many sources. Although the absolute values of these parameters are model dependent, the trends in their evolution can be robust. These provide a powerful tool to study the accretion flows in LMXBs.

To trace the relative contribution from the two emission components in a model-independent way, colour analysis has proven to be extremely valuable. A colour is defined as the ratio of count rates in two different energy bands. Colour versus colour diagrams (CD) and hard colour versus intensity diagrams (HID) are generally used to study outburst behaviour. With the right choice of energy bands, the colours are sensitive to subtle changes in the relative contribution. They also provide a model-independent tool to study outburst evolution across different sources as these trace similar patterns in these CD and HID. The position of a source in the CD or HID provides information about the relative strength of two emission components. The CD and HID diagnose the spectral ‘state’ of the source. Hence, these diagrams allow us to trace the outburst evolution of different sources through these spectral states.

1.5 Accretion states and phenomenology

The phenomena observed in LMXBs have many distinct features that can indicate the nature of the compact object: NS or BH. Presence of thermonuclear (type-I) X-ray bursts and X-ray pulsations are distinct signatures of LMXBs hosting a NS. Type-I X-ray bursts (Hoffman et al. 1978) are caused by unstable thermonuclear burning of the accreted matter accumulated on the surface of the NS. Coherent X-ray pulsations, observed at the spin frequency of the NS, come from the hot spots formed by magnetically channelled accreted matter (Alpar et al. 1982). These phenomena arise due to the presence of a physical ‘surface’ in NSs. For the NSs (that do not show these
**Figure 1.5:** The colour-colour diagram (CD, left panel) and the power spectra in the different states (right panel) indicated in the CD of an atoll source during outburst evolution (Image courtesy: M. Klein-Wolt).
phenomena), and the BHs (which instead have an event horizon and hence are not expected to show these phenomena), the CDs and HID along with the variability are useful to identify the possible nature of the compact object. Although dynamical measurement of the mass is necessary to confirm the compact object to be a BH, the HID and variability behaviour is an excellent tool to search for candidate systems. Below, I discuss the typical behaviour in NS and BH systems.

1.5.1 Neutron star states

Based on the paths traced in CDs and correlated timing evolution, most of the NS LMXBs can be classified in two classes - ‘Z’ and ‘atoll’ sources (Hasinger & van der Klis 1989), although recently it was shown that they are not mutually exclusive (Homan et al. 2010). The names of the classes are based on the shape traced in the CD. The luminosities spanned by these classes are also different: Z sources are bright and close to the Eddington luminosity \(^1\) while atoll sources are sub-Eddington. In this thesis, I present a study of the atoll source IGR J17511–3057. The general properties of atoll sources are discussed below.

The states exhibited by the atoll sources are: the extreme island state (EIS), the island state (IS), the lower left banana state (LLB), lower banana state (LB) and the upper banana state (UB). The spectrally hard island branches are traced at low luminosities typically over time intervals of days to weeks and the softer banana branches at high luminosities over hours to days. The states in the CD and the corresponding power spectra in each state are shown in Figure 1.5.

The kHz QPOs that are observed in the LLB, often seen in pairs, are amongst the fastest phenomena observed in an astrophysical object. As the orbital periods at small radii are of the order of ms, these QPOs have been associated with matter moving very close to the NS. Various models in the past have attempted to associate the QPO frequency, difference in the frequency of the pair, etc. with the spin frequency of the NS, as it can act as a measure of the spin for non-pulsating sources. A clear picture about the origin of these kHz QPOs and their association with the spin frequency is yet to emerge (see van der Klis 2006, for a detailed discussion).

1.5.2 Black hole states

In this section, I describe the typical behaviour of a BH LMXB (BHB) outburst, based on the outburst of the source GX 339–4 (Belloni et al. 2005). The different

\(^1\)The luminosity at which the gravitational pull is balanced by the outward radiation force, providing a limit to the accretion rate.
states can be traced along the HID. The HID with the corresponding power spectra and the energy spectra in each state are shown in Figures 1.6 and 1.7, respectively. The states can be broadly classified as hard and soft states. In the hard state at low intensity, called the low hard state (LHS), the energy spectrum is dominated by hard power-law emission extending to few tens of keV. The variability is strong in the hard state, where the power spectra show broad-band noise often accompanied by the so-called type-C QPOs (see below). The source stays in this state for a wide range of intensities, till at somewhat constant intensities the spectrum softens and the source enters the intermediate state (IMS). This is divided into hard and soft IMS (HIMS and SIMS, respectively). The spectral evolution is smooth in the IMSs; the softening of the energy spectrum due to increasing contribution from the disc is gradual. These states are distinguished by dramatically different variability properties; the variability is stronger in the HIMS (although weaker than in the LHS) than the SIMS. The HIMS power spectra show type-C QPO, while the SIMS power spectra often show one of the two different types of QPOs, type-A or type-B QPO. The main properties that distinguish the type-C from type-A/B QPOs are as follows: type-C QPOs are generally stronger and narrower, and cover a broader range of frequencies than type-A/B QPOs. In addition type-C QPOs are accompanied by strong broad-band noise, while type-A/B are accompanied by weak red (power decreases as frequency increases) noise (see Wijnands et al. 1999; Remillard et al. 2002; Casella et al. 2005, for details). Multiple transitions between the HIMS and SIMS are generally observed. When the soft component from the disc is the dominant one in the energy spectrum, the source is said to be in the high soft state (HSS). The variability is extremely weak in this state. At some point in time, the intensity decreases and the source goes back to the LHS through the IMSs. It should be noted that not all sources exhibit all states and the time spent in different states can be very different. There are also outflows in the form of jets associated with these systems, which are strong during the hard states and weak (or quenched) during the soft states (e.g., Fender et al. 2009).

1.6 Recent developments

Although the phenomenological behaviour is understood quite well, the structure and geometry of the accretion flow are strongly debated and form an active area of research. In the past, the standard picture for the disc was that it is cooler and truncated far from the BH in the LHS. It moves inwards and becomes hotter (as discussed in Section 1.2) as the outburst progresses and (may) reach at the inner-most stable circular orbit (ISCO) in the HSS. This has been recently questioned by some studies that suggest that the disc is close to the BH in the hard states (e.g., Miller et al. 2006; Reynolds & Miller 2013; Reis et al. 2010). The inner radius of the disc (truncation
Figure 1.6: The hardness-intensity diagram (HID, left panel) and the power spectra in the different states (right panel) indicated in the HID of a BHB during outburst evolution (Image courtesy- M. Klein-Wolt).
Recent developments

Figure 1.7: The energy spectra in different states (indicated in the HID, Figure 1.6) of a BHB during outburst evolution (Brocksopp et al. 2006).
radius) is estimated from the blackbody component, which depends on the spectral ‘model’ used. There are also additional uncertainties due to unknown distances and inclination angles of the sources. Hence, how ‘truncated’ the disc is, remains unclear.

Many models have been proposed that attempt to explain the structure and formation of the region where the hard power-law emission is generated. Some early suggestions are the formation of a corona or advection dominated accretion flow (ADAF). A corona can form in the presence of a cool disc very close to the BH. It consists of thermal/non-thermal (depending on the state) energetic electrons in ‘coronal regions’ above (and below) the disc and connected to it through magnetic reconnection (Bisnovatyi-Kogan & Blinnikov 1976; Miller & Stone 2000). In the ADAF scenario, the disc is truncated far from the BH and the region inner to the disc is filled with a geometrically thick, optically thin hot accretion flow. The ions and electrons are weakly coupled and the flow is radiatively inefficient. One of the stable ADAF solutions has the gas advected into the BH (Shapiro et al. 1976; Pringle 1976; Narayan & Yi 1994). It was recently suggested that the hard emission may originate at the base of the jet (Markoff et al. 2001).

The origin of variability is a long-standing question. There have been many models proposed, based on various mechanisms, to explain the broad-band noise and the low frequency QPOs (≲ 10 Hz), but the picture is not complete. To explain the low frequency type-C QPO, two state-of-the-art models are strong contenders. One requires the coronal geometry where the QPO arises due to oscillations in the disc, while the other requires the ADAF geometry where the QPO arises due to the Lense-Thirring precession of the hot flow. In the disc oscillation model, the dynamo cycles manifest themselves as oscillations in the azimuthal magnetic field in the ‘corona’ region elevated above the disc (see e.g., O’Neill et al. 2011), giving rise to the QPOs. However, this model can so far explain only the frequencies of the QPO and not the strength. The Lense-Thirring precession of a tilted hot flow gives the QPO (Stella & Vietri 1998; Fragile et al. 2007). This model requires the disc to be truncated in the hard states. The evolution in frequency, strength and coherence of the QPO are explained by the motion of the outer edge of the hot flow – the truncation radius of the disc. A unanimous picture is yet to emerge.

To explain the broad-band variability components, the propagating fluctuations model of Lyubarskii (1997) has recently gained acceptance. In this model, fluctuations in the mass accretion rate modulate the emission giving rise to variability. The fluctuations arise and propagate throughout the accretion flow. Churazov et al. (2001) showed that high frequency fluctuations can survive only if they arise at small radii
as they are damped viscously at large radii. Ingram & Done (2011) associated the lower break frequency of the broad-band noise with the outer truncation of the hot flow (the truncation radius of the disc). The upper break frequency arises deep in the hot flow. All these works suggested that the disc is stable and does not contribute to variability. Some recent works suggest that the fluctuations can also be intrinsic to the disc (Wilkinson & Uttley 2009; Uttley et al. 2011; Kalamkar et al. 2013b). These developments were made possible due to access to soft band provided by Swift where the disc emission dominates.

1.7 A guide to this thesis

In this thesis, the chapters focus on some of the challenges in the field of LMXBs discussed in Sections 1.5.1–1.6. The aim of this work is to address the questions of the origin of the variability, and the structure and the geometry of the accretion flow.

Chapter 1 reports possible twin kHz QPOs in the Accreting Millisecond X-ray Pulsar IGR J17511–3057. It describes the colour and variability evolution of the outburst using the RXTE data. The source does not fit in the NS LMXB scheme of variability evolution, which makes the correct identification of the frequency components, the kHz QPOs in particular, difficult. The separation between the kHz QPO frequency is close to half the spin frequency, contrary to the expectations for sources with spin frequency $< 400$ Hz. This result provides new input for the models that associate the spin frequency with the kHz QPOs. Chapter 2 reports the outburst of the BHB MAXI J1659–152 with RXTE data. We identify this source as a BH candidate LMXB based on the evolution of the outburst along the HID and variability properties. This source has the shortest orbital period (2.41 hr) observed in BHBs so far.

Chapter 3 forms a transition in the thesis as we study variability with Swift. We demonstrate that variability studies can be successfully performed with the Swift XRT. We study the various instrumental effects and shortcomings in performing power spectral studies with the imaging CCD detector, and suggest an optimal solution. The advantage of using Swift is the access to disc emission due to lower energy bandpass of 0.3 keV, not available with RXTE which could observe above 2 keV. With this, we present energy-dependent variability study of the first five years of the ‘atypical’ outburst of the BHB SWIFT J1753.5–012. The main finding of this work is that the hot flow is more variable in the peak of the outburst while the disc is more variable at low intensities. We explain this result in the context of the propagating fluctuations model. In Chapter 4, a similar energy-dependent variability study is performed for the BHB MAXI J1659–152 with Swift and simultaneous RXTE data.
1 Introduction

The aim is to test if the model used in Chapter 3 can explain variability in a more ‘typical’ outburst source. We attempt to explain the origin of all the broad-band variability components in the disc, in addition to the Lense-Thirring precession model for the type-C QPO in the hot flow.

In Chapter 5, a combined spectral and timing approach is used to study three BHBs MAXI J1659–152, SWIFT J1753.5–012 and GX 339–4 with the *Swift* data. The evolution along the spectral states along the outbursts is different in these sources; not all spectral states are observed in each source. Despite this, variability properties with similar frequencies and strengths are observed, a property common to most BHBs. Closer inspection reveals that the spectral-timing correlations are not same in different states; these are more complex than a single (linear) relation. We discuss the implications of this result on the models for the origin of variability.