Periastron Accretion in High Mass X-ray Binaries: Comparing Supergiant Fast X-ray Transients and Be/X-ray Binaries

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ABSTRACT

FACULTY OF PHYSICAL SCIENCES AND ENGINEERING
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PERIASTRON ACCRETION IN HIGH MASS X-RAY BINARIES: COMPARING SUPERGIANT FAST X-RAY TRANSIENTS AND BE/X-RAY BINARIES

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High Mass X-ray Binaries (HXMBs) are some of the brightest objects in the X-ray sky and test our understanding of accretion physics in extreme stellar environments. In this thesis, characterisation of the accretion processes around periastron in two Supergiant Fast X-ray Transients (SFXTs) and one Be/X-ray Binary (BeXRB) is presented. A combined XMM-Newton and INTEGRAL study of the SFXT SAX J1818.6−1703 reveals the source to be in an active state, presenting a low luminosity phase that can be explained by the onset of a subsonic propeller or transition to the radiative regime of quasi-spherical accretion (QSA). The strongest flaring activity coincides with significant spectral hardening and the associated luminosities of this phase suggest a potential transition to the Compton regime of QSA. Spectral analysis also reveals strong intrinsic absorption, an order of magnitude higher than previously observed and among the highest measured in an SFXT. Observations of the SFXT IGR J18450−0435 with XMM-Newton also show low luminosity phases that can be explained by the onset of the radiative regime of QSA. Fast flaring behaviour is attributed to transition to the Compton regime and evidence of the accretion of magnetised stellar wind is presented. Spectral analysis again reveals enhanced local absorption up to five times greater than previous reported. A multi-wavelength study of the BeXRB IGR J01217−7257 allows the discovery of X-ray periodicities of 82.5±0.7 days and 2.1562±0.0001 seconds attributed to the neutron star orbital and spin periods respectively. Detected X-ray outbursts are put into an orbital context and found to be consistent with Type-I outbursts. Analysis of long-baseline optical data reveals short periodicities (∼ 1 day) that are attributed to non-radial pulsations (NRPs) of the companion and an association between the NRPs, decretion disc growth and the onset of Type-I outbursts is suggested.
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Declaration of Authorship

I declare that all work presented in this thesis entitled ‘Periastron Accretion in High Mass X-ray Binaries: Comparing Supergiant Fast X-ray Transients and Be/X-ray Binaries’ is my own original research completed wholly during my candidature for a research degree at the University of Southampton. Where the published work of others has been consulted, the source of this is clearly attributed and where work presented was conducted jointly in collaboration with others I make clear the work done by each party.

The sections of this thesis where work presented is not wholly my own are as follows:


- In Chapter 5, the RXTE data analysis was performed by a collaborator at the University of Massachusetts Lowell, Silas Laycock. Temporal analysis of the Swift/BAT data was performed by Robin Corbet, a colleague based at the University of Maryland Baltimore County, NASA Goddard Space Flight Society and Maryland Institute College of Art. The reduction of Swift/XRT data as part of the Swift SMC Survey (S-CUBED) was performed by Phil Evans at the University of Leicester.

This thesis contains work published in the following sources:


- M. J. Coe, A. J. Bird, C. M. Boon et al. 2015, ATEL 8246, ‘SMC transient X-ray source IGR J01217−7257 detected by INTEGRAL’
In addition to the aforementioned publications, I have contributed to the following works that are not presented in this thesis:


Signed: ....................................................................................................
Date: ........................................................................................................
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Chapter 1

Introduction

X-ray binaries (XRBs) are luminous X-ray sources hosting a degenerate stellar remnant accreting matter from a binary companion star. Whilst the definition of an X-ray binary can be extended to include accreting white dwarfs (WDs), in this thesis I restrict the scope to systems hosting either a neutron star (NS) or black hole (BH). Since their discovery with the detection of Scorpius X–1 in 1962 (Giacconi et al., 1962), X-ray binaries have been widely studied with generations of space-based missions, revealing an extreme and transient X-ray sky.

XRBs are broadly classified according to the mass (and hence spectral type) of the companion star. High mass X-ray binaries (HMXBs) have companion stars with masses, $M \gtrsim 8 - 10 M_\odot$ and spectral types OB, whilst low mass X-ray binaries (LMXBs) typically have companion masses $\lesssim 1 M_\odot$ and spectral type later than A (Lewin et al., 1997; Lewin & van der Klis, 2006).

Whilst LMXBs and HMXBs are endpoints of stellar evolution, the differing spectral classes of the companion star result in each class tracing a differing aspect of star formation. As HXMBs contain both a high mass star and a compact object, these systems have comparatively short lifetimes (of order millions of years) and hence trace regions of recent star formation. This leads to clustering of known HXMBs in the Galactic Plane, as well as in the Magellanic Clouds, specifically the Small Magellanic Cloud (SMC), where tidal interactions with the Milky Way and Large Magellanic Cloud (LMC) within the last 60 Myr prompted a large increase in star formation (Harris & Zaritsky, 2004).

In the case of LMXBs, evolution of an initially massive star in the binary on $10^6$yr timescales results in the production of a compact object through a supernova. This stellar evolution, coupled with the subsequent binary interactions between the remnant and companion star initiate onset of the X-ray binary phase on time scales of $10^9$yr. These time scales associate LMXBs with older stellar populations, such as the Galactic Bulge and Globular Clusters, as sufficient time has elapsed since the
onset of binary evolution to the present such that the X-ray binary phase can be observed. Figure 1.1 shows the distribution of LMXBs and HMXBs in the Galaxy with a clear association between older stellar populations and LMXBs. The Galactic HXMB population can also be seen lying along the narrow Galactic Plane. Figure 1.2 shows the distribution of HXMBs in the SMC overlaid on the star formation tracing HI map of Stanimirovic et al. (1999). The lack of LMXBs in the SMC is attributed to the much longer evolutionary time scales of these systems with respect to HXMBs coupled with the recent star formation history of the SMC.

The distinction between LMXBs and HXMBs further extends to the mass transfer, accretion and X-ray generation processes occurring in each class, which I outline later in this chapter.

1.1 Neutron Stars

Originally proposed by Baade & Zwicky (1934), two years after the discovery of the neutron by Chadwick (1932), a neutron star is one possible end point of the evolution of massive stars. For stars with stellar masses greater than $8 \, M_\odot$, evolution off the main sequence leads to an iron-rich core, which is supported against collapse by electron degeneracy pressure. Subsequent addition of material by nuclear shell burning in the star causes the core to exceed the critical mass that can be supported by electron degeneracy pressure ($M_{ch} \approx 1.44 \, M_\odot$ - the Chandrasekhar mass), resulting in the collapse of the core. The core contracts until neutron degeneracy pressure can support the remnant against further collapse. The
Figure 1.2: Distribution of HXMBs in the SMC overlaid on the HI map of Stanimirovic et al. (1999) tracing star formation. Spin periods of the neutron stars in each HXMB are given in seconds. Image courtesy of M. J. Coe (http://www.soton.ac.uk/~mjcoe/smc/).
outer layers of the star subsequently fall inwards, rebound off the natal neutron star and are expelled into the interstellar medium.

Due to conservation of angular momentum of the progenitor core, young neutron stars are expected to be formed as rapidly rotating objects. Considering the core of the progenitor to be a spherical, electron-degenerate core (a white dwarf, WD) primarily composed of iron and assuming no mass loss during formation, conservation of angular momentum gives

\[
\frac{2}{5} M_i R_i^2 \omega_i = \frac{2}{5} M_f R_f^2 \omega_f
\]  

\[
\omega_f = \omega_i \left( \frac{R_i}{R_f} \right)^2
\]

where \( M_i, R_i \) and \( \omega_i \) are the initial mass, radius and angular frequency of the core and \( M_f, R_f \) and \( \omega_f \) are the final mass, radius and angular frequency of the core. The ratio of radii of the initial and final states can be found by equating the expected central pressure of each star with the corresponding degeneracy pressure for white dwarfs and neutron stars. This approach leads to

\[
\frac{R_i}{R_f} \sim \frac{m_n}{m_e} \left( \frac{Z}{A} \right)^{\frac{5}{3}} \sim 512
\]

where \( m_n \) and \( m_e \) are the masses of the neutron and electron, respectively and the ratio of proton and atomic number \( Z/A = 26/56 \) for Iron (Carroll & Ostlie, 2007).

This leads to a final spin period of the natal neutron star of

\[
P_{\text{ns}} \simeq 3.8 \times 10^{-6} P_{\text{core}}.
\]

If we assume that the core of the progenitor is rotating with a period of order 1000s, then neutron star spin periods of a few milliseconds are possible. The average spin period taken from the distribution of magnetic white dwarfs is approximately 1000s and hence can be used as a representative example of the progenitor core spin period. This approach is valid as an order of magnitude estimate of the core spin period, however the core and the outer envelope of the star are not isolated during core-collapse and hence accurate determination of core spin period is difficult to obtain.

The magnetic fields associated with neutron stars, particularly young neutron stars, are also fundamental to their interaction with material in binary systems. As magnetic fields lines are entrained in plasmas, during the collapse of the progenitor core magnetic flux through the cores surface is conserved. It can be shown that the

resulting magnetic field of the neutron star is given by

\[ B_{\text{ns}} \simeq B_{\text{core}} \left( \frac{R_{\text{core}}}{R_{\text{ns}}} \right)^2. \]  

(1.5)

Assuming a core radius of \(10^5 - 10^6\) km and a neutron star radius of 10 km, it is easy to see that for modest initial field strengths of \(10^2 - 10^4\) Gauss, young neutron stars can be born with magnetic fields in excess of \(10^{12}\) Gauss.

In recent years, strides forward in both instrumental sensitivity and computational techniques have allowed measurements of masses and radii of neutron stars. There are currently 35 measured masses of neutron stars, with the observed mass distribution ranging from 1.1–2.0 \(M_\odot\) and clustering around 1.4 \(M_\odot\) as expected from theoretical considerations. Measurements of neutron star radii reveal a tight grouping of 9.9–11.2 km, which is consistent with the commonly accepted value of 10 km. For an in-depth review of current knowledge regarding neutron star masses and radii see Özel & Freire (2016).

There are two radii that can be defined when considering the interaction of neutron stars with material in binaries. The first is the Alfvén radius (also known as the magnetospheric radius), defined as the radius at which the magnetic field dominates the flow of material around the neutron star. A first order estimate of this radius can be obtained by equating the magnetic and the kinetic energy densities and assuming a dipolar magnetic field,

\[ \frac{1}{2} \rho v^2 = \frac{B^2}{8\pi} \]  

(1.6)

\[ = \frac{\mu^2}{8\pi r^6} \]  

(1.7)

where B is the magnetic field strength, \(\mu\) is the magnetic moment, \(\rho\) and \(v\) are the density and velocity of the infalling material respectively. Assuming that the material is free-falling, \(v = v_{\text{ff}} = \sqrt{2GM/r}\) and substituting into Equation 1.6 gives

\[ \frac{1}{2} \frac{2GM}{r} = \frac{\mu^2}{8\pi r^6}. \]  

(1.8)

The density of the material can be eliminated by assuming mass continuity, \(\rho = \dot{M}/(4\pi v_{\text{ff}}^2)\) where \(\dot{M}\) is the mass infall rate. Substituting for density and free-fall velocity in Equation 1.8 and rearranging gives

\[ r_A = \left( \frac{\mu^4}{2GM\dot{M}^2} \right)^{\frac{1}{7}} \]  

(1.9)

\[ = 3.2 \times 10^8 \dot{M}_{17}^{-\frac{2}{7}} \mu_{30}^{-\frac{1}{7}} \left( \frac{M}{M_\odot} \right)^{-\frac{1}{7}} \text{ cm} \]  

(1.10)
where $\mu_{30}$ is the magnetic moment of the neutron star is units of $10^{30}\text{G cm}^3$ and $M_{17}$ is the mass accretion rate in units of $10^{17}\text{g s}^{-1}$. For typical neutron stars in HMXBs, the variables on the right hand side of Equation 1.10 are of order 1 and the Alfvén radius is far from the surface of the neutron star ($R_{ns} \sim 10^6\text{cm}$).

Inside the Alfvén radius, the infalling material is channelled along the magnetic field lines to the poles of the neutron star (Basko & Sunyaev, 1976). If there is misalignment between the magnetic and rotation axes, then the X-rays generated are modulated and a ‘lighthouse’ effect is seen. These objects are known as X-ray pulsars and they are only observable if the lighthouse beams pass across the line of sight to the pulsar.

The second characteristic radius is the corotation radius. This is defined as the radius at which the Keplerian angular velocity is equal to that of the neutron star. Equating these two angular velocities gives

$$\left(\frac{2\pi}{P_s}\right)^2 = \frac{GM_{ns}}{r_{co}^3}$$

Rearranging for $r_{co}$ gives

$$r_{co} = \left(\frac{GM_{ns}P_s^2}{4\pi^2}\right)^{1/3}$$

The Alfvén and corotation radii are of importance when discussing accretion mechanisms in X-ray binaries. These mechanisms are discussed in Section 1.3.

While neutron stars in binary systems are bright X-ray sources, there is a theoretical maximum power that can be generated by accretion on to a neutron star. This maximum power is the Eddington luminosity, $L_{Edd}$, and is the luminosity at which photon pressure equals the gravitational pull of the neutron star. Assuming that the photons generated at the surface of the neutron star are emitted isotropically, the energy flux at a distance $r$ from neutron star is given by

$$\frac{dE}{dA\,dt} = \frac{L}{4\pi r^2}$$

where $L$ is the source luminosity. The momentum imparted by a photon is given by $E = pc$ and hence the momentum flux is

$$\frac{dp}{dA\,dt} = \frac{L}{4\pi cr^2}$$

The rate of transfer of momentum or the force on an electron due to the radiation field is related to the momentum flux by

$$\frac{dp}{dt} = \sigma_T \frac{dp}{dA\,dt} = \sigma_T \frac{L}{4\pi cr^2}$$
where $\sigma_T$ is the Thomson scattering cross-section of an electron. Equating this with the gravitational force on the infalling matter gives

$$\sigma_T \frac{L}{4\pi cr^2} = \frac{Gm_p}{r^2} \quad (1.16)$$

$$L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} \quad (1.17)$$

$$= 1.2 \times 10^{38} \left( \frac{M}{M_\odot} \right) \text{ erg s}^{-1} \quad (1.18)$$

For a canonical mass of $1.4 M_\odot$ for a neutron star, the Eddington luminosity is approximately $2 \times 10^{38}$ erg s$^{-1}$. Theoretically, stable accretion cannot occur onto a neutron star above this limit, however, breaking the assumption of spherical accretion allows much higher luminosities to be achieved in practice.

### 1.2 Low Mass X-ray Binaries - LMXBs

Low Mass X-ray Binaries are a class of variable X-ray sources associated with main sequence stars. The luminosities of LMXBs, generated by accretion of material from the companion star onto a compact object, range from $10^{30.5} - 10^{39}$ erg s$^{-1}$. The low mass main sequence stars found in LMXBs have not been found to possess strong stellar outflows in the form of winds, hence the mass transfer mechanism generating the observed X-ray behaviour of LMXBs must be ‘Roche Lobe Overflow’ (RLOF). A Roche Lobe is a spherical region of gravitational influence associated with each component of the binary system. By considering the motion of a mass-less test particle in the gravitational potential of two orbiting masses, one can construct an effective potential in a corotating frame. This effective potential has five zero points, called ‘Lagrangian Points’, where the gravitational potential of each star nullifies the other. A schematic diagram of the equipotential surfaces of a binary with a mass ratio, $q = M_2/M_1 = 0.4$ is shown in Figure 1.3 with the five Lagrangian points marked.

In the case of interaction between the companion star and compact object in LMXBs, the $L_1$ Lagrangian point is the most important as this is the point of contact for the Roche Lobes of the binary components. For the companion star to overfill its Roche Lobe, the binary orbital period must be of order a few hours to days depending on the exact parameters of the system. The evolutionary pathways leading to such short period systems are not straight forward. In order for the system to host a neutron star or black hole, initially the binary must have hosted a massive star with $M \gtrsim 8 M_\odot$ and a lower mass companion. The high mass star evolves off the main sequence before the lower mass companion and fills its Roche Lobe. This process engulfs the secondary in what is known as a ‘Common Envelope’ (CE) phase. During the CE phase, frictional forces within the primary atmosphere...
Figure 1.3: Schematic diagram of the equipotential surfaces of a binary system with mass ratio $q = M_2/M_1 = 0.4$, where $M_1$ and $M_2$ are the masses of the more and less massive stars respectively. Lagrangian points, where the gradient of the effective potential is zero are clearly marked. Image taken from Benacquista & Downing (2013)
lead to an in-spiral of the secondary towards the primary core. Conservation of angular momentum leads to the expulsion of the Common Envelope leaving the lower mass companion in orbit of the stripped Helium core of the secondary. The Helium core subsequently undergoes a supernova leaving either a neutron star or black hole. Evolution of the binary orbit to shorter periods, due to either mass loss of the main sequence star or through emission of gravitational waves, on time scales of $10^9$yr, initiates the LMXB phase. This binary pathway and time scales and orbital periods associated with each phase are shown in Figure 1.4. It should be noted that the exact physical processes associated with the CE phase are poorly understood leading to large uncertainties in orbital parameters of such systems.

During the LMXB phase, material flows through the $L_1$ point toward the compact object. The specific angular momentum, $J$, of the material flowing through this point is too large to directly impact on the compact object. To conserve angular momentum, a ring of material must form in the orbital plane of the binary at the
circularisation radius

\[ R_{\text{circ}} = \frac{J}{GM_1} \]  

(1.19)

where \( M_1 \) is the mass of the accreting compact object (Lewin et al., 1997).

Assuming that energy is lost more efficiently than angular momentum by material orbiting at the circularisation radius, the system develops a series of circular orbits around the compact object, each with decreasing specific angular momentum in a disc structure. This is only possible if there is transport of angular momentum outwards from \( R_{\text{circ}} \), resulting in the disc edge extending to approximately \( 2R_{\text{circ}} \).

The energy and angular momentum transport in the disc is mediated by viscosity that converts the kinetic energy of the bulk motion of the gas to random thermal motions, producing emission across the electromagnetic spectrum that dominates over that of the companion star. A simple estimate of the radial temperature profile of the accretion disc can be calculated by considering the total energy of an annulus at radius \( r \) from the compact object with width \( dr \). Assuming a steady-state disc, where the amount of material transferred from the secondary, \( \dot{M} \), is constant and that there is no build up of mass in the annulus, conservation of energy gives

\[ dE = \frac{GM\dot{M}t}{2r^2}dr \]  

(1.20)

where \( M \) is the mass of the compact object and \( t \) is the time taken for mass to progress through the annulus. The luminosity of the ring \( dL_{\text{ring}} \) is then related to the energy radiated by the ring in time, \( t \) by

\[ dL_{\text{ring}} = dE = \frac{GM\dot{M}t}{2r^2}dr \]  

(1.21)

Using the Stefan-Boltzmann Law to calculate the emitted power of the ring gives

\[ dL_{\text{ring}} = 4\pi r^2 \sigma T^4 dr \]

where \( \sigma \) is the Stefan-Boltzmann constant. Substituting for \( dL_{\text{ring}} \) and rearranging for temperature gives

\[ T = \left( \frac{GM\dot{M}}{8\pi\sigma R^3} \right)^{1/4} \left( \frac{R}{r} \right)^{3/4} \]  

(1.22)

where \( R \) is the inner radius of the disc. This is a simplistic estimate of the disk temperature as it does not include the turbulent boundary layer close to the surface of a neutron star. When this is considered, the radial temperature profile of the disc is given by

\[ T = T_{\text{disk}} \left( \frac{R}{r} \right)^{3/4} \left( 1 - \sqrt{R/r} \right)^{1/4} \]  

(1.23)
where $T_{disk}$ is given by

\[
T_{disk} = \left( \frac{GM}{8\pi\sigma R^3} \right)^{1/4}
\]

(1.24)

The maximum temperature of such a disc occurs for $0.488T_{disk}$ which, assuming neutron star parameters $M = 1.4\, M_\odot$, $R = 10$ km and a mass accretion rate of $\sim 10^{-9}\, M_\odot\, yr^{-1}$, peaks in the X-ray part of the electromagnetic spectrum. The transfer of material from the accretion disc on to a neutron star also imparts significant angular momentum, resulting in a net increase in the angular rotation speed of the neutron star if the accretion disc and stellar rotation are aligned (‘spin up’).

In the case of NS LMXBs, there have been a number of X-ray periodicities detected where the magnetic field of the neutron star is strong enough to funnel accreted material on to the magnetic poles. However, the lack of detected pulsations from a system does not exclude the possibility that it harbours a NS. In NS LMXBs, it is expected that the natal field of the neutron star will have weakened over time. This decay in the field strength is thought to either result from the burying of the magnetic field due to accretion on to the star or from spin evolution of the neutron star (Bhattacharya & van den Heuvel, 1991). Suppression of the intrinsic magnetic field of the neutron star to below $10^9$ G dampens the effect of the field on infalling material such that the gas no longer follows the field lines to the magnetic poles, inhibiting the modulation of X-rays due to rotation (Alpar et al., 1982). In this case, accreted material builds up on the surface of the neutron star until the temperature and pressure at the base of the envelope is sufficient as to initiate nuclear fusion of Hydrogen. This manifests itself as an X-ray burst with a characteristic rise time of seconds and an exponential day known as a Type-I X-ray Burst.

There are, however a number of LMXB systems with Type-I outbursts that have detected pulsations in the millisecond range (Wijnands & van der Klis 1998; see Patruno & Watts 2012 for a review). Also known as recycled pulsars, these systems are thought to have undergone periods of high mass accretion and hence protracted spin-up intervals.

An in-depth discussion of X-ray properties of LMXBs is beyond the scope of this thesis. For a detailed consideration of these systems, readers are directed to Frank et al. (2002) and Lewin & van der Klis (2006). The remainder of this thesis is concerned with High Mass X-ray Binaries, the properties of which I now outline.
1.3 High Mass X-ray Binaries - HMXBs

High Mass X-ray Binaries are binary systems containing some of the most massive (M≥ 8 – 10 M⊙) stars of spectral class OB and the degenerate remnants of an even more massive companion. These systems are of particular interest as they test our understanding of physics in extreme stellar environments and can appear as some of the brightest objects in the X-ray sky. HMXBs preferentially appear to admit the presence of a neutron star over that of a black hole with over 50% of the HMXBs found in the catalogue of Liu et al. (2006) showing the presence of X-ray pulsations. As discussed in Section 1.1, for pulsations to be visible the lighthouse beams of emission have to cross our line-of-sight, suggesting the true proportion of NS HMXBs is actually much greater than 50%. Recent statistical confirmation of the association between HXMBs and regions of OB star formation has further confirmed the nature of HXMBs as young stellar binaries (Bodaghee et al., 2012). As such, the neutron stars present in these binaries are expected to possess magnetic field strengths of Bns > 10¹² Gauss and hence the interaction between binary components in HXMBs and the subsequent accretion of matter are heavily affected by the neutron star magnetic field.

There are a limited number of known BH HMXB systems, with examples such as Cyg X−1 and LMC X−3 having been extensively studied for over 40 years while the first BH BeXRB was only discovered in 2014 (Casares et al., 2014), suggesting there are yet-undiscovered examples of these systems, albeit a small number due to the finely tuned evolutionary pathway required to produce a Black Hole – massive star pair.

The exact processes involved in the evolutionary pathway through which HMXBs form are still not fully understood, however Tauris & van den Heuvel (2006) outline a potential formation channel for a generic X-ray binary that is shown in Figure 1.5. In this scenario, the binary system has a initial orbital period of 100 days and consists of two giant stars with masses of 14.4 M⊙ and 8 M⊙. In this scenario, the more- and less massive stars are referred to as the primary and secondary respectively. The primary evolves off the main sequence more rapidly than the secondary, fills its Roche Lobe and transfers mass to the secondary. This process is short lived but leads to the stripping of the primary and the inversion of the binary mass ratio such that the secondary is now the more massive component. The remaining Helium core of the primary subsequently undergoes a supernova forming a NS. The commencement of mass transfer from the secondary to the primary marks the start of the HXMB phase, however the nature of this mass transfer varies between different subclasses of HMXB.

The apparent dearth of BHs in HMXBs may be due to the mass loss through stripping during the RLOF phase. In order for a Helium core to remain with
enough mass to form a BH, the initial mass of the star would have to be much larger. While the formation of massive stars in binaries is common (Sana et al., 2012), the formation rate of stars massive enough to form BHs after stripping is likely to be small. Another contributing factor is the supernova kick experienced by the compact object. The supernova kick associated with a star with enough mass to form a black hole may be strong enough to unbind the binary system completely and the initial parameters of the binary would have to be finely tuned so as to avoid this unbinding event.

There are three main classes of HMXB broadly classified by their companion luminosity class and the accretion mechanism generating the observed X-ray behaviour. These are Be/X-ray binaries (BeXRBs), Supergiant X-ray Binaries (SgXRBs) and Roche Lobe filling Supergiant X-ray binaries (RLOF SgXRBs). As the majority of HXMBs are formed with neutron stars as the accreting masses, these systems can be compared and contrasted by plotting the determined spin and orbital periods of the neutron stars against each other. This is called the Corbet Diagram (also known as the $P_{\text{spin}} - P_{\text{orb}}$ diagram, Corbet 1986) and Figure 1.6 shows the Corbet Diagram for galactic X-ray binaries. Be/X-ray binaries are denoted by blue crosses, SgXRBs by red circles and RLOF SgXRBs by black squares. It is clear that each different binary class occupies a separate region of the parameter space, with the SgXRBs occupying a short spin period - short orbital period region and BeXRBs following a distinct track with shorter spin period systems exhibiting shorter orbital periods and the converse in a $P_{\text{spin}} \propto P_{\text{orb}}^2$ relationship. The
Figure 1.6: Corbet diagram of HMXBs (Corbet, 1986). Be/X-ray binaries are denoted by blue crosses, wind-fed supergiant X-ray binaries (SgXRBs) by red circles and Roche Lobe Overflow (RLOF) supergiant X-ray binaries by black squares. Period data are taken from Liu et al. (2006) and Bodaghee et al. (2007)
SgXRBs occupy a region of shorter orbital periods with longer spin periods and show no obvious correlation. These properties largely arise from the mass transfer and accretion mechanisms at work in each system discussed below.

1.3.1 Be/X-ray Binaries - BeXRBs

Be/X-ray binaries (BeXRBs) are a class of HMXB defined by their association with Be stars of luminosity classes III–IV that show spectral lines in emission and an infra-red excess above that of a normal B star. These features are attributed to the presence of a dense equatorial disc, known as a decretion disc. The simple picture of a Be star as a rapidly rotating star with an equatorial disc supported against stellar gravity by centrifugal force was proposed over 80 years ago by Struve (1931) and although basic, this picture still seems to be a good first order approximation of the system. It does not, however, explain the origin of such a structure. The fast rotation of Be stars, at nearly the break-up velocity of the star, is not thought to be enough to generate sufficient mass loss to form a disc and hence Osaki (1999) suggested that non-radial pulsations (NRPs) of the Be star could impart sufficient extra velocity to material in the equatorial regions to exceed the break-up velocity of the star and form a decretion disc. The origin of such disc has been an active area of research for many decades with other mechanisms invoked to explain the presence of a disc including wind compression and magnetic field effects (Porter & Rivinius, 2003).

In the optical and infra-red (IR) bands, the Be companion star completely dominates the observed flux of the system and observations in these bands provide diagnostic information of the environment around the companion. As mentioned above, Be stars show spectral lines in emission rather than absorption, of which Hα is the primary indicator of a circumstellar disc due its double peaked nature. The spectral emission lines and IR excesses observed in BeXRBs are the result of bound-free and free-free emission from recombination of the optical/UV flux of the star in the circumstellar disc (Woolf et al., 1970; Gehrz et al., 1974). Strong modulations of the optical light curves of a number of systems with periods of tens of days have been interpreted as the orbital period of the neutron star and the presence of quasi-periodic, short period signals of order a few days have been attributed to NRPs of the Be star (e.g Schmidtke & Cowley 2006). A number of sources have been observed undergoing optical flaring co-incident with detected X-ray outbursts. Such behaviour is thought to arise from the perturbation of the stellar decretion disc by the passage of the neutron star that increases the surface area of the disc (Okazaki & Negueruela, 2001). On longer time scales, large variations in the optical/IR flux observed in BeXRBs over the course of years is likely due to significant changes in the size and structure of the circumstellar disc and can potentially effect the observed X-ray behaviour of these sources (as
Most BeXRBs are transient objects in the X-ray band with variability in X-ray luminosity varying from $10^{33}$ erg s$^{-1}$ in quiescence up to almost Eddington limited luminosities of $10^{38}$ erg s$^{-1}$ during the brightest outbursts. Though there are examples of persistent sources (Reig & Roche, 1999) these systems are generally of lower average luminosity and show no large outbursts when compared with transient BeXRBs. In the case of transient systems, the observed X-ray emission is the result of mass transfer from the decretion disc to the neutron star during a periastron passage rather than RLOF or capture of stellar winds as the Be star sits deep in its own Roche Lobe and the stellar winds associated with Be stars being too weak to drive the observed X-ray emission. The neutron stars in BeXRBs are often in long, eccentric orbits with orbital periods greater than 10 days and moderate eccentricities of $e \gtrsim 0.3$. A schematic diagram of the orbital configuration of a NS BeXRB is shown in Figure 1.7. While in the vast majority of cases, the compact object in BeXRBs is a neutron star, recent discoveries of both white dwarfs and a single black hole as accreting bodies in these systems suggest the observed BeXRB behaviour is not driven by the nature of the compact object (Kahabka et al., 2006; Sturm et al., 2012; Li et al., 2012; Casares et al., 2014).

Interaction of the neutron star with expelled stellar material from the Be companion gives rise to two types of observed X-ray outburst referred to as Type-I and Type-II outbursts. Type-I outbursts arise when the neutron star interacts with and accretes from the decretion disc of the Be star during periastron passage, reaching luminosities up to $10^{37}$ erg s$^{-1}$ and typically lasting between 20–30% of the orbital period. Initially it was thought that these events were a result of the neutron star passing through the decretion disc, however subsequent studies have revealed that the disc is truncated at radii in resonance with the binary orbit and the decretion disc keplerian orbit due to viscous and tidal forces (Okazaki & Negueruela, 2001). In the case that the binary orbit is circular, no Type-I outbursts are expected as the truncation of the disc is such that the separation of the outer disc radius and the $L_1$ Lagrange point is too great for any accretion of material to take place. In eccentric orbits, as one expects in BeXRBs, this is not the case and the disc truncation radius is further from the Be star such that, as the neutron star approaches periastron the $L_1$ point is close to or inside the outer disc edge allowing the neutron star to capture disc material. The material captured by the neutron star during the periastron approach has low velocity relative to the motion of the neutron star and carries with it significant angular momentum, leading to the formation of a temporary accretion disc and the spin-up of the neutron star. Type-I outbursts are not present during every periastron passage in BeXRBs due to intrinsic variation in the decretion discs such as growth and shrinking of the disc and warping due to asymmetries in the disc. Only periastron passages where the $L_1$ point passes inside these density structures will generate Type-I outbursts.
Figure 1.7: Schematic diagram of a Be X-ray binary. The neutron star orbits the Be star in a wide, eccentric orbit encountering the decretion disc as it approaches periastron generating X-ray emission as illustrated in the representative light curve. Image courtesy of I. Negueruela (http://dfists.ua.es/ignacio/bex.html).
Type-II outbursts are major increases in the observed luminosity of BeXRBs by a factor of $10^4$ up to Eddington limited luminosities. Type-II outbursts have no apparent phase bias and can last a large fraction of, or longer than, the binary orbit. The material fuelling these outbursts, like those of the Type-I variety, comes from the decretion disc of the Be star. In the case of Type-II outbursts it is thought that a major enhancement of the disc results in accretion of material from the disc by the neutron star along the entirety of the orbit. This disc enhancement is visible as large amplitude changes in both the optical and infra-red photometric and spectroscopic features such H$_\alpha$ equivalent width and $I$-band magnitude (see for example 4U 0115+63, Reig et al. 2007). In the case of 4U 0115+63, following a Type-II outburst, the change of sign in equivalent width of H$_\alpha$ from negative to positive is indicative of a Balmer line transition from emission to absorption suggesting complete dissipation of the decretion disc, however this is not always the case. During Type-II events, there is evidence of large and steady spin-up of the neutron star, when coupled with the discovery of quasi-periodic oscillations (see Table 3 of James et al. (2010) for a list of HXMBs with detected QPOs) suggests formation of an accretion disc is possible.

Figure 1.8 shows the Swift/BAT 15–50 keV light curve of the prototypical BeXRB, EXO 2030+375. This source has a mildly eccentric ($e = 0.4$), 46 day orbit (Wilson et al., 2001) and shows clear Type-I outbursts every periastron passage, however in recent years, the source has undergone an extended period of low activity. During this period, EXO 2030+375 has seen a torque reversal, with the neutron star evolving from constant spin-up to spin-down before outburst behaviour restarted (Fuerst et al., 2016; Kretschmar et al., 2016). Though no explanation for this change in observed X-ray behaviour has yet been discussed in the literature, centrifugal inhibition of accretion due to the fast rotation of the neutron star could be one explanation. EXO 2030+375 also shows a Type-II outburst around MJD 53950 lasting almost two orbital cycles before resuming the typical Type-I outburst behaviour every periastron approach of the neutron star, suggesting there was no full dissipation of the decretion disc following the Type-II outburst in this system.

As discussed above, BeXRBs show a clear correlation in the Corbet Diagram of the form $P_{\text{spin}} \propto P_{\text{orb}}^2$. This relationship can be explained intuitively by considering the transfer of angular momentum during accretion episodes. In the case of shorter binary orbits, the average density of ambient material experienced by the neutron star is greater due to a larger fraction of the orbit spent in the vicinity of the decretion disc. The accretion of this material spins the neutron star up and results in a short spin period. The decrease in spin period of the neutron star works to inhibit further accretion by increasing the centrifugal barrier experienced by material in the neutron star, leading to a minimum possible spin period of the neutron star. In the case of longer period BeXRBs, the converse is true. The neutron star spends a smaller fraction of its binary orbit in contact with the
Figure 1.8: *Swift*/BAT 15–50 keV light curve of BeXRB, EXO 2030+375. This source shows clear Type I outbursts in the majority of periastron passages. Also present is a Type II outburst lasting longer than a single orbital period. Light curve data available from the BAT Transient Monitor (Krimm et al. 2013, https://swift.gsfc.nasa.gov/results/transients/).
decretion disc and hence spin up phases are more sporadic than the shorter period systems. As the neutron star progresses away from periastron, the accretion of material is severely reduced in the low density plasma environment which leads to a net reduction in the rotation rate of the neutron star.

It is worth noting that BeXRBs are the most common class of HMXB with the majority of HMXBs in the Galaxy and both Magellanic Clouds being of this class (Liu et al., 2005, 2006), however the population of BeXRBs in the SMC is comparable in size to that of the Milky Way despite the 1:100 mass ratio of the two galaxies. Under such a ratio, there is an over-abundance of HXMBs in the SMC by a factor of 50 which cannot be accounted for by the lower metallicity environment the SMC presents \( \left(Z_{SMC} \sim 0.2Z_\odot \right) \) for star formation (Dray, 2006). The mechanism driving this over-abundance of HXMBs in the SMC is largely accepted to be tidal interactions with the Milky Way and LMC within the last 60 Myr prompting a large increase in star formation (Harris & Zaritsky, 2004). The abundance of HXMBs, specifically BeXRBs in the SMC, provides a rich target for monitoring these sources at known distance with low Galactic obscuration. The ratio of HXMBs in the LMC to the Milky Way however is roughly in line with that expected based on the mass ratio of the galaxies.

The abundance and recurrence rate of BeXRBs makes them excellent targets for characterising accretion processes involving stellar outflows and neutron stars. However, there are a class of HXMBs with more massive stellar companions and extreme X-ray behaviour where the picture is less clear. These are the Supergiant X-ray binaries, the known properties of which I outline now.

1.3.2 Wind-fed High Mass X-ray Binaries - SgXRBs

Supergiant X-ray binaries (SgXRBs) are a class of HXMB associated with OB supergiants and are the most extreme examples of stellar companions in X-ray binaries. The discovery of P Cygni profiles in spectra of OB supergiants during early ultra-violet rocket experiments by Morton (1967a,b) revealed high-velocity mass ejection that could not be explained as a simple extension of solar wind theory of the time. This led to the development of radiative wind models, the details of which are discussed later in this section. The strong stellar wind found in supergiants is the principle mass transfer mechanism in most SgXRBs, though there are small number of examples where RLOF of the stellar atmosphere is the primary mass transfer mechanism. These RLOF SgXRBs are discussed in Section 1.3.4. In the case of wind-fed SgXRBs, all known compact objects in these systems are neutron stars and it is the capture and accretion of stellar wind by the neutron star that drives the observed X-ray behaviour. Wind-fed systems are detected as persistent X-ray sources with a typical luminosity of \( L_X \gtrsim 10^{35} \text{ erg s}^{-1} \) but can
exhibit a dynamic range of up to 100 in flux. The persistent nature of SgXRBs suggests the neutron star orbital period is short with the observed variability generated by eccentricity of the orbit, accretion quenching mechanisms or a combination of these mechanisms.

The launch of the INTEGRAL mission (Winkler et al., 2003) radically changed our understanding of SgXRBs and their abundance in the Galaxy. The discovery of 13 new systems early in the mission more than doubled the number of known SgXRBs and also revealed for the first time six systems with high intrinsic absorbing column density ($N_H > 10^{23} \text{cm}^{-2}$), dubbed the ‘obscured’ SgXRBS (Walter et al., 2003). These discoveries were facilitated by the unique wide field of view and instantaneous sensitivity of the IBIS instrument (Ubertini et al., 2003) above 15 keV, where absorption effects of material both local to the binary environment and along the line of sight are drastically reduced. These unique characteristics also contributed to the discovery of a separate subclass of wind accreting systems, Supergiant Fast X-ray Transients, which are discussed in depth in Section 1.3.3. The capabilities of the INTEGRAL satellite are discussed in further detail in Chapter 2.

In order to explain the broad P Cygni profiles observed in the UV spectra of supergiants that suggested large ($10^{-8} - 10^{-5} M_\odot \text{yr}^{-1}$) and fast ($600-3500 \text{km} \text{s}^{-1}$) stellar winds, the theory of radiatively driven winds was developed. Initially proposed by Lucy & Solomon (1970), the theory states that UV resonance lines in heavier elements such as Carbon, Nitrogen and Silicon can generate large negative gravities in the outer atmosphere of the star and hence drive stellar winds. This model was subsequently refined by Castor et al. (1975) to include a greater number of spectral lines in the driving of the wind, which leads to the force exerted by the stellar continuum being a function of the local velocity gradients. The model (also known as the CAK model) predicts mass loss rates a factor of 100 greater than that of Lucy & Solomon (1970) as well as the supersonic nature of OB supergiant winds, with terminal wind velocities of $\sim 1500 \text{km} \text{s}^{-1}$. The model also suggests that mass loss rates on such a scale over the course of the main sequence lifetime of the star represents a significant fraction of the mass of the star (up to 25%) and have potential consequences for future stellar evolution. The CAK model produces a homogeneous, steady state stellar wind that is accreted by the orbiting compact object to produce X-rays. An artist impression of this process is shown in Figure 1.9.

The accretion of material from the stellar wind by the neutron star is, to first order, described by the Bondi-Hoyle accretion model (Hoyle & Lyttleton, 1939; Bondi & Hoyle, 1944). In this model, the supersonic stellar wind flows toward the compact object and forms a bow shock. Inside this shock, material is deflected by the gravitational potential of the neutron star and forms a region of shocked gas that trails the NS called the accretion wake. The material that is focussed into this
accretion wake can then fall inwards towards the neutron star and be accreted. Figure 1.10 shows the resulting density contours from two dimensional gas dynamic simulations of stellar winds interacting with a neutron star in a circular orbit of varying binary separations around a supergiant companion (Blondin et al., 1991). The resulting accretion wake from gravitational focussing is clearly seen for all binary separations simulated with increasing turbulent behaviour occurring at smaller binary separations.

The radius at which material is deflected by the neutron star gravitational potential is known as the accretion radius, $R_a$, defined as

$$R_a = \frac{2GM}{v_{rel}^2 + c_s^2}$$  \hspace{1cm} (1.25)

where $M$ is the mass of the compact object, $v_{rel}^2$ is the relative velocity between the compact object and the wind and $c_s^2$ is the sound speed in the gas which is often neglected due to its small magnitude relative to the velocities of the wind and neutron star, leading to the more common definition of the accretion radius,

$$R_a = \frac{2GM}{v_{rel}^2}. \hspace{1cm} (1.26)$$

Assuming all the material captured at this radius falls efficiently onto the neutron
Figure 1.10: Density contours resulting from 2D gas dynamic simulations of stellar winds showing a shocked accretion wake trailing the NS. The four panels show binary separations $D/R_*$ of 1.7, 1.62, 1.59 and 1.57 for panels a – d, respectively. Image taken from Blondin et al. (1991)
star the resulting accretion rate can then be approximated by

$$\dot{M} = \frac{4\pi G^2 M^2 \rho}{v_{rel}^3} \quad (1.27)$$

where $\rho$ is the stellar wind density. This assumption, however, does not hold in the case of SgXRBs due to the strong magnetic fields of the neutron stars in these systems. The captured plasma will encounter the magnetosphere of neutron star and upon entering the magnetosphere, the accreted material is funnelled along the field lines to the magnetic poles of the neutron star where an accretion column of hot, shocked gas is formed and generates X-ray emission. As described in Section 1.1, the misalignment of the rotation and magnetic axes of the neutron star generates a ‘lighthouse’ effect revealing the spin period of the neutron star.

The emission generated in the accretion column has two possible geometries based upon the accretion rate, $\dot{M}$ and hence luminosity (Basko & Sunyaev, 1976). In the case of low $\dot{M}$, the accreted gas can fall freely to the surface of the neutron star, converting kinetic energy into X-ray emission forming a small accretion column, often referred to as an ‘accretion mound’. The X-ray photons generated in this mound stream along the magnetic field lines in a ‘pencil beam’ configuration as the line of sight along the field lines is optically thin. In the case of increased $\dot{M}$, the material forms a radiative shock standing off the surface of the neutron star. This shock rapidly decelerates the flow and converts much of the kinetic energy into radiation leaving a ‘sinking flow’ behind the shock onto the neutron star forming an accretion column. The height of the shock increases for increasing accretions rates and can result in the accretion column extending up to the Alfvén radius. In the high $\dot{M}$ regime, the optical depth of the accretion column is greater than 1 and hence photons cannot exit the accretion column along the field lines. The sinking gas of the accretion column instead radiates photons perpendicular to the magnetic field lines in a ‘fan beam’ configuration. These geometries are illustrated in Figure 1.11.

As discussed in Section 1.1, the young neutron stars found in SgXRBs are expected to possess magnetic fields in excess of $10^{12}$ Gauss, which can only be directly measured by identification of Cyclotron Resonance Scatter Features (CRSFs, also ‘cyclotron lines’) in the X-ray spectra of accreting pulsars. CRSFs are formed by the scattering of photons by electrons accelerated in the magnetic fields of the neutron star. In strong magnetic fields, the orbits of electrons around the magnetic field are quantised into Landau levels. Landau orbits are discrete energy levels with the energy of each referred to as the cyclotron energy, $E_{cyc}$ (Daugherty & Harding, 1986). Collision of photons with the electrons in these quantised levels results in the
loss of energy equal to the cyclotron energy, the analytic form of which is given by

\[ E_{\text{cyc}} = n \frac{\hbar e B}{m_e c} \]  

(1.28)

where \( \hbar \) is Planck’s constant, \( e \) is the electron charge, \( B \) is the neutron star magnetic field, \( m_e \) is the electron mass and \( n \) is the quantum number of the orbital where \( n = 1 \) corresponds to the fundamental cyclotron energy. The strong gravitational field of the neutron star results in a shift in the cyclotron energy by a factor of \((1 + z)^{-1}\), where \( z \) is the gravitational redshift factor of the neutron star which is typically around 0.3. The expression for the cyclotron line energy then becomes

\[ E_{\text{cyc}} = n \frac{\hbar e B}{m_e c} (1 + z)^{-1} \]  

(1.29)

\[ = 11.57 n B_{12} (1 + z)^{-1} \text{ keV} \]  

(1.30)

where \( B_{12} \) is the neutron star magnetic field in units of \( 10^{12} \) Gauss. Often, only the fundamental cyclotron energy is detected in X-ray spectra, however there are some sources with higher harmonics detected such as 4U 0115+63 where the third harmonic of the fundamental has been detected (Heindl et al., 1999). Measurements of cyclotron lines in SgXRBs such as Vela X−1 have found magnetic field strengths of \( \sim 10^{12} \) Gauss in line with theoretical expectations for young neutron stars (Makishima & Mihara, 1992).
The picture of supergiant stellar winds and their accretion described above is however, a simplification. Theoretical models of the stellar winds of supergiant stars have long predicted inhomogeneities in the winds. Lucy & White (1980) suggested strong instabilities in the wind acceleration generate shocks in the wind, leading to clump-like structures in the wind, with small perturbations in velocity or density growing in time. Subsequent time-dependent hydrodynamical simulations of line-driven winds by Owocki et al. (1988) revealed a strong tendency of the stellar wind flow to form sharp density gradients, with regions of low-density, high-speed wind material and high-density, slow moving clumps due to the sensitivity of the line-driving force to small velocity gradients at the stellar photosphere. Further numerical studies by Runacres & Owocki (2002) found the evolution of structure in the stellar winds is influenced by two mechanisms. The first of these is the expansion of the dense clumps into the rarefied intra-clump gas, while the second is the compression of the clumps due to supersonic collisions which acts to counter the expansion. These two mechanisms can preserve structure in the stellar wind out to \( \sim 1000 \) stellar radii.

Theoretical predictions of structured stellar winds have been confirmed using a variety of observational techniques. Lucy (1982) analysed UV spectral lines to infer sharp changes in the velocity fields of the winds and variable structures in HeII emission lines from O-type supergiants found by Eversberg et al. (1998) were explained as excess emission from clumps in supergiant winds. Clumping was also invoked by Markova et al. (2005) to explain the observed variability in H\( \alpha \) line profiles in a large population study of O supergiants. Spectroscopic detection of transient substructures in stellar winds of O, B and Wolf-Rayet stars has also been reported in recent years (Lépine & Moffat, 2008; Prinja & Massa, 2010).

Recent studies have considered the effects of such clumping on the X-ray emission generated in supergiant binaries. The time-dependent hydrodynamic simulations of Oskinova et al. (2012) revealed large variations in both density and velocity in the stellar wind that remained present out to large radii from the supergiant. This behaviour is illustrated in Figure 1.12. The variations in density close to the star represent the formation of dense shells with small radial extent by line driven instabilities with these structures growing at larger radii from the star due to collision between shells. The simulations also showed that on average the stellar wind velocity profile followed the theoretical \( \beta \)-relation of the CAK model, however close to the star, steep negative velocity gradients are present across the shells. The simulations were then used to calculate the expected luminosity generated by accretion of the stellar wind using the Bondi-Hoyle model. Synthetic light curves generated by this method are shown in Figure 1.13 for a variety or neutron star-supergiant orbital separations. In all cases the X-ray variability shows an extreme dynamic range, from six to eight orders of magnitude across the differing orbital separations, driven by the \( v^{-3} \) dependence of the mass accretion rate in the
Bondi-Hoyle model. These large variations rule out the Bondi-Hoyle accretion model as the mechanism driving the observed X-ray behaviour of SgXRBs and instead suggest that there must be an effect damping the accretion of material from the stellar wind by the compact object.

More recently, hydrodynamic simulations of Manousakis & Walter (2015) included the effects of photo-ionisation by the neutron star on the line-driven acceleration of the stellar wind. These simulations sought to explain the origin of so called ‘off-states’ in the prototypical wind accreting SgXRB, Vela X$-$1. Off-states in wind-fed X-ray binaries are periods during which the X-ray flux reduces by a factor of $\sim$10 relative to the average flux of the source, however the observed drop in flux is not due to the cessation of accretion as detection of the NS spin period is still possible (Doroshenko et al., 2011). The simulations of Manousakis & Walter (2015) revealed the generation of a non-stationary shock that regularly moves inwards and outwards relative to the NS between $10^{11}$ cm and the accretion radius. The authors refer to this as a ‘breathing mechanism’ that generates luminosity variations of up to three orders of magnitude globally, a reduction in the instantaneous accretion rate of a factor of ten corresponding to off-states and generates quasi-periodic variations on the $\sim$6 ks time scales observed in Vela X$-$1. Figure 1.14 illustrates the motion of the shock outside and during off-states in the simulations. The density distribution shows the motion of the shock from away from the NS during the off-state, while outside these times the neutron star is surrounded by an increased stellar wind density. While accounting for much of the observed behaviour in SgXRBs, the model produces too narrow a luminosity distribution
Figure 1.13: Synthetic X-ray light curve derived from time-dependent hydrodynamic simulations of Oskinova et al. (2012), assuming the stellar wind material is accreted onto the neutron star by Bondi-Hoyle accretion. The light curves show extreme variability of up to eight orders of magnitude at its apex. This level of variability is not seen in any wind-accreting systems.
when compared with observations of Vela X−1 with RXTE and INTEGRAL, suggesting other factors need to be considered when modelling the gas dynamics and accretion in SgXRBs.

Other models have invoked magnetic effects of the neutron star to damp the accretion rates. Such methods invoke instabilities at the magnetosphere to drive material through the magnetic barrier and onto the neutron star poles. The two main instabilities considered are the Rayleigh-Taylor (Arons & Lea, 1976) and the Kelvin-Helmholtz Instabilities (Burnard et al., 1983). In the case of the Rayleigh-Taylor Instability (RTI), the accreted matter sitting above the magnetosphere of the neutron star is treated as a more dense fluid than that inside the magnetosphere and hence can penetrate the magnetic barrier and proceed toward the neutron star. The Kelvin-Helmholtz Instability (KHI) is generated by the motion of the magnetosphere relative to that of the accreted material and shear forces due to this motion allow the material to transfer into the magnetosphere.

The work of Bozzo et al. (2008b) considered the effect of the neutron star magnetic field and the applicability of the aforementioned instabilities in generating the observed behaviour of SgXRBs. Within this framework, the accretion processes at work depends on the three characteristic radii of neutron stars outlined above and their relative positions: the accretion radius $R_a$, the corotation radius, $R_{co}$ and the magnetospheric radius, $R_M$. In their work, the authors rescale the definition of the magnetospheric radius given by Davies & Pringle (1981) and define the corotation radius in terms of the spin period. The expressions for these radii given in
observable quantities are

\[
R_M = 3 \times 10^{10} \frac{M_{-6}^{-1/6} v_8^{-1/6}}{a_{10d}^{1/3} \mu_{33}^{1/3}} \text{ cm}
\]  
(1.31)

\[
R_{co} = 1.7 \times 10^{P_{s3}^{2/3}} \text{ cm}
\]  
(1.32)

where \(M_{-6}\) is the stellar wind mass loss rate in units of \(10^{-6} M_\odot \text{ yr}^{-1}\), \(v_8\) is the relative wind velocity in units of \(10^8 \text{ cm s}^{-1}\), \(a_{10d}\) is the binary separation assuming circular orbits and in units scaled using an orbital period in units of 10 days. Also, \(\mu_{33}\) is the magnetic moment in units of \(10^{33} \text{ G cm}^{3}\) and \(P_{s3}\) is the spin period of the neutron star in units of \(10^3\) s.

The relative position of \(R_M, R_{co}\) and \(R_a\) define a number of possible accretion scenarios that broadly fall into two main categories; regimes where accretion is inhibited by the magnetic field of the neutron star \((R_M > R_a)\) and those where material is captured by the neutron star \((R_M < R_a)\). In the case where the magnetospheric radius lies outside the accretion radius, then the stellar wind of the supergiant interacts directly with the magnetosphere of the neutron star. This forms a bow shock at \(R_M\) creating a region of shocked gas around the magnetosphere. The relative positions of the magnetospheric radius and corotation radius define two different accretion regimes:

- **Super-Keplerian Magnetic Inhibition Regime**: \(R_M > R_a, R_{co}\)
  
  If the magnetospheric radius is larger than both the accretion radius and the corotation radius, then the matter that is shocked and held close to magnetosphere cannot progress inwards. This is due to the rotational drag of the magnetosphere which is locally supersonic. The interaction of the matter with the magnetic field dissipates rotational energy and leads to NS spin down

- **Sub-Keplerian Magnetic Inhibition Regime**: \(R_a < R_M < R_{co}\)
  
  In this regime, the drag force is sub-Keplerian and the matter can enter the magnetosphere through the Kelvin-Helmholtz Instability (Harding & Leventhal, 1992) and fall onto the neutron star.

In the case where material is captured by the neutron star, it is shocked at \(R_a\) and forms an ‘atmosphere’ above the magnetosphere. The properties of the shell are set by the interaction of the matter and the magnetosphere and define three accretion regimes:

- **Supersonic Propeller Regime**: \(R_{co} < R_M < R_a\)
  
  In this regime the magnetosphere is supersonic with respect to the matter. Turbulent motions are generated at \(R_M\) which convect the dissipated rotational energy of the neutron star to the outer boundary of the ‘atmosphere’. No matter can penetrate the magnetosphere in this regime.

- **Subsonic Propeller Regime**: \(R_M < R_a, R_{co}, \dot{M}_w < \dot{M}_{lim}\)
In this case, the centrifugal barrier does not exist but matter cannot enter the magnetosphere directly. It can enter however by the Kelvin-Helmholtz Instability and Bohm diffusion. This regime is applicable until the accretion rate, $\dot{M}_{\text{lim}}$, is reached at which point radiative gas cooling dampers convective motions, allowing direct accretion on to the NS surface.

- **Direct Accretion:** $R_M < R_a, R_{co}, \dot{M}_w > \dot{M}_{\text{lim}}$

In this regime, the matter outside the magnetosphere cools efficiently and can fall onto the neutron star at the rate at which it flows toward the magnetosphere. There is no gating in this regime, which corresponds to the standard accretion regime which achieves the highest mass-to-luminosity conversion efficiency.

A schematic diagram of the possible accretion mechanisms outlined in this model is shown in Figure 1.15. Transition between different accretion regimes is invoked to explain the abrupt changes in luminosity of SgXRBs including 'off-states' and flaring behaviour. Doroshenko et al. (2011) utilised this framework as a possible explanation for the 'off-states observed by Vela X−1 by invoking magnetic field strengths of $2 - 10 \times 10^{13}$ Gauss. However, subsequent measurement of the neutron star magnetic field using CRSFs by using *NuSTAR* are interpreted as a surface magnetic field of $2 \times 10^{12}$ G, casting doubt on the applicability of this framework to explain such observed temporal features.

Subsequent work by Bozzo et al. (2016a) combined the hydrodynamic simulations of Oskinova et al. (2012) with the above theoretical framework to model the accretion and subsequent luminosity generated by the non-stationary stellar wind. The authors found that across the parameter space containing typical values for SgXRBs, all the accretion regimes are realised and despite inherent simplifications in the theoretical framework, significant reductions in the expected luminosities of SgXRBs are achieved by including the effects of the magnetic and centrifugal barriers.

Another theoretical framework invoking transition between accretions regimes to explain the observed behaviour of SgXRBs is the theory of quasi-spherical accretion (Shakura et al., 2012). In the slowly rotating pulsars found in SgXRBs, the corotation radius is expected to be much larger than that of the magnetospheric radius and hence should have no influence on the accretion mechanisms in these systems. In the theory of quasi-spherical accretion, there are three possible regimes under which material can be accreted by the neutron star once it is captured at the accretion radius. The key aspect in this theory is the mechanism by which infalling plasma is cooled. Above a luminosity of $L_\ast \sim 4 \times 10^{36}$ erg s$^{-1}$ the direct accretion regime is realised as the material falling towards the neutron star is rapidly and efficiently cooled by Compton processes allowing entry into the magnetosphere by the Rayleigh-Taylor Instability. This regime is also known as supersonic accretion.
Figure 1.15: Schematic diagram of the interaction between a magnetised neutron star and the supergiant stellar wind. The relative position of the 3 characteristic radii for each regime are shown. The magnetospheric radius is shown as a solid line, the corotation radius as a dashed line and accretion radius as a dotted line. The wavy solid line illustrates when a regime is Kelvin-Helmholtz unstable at the magnetospheric radius. Small eddies represent convective motions where they appear. Taken from Bozzo et al. (2008b).

in this framework.

The model was further expanded by Shakura et al. (2013) to show that below $L_*$, two possible regimes of subsonic accretion are realised. In these regimes matter settles on the rotating magnetosphere in a quasi-static shell as the photon field is insufficient to cool the material rapidly enough to enter the magnetosphere. For moderate luminosities of $\sim 10^{36}$ erg s$^{-1}$, the plasma at the base of this shell is cooled by Compton processes in the equatorial region of the magnetosphere until it can penetrate the magnetic barrier by the Rayleigh-Taylor Instability. In this regime, the accretion rate into the magnetosphere is such that the accretion column optical depth is greater than one and hence the emitted photons exhibit a fan beam geometry. A decrease in the rate of material entering the magnetosphere (and hence luminosity) leads to the accretion column becoming optically thin and the photon field takes on the pencil beam configuration. The critical luminosity for this transition is $L_\text{t} \sim 3 \times 10^{35}$ erg s$^{-1}$. In this configuration, the photon field density at the magnetospheric equator is reduced and Compton processes becomes inefficient in cooling the material. Instead, the plasma is cooled by radiative processes (bremsstrahlung) before entering the magnetosphere by the Rayleigh-Taylor Instability. The cooling of the material by bremsstrahlung is inefficient relative to Compton scattering and hence the mass accretion rate during the radiative regime is up to a factor of 30 smaller than that during the Compton cooling regime. A schematic diagram of the possible regimes in the theory of quasi-spherical accretion is shown in Figure 1.16. Transition from the Compton to radiative cooling regime in this model was invoked by Shakura et al. (2013) to explain the off-states observed in the SgXRBs, Vela X$-1$, GX 301$-2$ and 4U 1907+09.

As discussed above, the observed distribution of wind-fed SgXRBs in the $P_{\text{spin}} - P_{\text{orb}}$ shows no correlation between these two fundamental system parameters. This is explained by considering the accretion torques imparted upon
the accreting neutron star by the stellar wind. Due to the chaotic nature of the stellar winds, unlike the decretion disc in BeXRBs, the material accreted in the stellar wind can be both prograde and retrograde with respect to the neutron star spin. This lack of preferred orientation within the stellar wind accreted by the neutron star causes both spin up and spin down phases and hence the position in the Corbet Diagram of the population as a whole shows no clear correlation.

1.3.3 Supergiant Fast X-ray Transients - SFXTs

Supergiant fast X-ray transients (SFXTs) are a subclass of wind-accreting high mass X-ray binary recognised as a separate class over the course of the INTEGRAL mission. In the hard X-ray band (20–100 keV), SFXTs exhibit short flaring behaviour lasting a few hours with peak fluxes of up to a few hundred milliCrab before returning to a deep quiescent state, leading to them initially being referred to ‘fast X-ray transients’ (Sguera et al., 2005). Due to the sporadic nature of SFXT flares, their discovery was also facilitated in the main thanks to the wide field of view and high instantaneous sensitivity of the IBIS instrument, combined with the INTEGRAL core programme observing strategies such as the Galactic Plane Scan.

The ability of the IBIS and JEM-X instruments to localise the positions of new fast X-ray transients to arcminute precision allowed follow up observations with soft X-ray instruments such as Swift, Chandra and XMM-Newton that further constrained source positions to arcsecond precision. Accurate X-ray source positions facilitated optical and infra-red observations leading to the identification...
of the companion stars as OB supergiants and the classification of SFXTs as a subclass of the wind-fed SgXRBs (see for example the works of Masetti et al. 2006a,b; Chaty et al. 2008; Bodaghee et al. 2012). Observations in these bands using SED fitting of the companion stars have subsequently been used to infer source distances of between 3 and 13 kpc as well as stellar wind properties such as mass loss rate and terminal wind velocity (Rahoui et al., 2008; Giménez-García et al., 2016). A list of currently known SFXTs along with source distance and detected periodicities is given in Table 1.1.


<table>
<thead>
<tr>
<th>Name</th>
<th>Distance (kpc)</th>
<th>Orbital Period (days)</th>
<th>Spin Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGR J08408−4503</td>
<td>2.7, 3.4±0.35 (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGR J11215−5952</td>
<td>6.2, 8, 7.3±0.68 (1)</td>
<td>164.6</td>
<td>186.78±0.3</td>
</tr>
<tr>
<td>IGR J16328−4726</td>
<td>7.2±0.3 (2)</td>
<td>10.068±0.002 (3,4)</td>
<td></td>
</tr>
<tr>
<td>IGR J16418−4532</td>
<td>13</td>
<td>3.753±0.004</td>
<td>1212 ±6</td>
</tr>
<tr>
<td>IGR J16465−4507</td>
<td>9.5±14.1, 12.7±1.3 (1)</td>
<td>30.243±0.035</td>
<td>228±6</td>
</tr>
<tr>
<td>IGR J16479−4514</td>
<td>4.9, 2.8</td>
<td>3.3194±0.001</td>
<td></td>
</tr>
<tr>
<td>IGR J17354−3255</td>
<td>8.5 (5)</td>
<td>8.4474±0.0017 (6,7)</td>
<td></td>
</tr>
<tr>
<td>XTE J1739−302</td>
<td>2.7</td>
<td>51.47±0.02</td>
<td></td>
</tr>
<tr>
<td>IGR J17544−2619</td>
<td>3.6</td>
<td>4.926±0.001</td>
<td>71.49±0.02</td>
</tr>
<tr>
<td>SAX J1818.6−1703</td>
<td>2, 2.1, 2.7±0.28 (1)</td>
<td>30.0±0.2</td>
<td></td>
</tr>
<tr>
<td>IGR J18410−0535</td>
<td>3.2±2.0</td>
<td>7.8±0.74</td>
<td></td>
</tr>
<tr>
<td>IGR J18450−0435</td>
<td>6.4±0.76 (1)</td>
<td>5.7195±0.0007</td>
<td></td>
</tr>
<tr>
<td>IGR J18483−0311</td>
<td>3</td>
<td>18.55 ±0.03</td>
<td>21.0526±0.0005</td>
</tr>
</tbody>
</table>

Long-term monitoring of SFXTs using INTEGRAL and Swift allowed the discovery of X-ray modulation attributed to the orbit of the compact object around the supergiant companion. Periodicities found in these systems are similar to those found in the classical SgXRBs and range from 3.3 days to 51.47 days. However, unlike the SgXRBs, a number of the SFXT systems have been found to have eccentric compact object orbits with eccentricities found to be 0.4 or greater in SAX J1818.6−1703 and XTE 1739−302 (Zurita-Heras & Chaty, 2008; Drave et al., 2010). The only exception to the general trend of orbital periodicities is IGR J11215−5952. An orbital period of ∼330 days was initially proposed for this system based on outbursts recurrent on this time scale, however the subsequent detection of an outburst at the proposed apastron passage led to the period determination being refined to 165 days (Sidoli et al., 2006, 2007). Subsequent soft X-ray observations have revealed a number of periodicities in a wide range from 21–1212 s that are interpreted as the spin periods of neutron stars, however currently under half of the known SFXTs have associated spin periods. The detection of spin
Figure 1.17: Corbet diagram of HMXBs (Corbet, 1986) as shown in Figure 1.6 with the locations of SFXTs with known orbital and spin periodicities marked. Be/X-ray binaries are denoted by blue crosses, wind-fed supergiant X-ray binaries (SgXRBs) by red circles and Roche Lobe Overflow (RLOF) supergiant X-ray binaries by black squares. SFXTs are marked with green triangles. Period data are taken from Liu et al. (2006) and Bodaghee et al. (2007).

Initial detections of SFXTs in the hard X-ray band by INTEGRAL were found to reach peak luminosities in the most extreme cases of $10^{36–37}$ erg s$^{-1}$, though the detection of an outburst reaching $3 \times 10^{38}$ erg s$^{-1}$ from IGR J17544–2619 using Swift expanded the potential maximum luminosities of these sources to Eddington-limited values for accreting neutron stars (Romano et al., 2015).
Observations of SFXTs outside these large outburst events with soft X-ray telescopes such as *Chandra* have revealed periods of deep quiescence with luminosities reaching $10^{32} \text{ erg s}^{-1}$ (in’t Zand, 2005), suggesting dynamic ranges of $10^6$ are possible in SFXTs. Sources displaying a dynamic range in excess of $10^3$ are often referred to as prototypical SFXTs, examples of which include IGR J17544–2619 and XTE 1739–302. Other systems such as IGR J16465–4507 have been found to have a much smaller dynamic range in flux of $\sim 100$ (Clark et al., 2010), that is more akin to the dynamic range in SgXRBs though the fast flaring behaviour in these source led to their classification as ‘intermediate SFXTs’.

Due to the sensitivity limits of *INTEGRAL* and observational scheduling constraints for soft X-ray instruments, the initial picture of SFXT behaviour was that of a bimodal distribution of flux values with the source either being in outburst or quiescence. In the case of a few sources, *BeppoSAX* initially classified them as ‘burst-only’ sources. This picture was radically altered by the long-term monitoring programme of SFXTs using *Swift* (Sidoli et al., 2008; Romano et al., 2011a). Outside of outburst periods, it was found that SFXTs in fact occupy moderate luminosities of $10^{33}–34 \text{ erg s}^{-1}$ for the majority of the time, suggesting that these systems persistently accrete material though at a much reduced rate and only occasionally experience periods of deep quiescence or outbursts. This monitoring has also shown that large outbursts reaching $> 10^{36} \text{ erg s}^{-1}$ in a number of systems have an orbital phase bias toward periastron, however systems exist where there is no apparent phase preference in the detected outbursts. Two SFXTs have also been observed to be eclipsing systems suggesting the inclinations of the orbit is sufficient such that the neutron star is obscured by the supergiant for part of the binary orbit. The first system with a detected eclipse was IGR J16479–4514 where the eclipse was observed using *XMM-Newton* and lasted 0.6 days or approximately 20% of the neutron star orbit (Bozzo et al., 2008c). The second was observed in IGR J16418–4532 by Drave et al. (2013) using combined *XMM-Newton* and *INTEGRAL* observations and also lasts approximately 20% of the orbit (0.75 days). Along side these two systems, there is also one other SFXT with potential eclipsing behaviour (IGR J17354–3255, Ducci et al. 2013) and one candidate SFXT that has shown an eclipse (IGR J16207–5129, Bodaghee et al. 2010).

Long term monitoring of these sources also allowed quantitative studies of the X-ray activity of the SFXTs. Paizis & Sidoli (2014) used nine years of *INTEGRAL*/IBIS data to evaluate the duty cycles for a large sample of SFXTs. In the case of systems showing large dynamic ranges of up to five orders of magnitude, the authors find that the duty cycles (the amount of time the source spends with a luminosity $L \gtrsim 10^{35} \text{ erg s}^{-1}$) of these sources where the are typically below 1%, while the sample as a whole have duty cycles less than 5% (though typically less than 1%). Comparing this with typical HMXBs such as Vela X–1 and 4U 1700377 where duty cycles are $\sim 80\%$, it is clear that SFXTs are an underluminous class of
SgXRBs in the hard X-ray band. Romano et al. (2014b) studied the long-term properties of three unexplored SFXTs in the soft X-ray band using Swift/XRT relative to prototypical systems and found that these SFXTs have inactivity duty cycles of greater than 60%. The difference between the duty cycles in the hard and soft X-ray bands likely arises from the increased sensitivity of Swift/XRT relative to INTEGRAL/IBIS.

The X-ray spectra of SFXT flares are often characterised by a cutoff power law with hard photon indices of 0.5–2.0 and high energy cutoffs in the range 10–30 keV (Sguera et al., 2007b; Sidoli et al., 2009a,c), consistent with the spectra of young X-ray pulsars. Another spectral feature of SFXTs is the enhanced absorbing column densities of $>10^{22}$–$10^{23}$ cm$^{-2}$—far exceeding the Galactic line-of-sight value, the source of which is often attributed to the dense stellar winds of the supergiant companion (for example Walter et al. 2006, Sidoli et al. 2009c). Other spectral features such as thermal components have been observed in SFXTs. The clearest observations of thermal components have been in the intermediate SFXTs, IGR J18450−0435 and IGR J08408−0433 (Zurita Heras & Walter, 2009; Sidoli et al., 2009b) where the emission features are consistent with the temperatures and sizes of hot spots on the neutron star where material has been funnelled to the magnetic poles. Over the course of flares, some SFXTs spectra have shown a ‘harder-when-brighter’ effect where the photon index of the power law tends to decrease for increasing flux, which has also been observed to happen in the spectra of other HMXBs (Sidoli et al., 2012, 2013; Odaka et al., 2013; Romano et al., 2014a; Kennea et al., 2014). Outside of outbursts, the quiescent spectra of SFXTs have been found to be particularly soft with photon indices $\Gamma \sim 6$ in the case of a Chandra observation of the prototypical SFXT, IGR J17544−2619 and this spectrum is also consistent with black body emission from the neutron star stellar surface (in’t Zand, 2005). Recently, the launch of the NuSTAR X-ray telescope has enabled detailed spectral studies of accreting compact objects in the 3–79 keV band thanks to the focussing nature and high spectral resolution of the telescope. Observations of IGR J17544−2619 by Bhalerao et al. (2015) led to the first direct measurement of a neutron star magnetic field in an SFXT by detecting the presence of a CRSF in the X-ray spectrum at 17 keV suggesting an intrinsic magnetic field strength of $1.4 \times 10^{12}$ Gauss that is consistent with magnetic fields measured in other supergiant binaries. However, subsequent observations of this source again with NuSTAR could not confirm the presence of the cyclotron line suggesting the detection of this magnetic field strength is tentative (Bozzo et al., 2016b).

In order to explain the observed dynamic X-ray behaviour of SFXTs, in’t Zand (2005) and later Walter & Zurita Heras (2007) proposed that the interaction of the neutron star with dense clumps of stellar wind material (as described in Section 1.3.2) drove the large X-ray outbursts observed with INTEGRAL. Outside these interactions, the neutron star accretes from the rarefied intra-clump medium.
providing the observed deep quiescent states. In order to unify the picture of accretion across SFXTs and SgXRBs, Chaty (2008) suggested orbital geometry could be the main distinction between the classes. In this model, the SgXRBs have short, circular orbits and hence the neutron star accretes persistently from the dense stellar wind in this region. SFXTs on the other hand have eccentric orbits and as a result rarely encounter the dense stellar wind region, leading to short periods of activity and long quiescent phases. Outbursts at phases other than periastron can be explained with sporadic encounters with over-densities that intersect the binary orbit. The occurrence of these however should be rare. Negueruela et al. (2008b) suggested that within this model, SFXTs fall into two classes: (1) Systems with circular orbits where the compact object orbit is outside a region where the wind density is enhanced and (2) systems where the neutron star is in a wide eccentric orbit around the supergiant. For Case (1), the orbit of the compact object does not bring it to within $\sim 2R_*$ of the supergiant. In this region the stellar wind is denser and the compact object is less likely to encounter a clump resulting in the system experiencing only moderate X-ray luminosity variations. This is the explanation for the so-called intermediate SFXTs. For Case (2), the eccentric orbit of the compact object means that at periastron the compact object enters this region of denser wind, making interaction with a clump more likely. Conversely, at apastron the compact object is far from the supergiant, meaning interaction with a clump is unlikely. This leads to periods of quiescence or low level accretion. In these models, the difference between SgXRBs and SFXTs is purely a function of orbital geometry, with SgXRBs having short orbits inside the dense stellar wind and SFXTs having eccentric orbits making emission sporadic. These different classes are schematically illustrated in Figure 1.18. In these schematics, the persistent SgXRBs would orbit continually in the shaded region of increased stellar wind density.
Ducci et al. (2009) also formulated a model for the structure of blue supergiant winds and their effect on accretion in supergiant X-ray binaries. In this work, the authors computed the expected X-ray light curve for Bondi-Hoyle accretion with the modification that the wind is inhomogeneous (schematic shown in Figure 1.19). In this model the clumps in the wind are confined by ram pressure of the ambient stellar wind and as the clumps move out from the supergiant, they expand and become less dense. The typical clump size and mass in this model range from $10^6-11$ cm and $10^{16-20}$ g respectively. As with the model of Negueruela et al. (2008b), for increasing orbital period, the number of flares decreases as the compact object accretes from lower density clumps and increasing the eccentricity increases the density range of accreted clumps leading to a larger range in emitted luminosities. This model was used to explain the observed X-ray behaviour of the classical HMXBs Vela X−1, 4U 1700−377 and the SFXT, IGR J11215−5952 though required a decrease in overall mass loss rate from the supergiant by a factor of 3−10 compared with values from UV studies assuming a homogeneous outflow.

In order to explain the observed periodic outbursts from IGR J11215−5952, anisotropic winds, rather than clumpy winds were proposed by Sidoli et al. (2007). The observed shape of the outbursts was interpreted as evidence that the outflow
from the supergiant is not spherically symmetric. Short sharp outbursts can be explained by the presence of an equatorially enhanced wind component that is denser and slower than the polar wind (such as is seen in the solar wind of the Sun in Parker’s solar wind model) and inclined with respect to the orbital plane of the compact object. This is also similar to the explanation of outburst behaviour seen in BeXRBs. This model has been used to explain the different phenomenologies in SFXT outbursts with the differing outburst profiles due to orientation of the orbital plane with respect to the enhanced wind component and the geometry of the enhanced component. This model also allows for outburst generation at other phases other than periastron. If the equatorial component intersects the orbit of the compact object at other phases than periastron, then two regions of enhanced wind densities can be produced leading to production of outbursts outside of periastron. This model was also invoked by Drave et al. (2010) to explain the presence of two ‘side peaks’ in the INTEGRAL/IBIS phase folded light curve of the long period SFXT XTE J1739−302 (P = 51.47 days). These ‘side peaks’ are 4 and 5σ features in the folded curve approximately one fifth of the orbit either side of periastron that were used to infer a lower limit in the orbital eccentricity of e > 0.16 assuming the enhanced equatorial structure is inclined at 90° to the neutron star orbit.

Other effects invoked to explain the observed X-ray behaviour of SFXTs include magnetic gating mechanisms. Bozzo et al. (2008b) applied their model incorporating magnetic and centrifugal barriers, as outlined in Section 1.3.2, to SFXTs. The authors found that irrespective of the accretion inhibition method, the slow rotation of the neutron stars in SFXTs requires that the associated magnetic field strengths must be magnetar-like, of order 10^{14} Gauss. As described above, field strengths of this magnitude have yet to be observed in this class of sources. The subsequent work of Bozzo et al. (2016a), where simulated stellar wind density and velocity profiles were included as inputs to this model, still requires strong neutron star magnetic fields. The authors do however suggest that future studies including multi-dimensional stellar wind models, gravitational focus and stellar wind ionisation by the neutron star could show the applicability in explaining the differences between SFXTs and SgXRBs.

In recent years, the quasi-spherical accretion framework of Shakura et al. (2012) and its subsequent elaboration (Shakura et al., 2013) have been used to describe the accretion phenomenology observed in HXMBs including a number of SFXT systems (Drave et al., 2013, 2014; Shakura et al., 2014; Fiocchi et al., 2016; Sidoli et al., 2016; Postnov et al., 2017; Lutovinov et al., 2017). In this model, SFXTs occupy the radiative cooling regime for the majority of time, with captured stellar wind material mediated through the hot, quasi-static shell until it cools sufficiently to enter the magnetosphere by the Rayleigh-Taylor Instability. The rate at which the material cools and hence the magnetosphere mass loading rate is set by the density at the base of the shell. When the mass entry rate is sufficient, the accretion
column becomes optically thick, the photon beam geometry switches to a fan beam and the dominant cooling mechanism becomes Compton cooling. This more efficient regime increases the accretion rate through the magnetosphere and hence drive the observed flaring behaviour. Further development of the model (Shakura et al., 2014), suggested that bright flares seen in SFXTs that reach $>10^{36}$ erg s$^{-1}$ can be caused by a sporadic increase in the accretion rate through capture of magnetised stellar wind. Recent studies have shown that approximately 10% of OB-stars have magnetic field strengths of a few kGauss (for a review see Donati & Landstreet 2009). The magnetisation of the stellar wind can result in two main effects. One possible effect is that of magnetic reconnection, where the magnetic fields of the plasma and the NS magnetosphere reconnect in a manner similar to dayside reconnection observed in the Earth’s magnetosphere. The second is the reduction in velocity of clumps due to the presence of magnetic fields tangential to the direction of motion. The reduction in velocity of the magnetised wind increases the Bondi radius (Equation 1.26) and hence more material can be captured. Magnetic reconnection then enhances the magnetospheric entry rate, increasing the number of X-ray photons and hence Compton cooling leading to unstable accretion of the entire shell on the free fall time scale. Studies of the cumulative luminosity distributions of SFXTs (Paizis & Sidoli, 2014) find a power law shape distribution indicative of self-organised criticality systems. These systems are characterised by an avalanching effect whereby built up matter or energy is released once a critical threshold is reached. The transition between accretion regimes in the theory of quasi-spherical accretion is a potential example of this phenomenon.

1.3.4 Roche Lobe filling Supergiant Binaries - RLOF SgXRBs

In some SgXRBs the companion star fills its Roche Lobe and material is transferred to the compact object through the $L_1$ point. There are currently only four known examples of these systems hosting neutron stars (Cen X−3, LMC X−4, SMC X−1, RX J0648.1−4419) and a handful of black hole systems (e.g Cyg X−1, Cyg X−3 and LMC X−1). RLOF SgXRBs are observed as persistent sources in the X-ray band with average luminosities in the range $10^{37−38}$ erg s$^{-1}$. The exact details of the Roche Lobe overflow in these systems is not fully understood as for binary systems with extreme mass ratios such as supergiant binaries, any mass transfer is expected to be unstable and rapidly shrinks the binary orbit leading to the merger of the binary components. Instead, it is believed that the companion stars almost fills the Roche Lobe and the strong stellar winds and warping of the companion due to the gravitational influence of the compact object result in the focussing of the winds through the inner Lagrangian point. The infalling matter subsequently forms an accretion disc and the physics of which are similar to that observed in LMXBs.

In the Corbet Diagram, RLOF SgXRBs occupy a region characterised by both
short orbital and spin periods (where the compact object is a NS). This class of object appear to show anti-correlation between the spin and orbital periods as noted by Corbet (1986), however it is difficult to draw any conclusions from the data due to the small number of systems presently known.

1.4 Thesis Outline

In this thesis I present the analysis of three observations of High Mass X-ray Binaries around the compact object periastron passage in order to categorise the accretion processes inherent to each object. In this chapter, I have outlined the known properties of neutron stars and their behaviour when found in binary systems, in particular I have focussed on high mass systems as these are the main focus of this thesis. Chapter 2 provides an overview of X-ray telescopes in general followed by specific details of the suite of observatories utilised in this thesis. It also outlines temporal analysis techniques used in order to search data for the presence of characteristic periodicities in HMXBs. Chapter 3 presents the results of phase targeted temporal and spectral analysis of the prototypical supergiant fast X-ray transient SAX J1818.6−1703. This source was observed with XMM-Newton for a total of 30ks and I also present the results of contemporaneous hard X-ray data from INTEGRAL. Chapter 4 presents the analysis of two periastron targeted XMM-Newton observations of the intermediate SFXT IGR J18450−0435, along with simultaneous INTEGRAL data. Chapter 5 presents the results of a multi-wavelength study of the SMC BeXRB IGR J01217−7257. I present analysis of INTEGRAL, OGLE and Swift data, archival RXTE presenting the discovery of the source along with the characterisation of the X-ray-Optical behaviour of the source around periastron. In Chapter 6, I compare and contrast the results presented in the previous chapters and comment on the future direction and challenges in the field.
Chapter 2

Methods

In this chapter, I discuss important X-ray instruments and techniques used throughout this thesis. I discuss the origin and capabilities of three telescopes from which the majority of the data in this thesis are taken. In Section 2.2, I outline methods for detection of periodic signals used in this thesis, in particular these methods are used in Chapter 5 to obtain the main scientific results.

2.1 X-ray telescopes

Studies of the X-ray sky began over half a century ago with detectors placed on sub-orbital rockets and balloon missions. The discovery of the first extrasolar X-ray source, Scorpius X−1 by Giacconi et al. (1962) and subsequent discoveries of bright sources such as Hercules X−1 and Cygnus X−1 prompted the development of space-based X-ray missions to probe the nature of, and search for more, extrasolar sources. Over the course of the next fifty years, X-ray telescopes have improved in sensitivity by nine orders of magnitude and have been used to study a vast array of objects from active galactic nuclei to stars and X-ray binaries, revealing an extreme and dynamic sky. The telescopes discussed below have been key to discovering and categorising new X-ray objects for almost twenty years and I outline the capabilities that have facilitated these discoveries.

2.1.1 INTErnational Gamma Ray Astrophysical Laboratory - INTEGRAL

The INTErnational Gamma Ray Astrophysical Laboratory, INTEGRAL (Winkler et al., 2003), is an ESA project with instruments and science data centre funded by ESA member states, the Czech Republic and Poland, and with the participation of Russia and the USA. Launched in 2002 from Baikonur, Kazakhstan on a PROTON
launcher provided by the Russian Academy of Sciences and Rosaviakosmos, **INTEGRAL** was inserted into a 72 hour highly elliptical orbit. With an inclination of 52.2 degrees and perigee and apogee heights of 9000 and 150,000 km respectively, the orbit is optimised to provide long, uninterrupted observations of objects in the sky avoiding radiation belts in order to keep a near-constant background. In order for **INTEGRAL** to comply with ESA safety regulations regarding disposal of satellites at the end of their lifetime, the orbit of **INTEGRAL** was modified in early 2015 such that the satellite will re-enter the Earth’s atmosphere in 2029, resulting in the orbital period of **INTEGRAL** now being approximately 2 days and 16 hours. The timely execution of these manoeuvres allow for maximum use of the remaining and hence maximise the science return for the remainder of the satellite lifetime.

There are two primary instruments and one X-ray monitor carried by **INTEGRAL** allowing it to cover a large energy range from soft X-ray to gamma-ray using ‘Coded Aperture’ techniques. The ‘Imager on Board the **INTEGRAL** Satellite’ (IBIS, Ubertini et al. 2003) is the main imaging instrument carried by **INTEGRAL** that has a 30 square degree field of view (FOV, 9 square degrees fully coded) and allows for high angular resolution imaging from 15 keV–10 MeV as well as coarse broad-band spectroscopy. The ‘Spectrometer on **INTEGRAL**’ (SPI, Vedrenne et al. 2003) performs high resolution gamma-ray spectroscopy and coarse imaging in the 20 keV–8 MeV energy range. The ‘Joint European X-ray Monitor’ (JEM-X, Lund et al. 2003) is the X-ray monitor of **INTEGRAL** operating in the 3–35 keV range and is composed of two separate, co-aligned X-ray telescopes (JEM-X1 and JEM-X2) that allow for fine imaging and coarse spectroscopy. **INTEGRAL** is also equipped with an optical monitor (OMC, Mas-Hesse et al. 2003) for simultaneous V-band monitoring of X-ray sources thanks to its 5 square degree field of view (FOV). A diagram of **INTEGRAL** is shown in Figure 2.1 with each of the aforementioned co-aligned instruments marked.

Until the launch of **NuSTAR** in 2013 (Harrison et al., 2013), hard X-ray and gamma-ray telescopes used coded aperture techniques to perform imaging and spectroscopy due to the infeasible nature of focussing these wavelengths of the electromagnetic spectrum. In a coded aperture telescope, a ‘mask’ is placed between the position sensitive detectors of the detector plane and the source that consists of a series of transparent and opaque cells to create a shadow of the mask pattern on the detector plane. The resulting image on the detector plane is referred to as a ‘shadowgram’. In reality, there will often be more than one source in the field of view. The effect of multiple sources is to produce a shadowgram that is dependant on the relative position and intensities of the sources. The shadowgram can be converted into an image of the sky by correlating the mask pattern with the shadowgram to create a correlation map, giving the relative positions and intensities of sources in the FOV. This map can be back-projected to form a sky image with knowledge of the satellite orientation, position and pointing direction.
**Figure 2.1:** Exploded diagram of the *INTEGRAL* satellite. The IBIS and JEM-X coded masks and detector planes can be seen as part of the main body of the satellite with SPI co-aligned. Image Credit ESA/Medialab.
Table 2.1: Key parameters of the IBIS and JEM-X instruments located on board INTEGRAL. Adapted from Winkler et al. (2003)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IBIS</th>
<th>JEM-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>15 keV–10 MeV</td>
<td>3–35 keV</td>
</tr>
<tr>
<td>Detector Area (cm²)</td>
<td>2600</td>
<td>500</td>
</tr>
<tr>
<td>Sensitivity (ph cm⁻² s⁻¹ keV⁻¹)</td>
<td>3.8 × 10⁻⁷ (3σ in 10⁶ s @ 100 keV)</td>
<td>8.5 × 10⁻⁵ (3σ in 10⁶ s @ 30 keV)</td>
</tr>
<tr>
<td>Field of View (fully coded)</td>
<td>9° × 9°</td>
<td>4.8°</td>
</tr>
<tr>
<td>Field of View (zero response)</td>
<td>30° × 30°</td>
<td>13.2°</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>12’</td>
<td>3’</td>
</tr>
<tr>
<td>Source location (10σ source)</td>
<td>≤1’</td>
<td>≤30”</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>8 keV @ 100 keV</td>
<td>2 keV @ 22 keV</td>
</tr>
</tbody>
</table>

This process is executed during analysis of the observation by the Offline Science Analysis (OSA) software in the case of INTEGRAL (Goldwurm et al., 2003). The high energy nature of the X-ray and gamma-ray photons requires that the mask be made out of a dense substance, in most cases tungsten. For IBIS, the mask is 16 mm thick with 50% of the cells in the mask being opaque to energies of up to 10 MeV, while both JEM-X telescopes have masks that are 75% opaque to photons in the 3–35 keV energy range. The advantage of using coded aperture techniques is the near-perfect background subtraction resulting from the detector pixels unable to see the source being used as a contemporaneous background measurement.

The field of view of a coded mask telescope is determined by the dimensions of the mask, detector and the distance separating the two. Often, to maximise both the sensitivity and field of view of the telescope, masks are made larger than the detector plane. This has the effect of creating two zones in the field of view, the fully coded field of view (FCFOV) and the partially coded field of view (PCFOV). In the FCFOV, all the source intensity incident on the detector plane is modulated by the mask, whereas in the PCFOV only a fraction is modulated by the mask. The co-alignment of all the instruments carried by INTEGRAL means the FCFOVs (IBIS: 9° × 9°, SPI: 16° corner-to-corner, JEM-X: 4.8° diameter) all overlap allowing broad-band energy coverage of sources across all the instruments.

INTEGRAL data presented in this thesis is taken from the IBIS instrument, though quoted source positions are taken from the JEM-X instruments. SPI data is not used due to the coarse imaging and decreased sensitivity provided by this instrument relative to IBIS, which hinder the use of any data in characterising faint sources such as SFXTs and BeXRBs in the SMC. The JEM-X instrument is utilised for source position location due to its arcsecond accuracy relative to the arcminute accuracy of IBIS. The key parameters of the IBIS and JEM-X instruments are summarised in Table 2.1.

Over the course of an orbit (also referred to as a Revolution), INTEGRAL
performs individual pointings lasting approximately 2000 s called Science Windows (ScWs). In order to minimise systematic errors during the image reconstruction process, observations are typically carried out using a dither pattern where the satellite is repositioned every 1200–3600 seconds to a new location around the target source. The dither patterns utilised by INTEGRAL for observations cover either a $5^\circ \times 5^\circ$ rectangle or a 7 point hexagon (one point on source, 6 pointings off centre) depending on the scientific goals of the observation.

The wide field of view and sensitivity of the instruments on board INTEGRAL particularly IBIS and JEM-X make it an excellent facility to survey the Hard X-ray/soft gamma-ray sky. One of the primary mission focusses of INTEGRAL was the study of compact objects and high energy transients and to this end, a number of key monitoring programmes of the Galaxy have been undertaken since launch. The first of these is the Galactic Plane Scans (GPS, first announced by Winkler et al. 2003, subsequently Bazzano et al. 2011 and Fiocchi et al. 2012) that was a key part of the Core Programme of INTEGRAL post-launch. Over the course of a year, the Galactic Plane would be scanned by INTEGRAL every 3 days for a total exposure of 2 Ms, which has led to the discovery of new sources and source types such as the SFXTs and obscured SgXRBs. To date, this programme is ongoing and monitors known sources in the Galactic plane above 18 keV and continues to make science products available to the public\textsuperscript{1}. The Galactic Bulge has also been extensively observed by INTEGRAL as part of the Galactic Bulge monitoring programme (Kuulkers et al., 2007). Like the GPS, the Galactic Bulge was monitored every 3 days during observation periods in the year and was intended to monitor a field of 76 known hard X-ray sources for transient activity and source variability and now regularly monitors 195 sources. This programme has had significant success in characterising the variability observed in this source sample in the 18–40 and 40–100 keV band. As with GPS, the Bulge monitoring is ongoing and data products are available to the public\textsuperscript{2}. As discussed in Chapter 1, the Small Magellanic Cloud has been known to host a population of HMXBs for decades and presents a rich target for study by INTEGRAL in the Hard X-ray band. The SMC has been regularly monitored for almost a decade with a total exposure of approximately 1 Ms per year broken into $\sim$10 observations of 100 ks with between three and seven days separating each observation (Coe et al., 2010). This survey programme has led to the discovery of many new sources, almost all of which are BeXRBs, the discovery of a new population of sources in the Magellanic Bridge and has provided continued monitoring of known BeXRBs for transient outbursts. The work presented in Chapter 5 is a result of the ongoing hard X-ray monitoring of the SMC with INTEGRAL. Figure 2.2 shows the INTEGRAL/IBIS exposure map up to the end of the 14\textsuperscript{th} Announcement of Opportunity\textsuperscript{3} (2018 January 01). In this

\textsuperscript{1}http://gpsiasf.iaps.inaf.it/
\textsuperscript{2}http://integral.esac.esa.int/BULGE/
\textsuperscript{3}https://www.cosmos.esa.int/web/integral/ao14
Figure 2.2: INTEGRAL/IBIS total exposure map in units of $10^6$ s up to the end of the 14th Announcement of Opportunity (2018 January 01). Exposure is greatest along the Galactic Plane and in the Bulge region especially in the regions of bright sources due to the GPS and Bulge monitoring programmes. Both the SMC and LMC are evident below the Galactic Plane with exposures of 10 and 6 Ms resulting from survey programmes (Coe et al., 2010; Grebenev et al., 2012, 2013; Mereminskiy et al., 2016).

It is clear that exposure is greatest along the Galactic Plane and in the Bulge as a result of the aforementioned monitoring programmes. Other areas covered include regions of bright sources along the Galactic Plane. The Magellanic Clouds are also clearly visible below the Galactic Plane with exposures of approximately 10 and 6 Ms for the SMC and LMC respectively. In the case of the SMC this exposure is the result of the SMC monitoring campaign outlined by Coe et al. (2010) while the observations of the LMC are the result of a multi-year observing campaign studying the supernova, SN 1987A (Grebenev et al., 2012) along with dedicated surveys of the region (e.g Grebenev et al. 2013; Mereminskiy et al. 2016).

Figure 2.3 shows the INTEGRAL/IBIS 18–60 keV light curves of SAX J1818.6−1703 from the catalogue of Bird et al. (2016) both with and without filtering for large off axis angles and short exposure times that results in approximately 50% of points in the light curve being discarded in the case of this source. The reasoning behind this filtering is discussed in Section 2.2.1. As a result of the observing strategies of INTEGRAL discussed above, the light curves of sources often have large gaps in the data, however the higher sensitivity of INTEGRAL relative to other coded mask telescopes during pointed observations is such that source variability can be monitored at ScW resolution and short outbursts such as the one seen prior to MJD 53000 can be detected.
Figure 2.3: *INTEGRAL/IBIS* 18–60 keV light curves of SAX J1818.6–1703 from the catalogue of Bird et al. (2016). Top panel: The total light curve from the IBIS survey after 1000 revolutions with no filtering of points applied. Bottom panel: As the top panel with events filtered for short exposures (<200 s) and large off axis angles (> 12°). These filtering criteria result in approximately 50% of points in the unfiltered light curve being discarded.
While *INTEGRAL* was, until recently, the most sensitive and positionally accurate hard X-ray telescope available, the positional uncertainty and sensitivity of the JEM-X monitors in the soft X-ray are insufficient to associate the hard X-ray transients with stellar companions and perform detailed spectral studies of the soft X-ray emission. To this end, the use of more sensitive soft X-ray telescopes compliment the discoveries made by *INTEGRAL* and aide in categorising the physical processes generating the observed source behaviour. I now outline other observatories used in this thesis that carry sensitive soft X-ray telescopes.

### 2.1.2 X-ray Multi-Mirror Mission - *XMM-Newton*

*XMM-Newton*, like *INTEGRAL*, is an ESA mission and part of the Horizon 2000 programme (Jansen et al., 2001). Launched in 1999 from Guiana Space Centre on an Ariane 504 rocket, *XMM-Newton* was placed into a long, elliptical \(~48\text{ hour}\) orbit with perigee and apogee at heights of \(\sim7000\) and \(\sim114\,000\text{ km}\), respectively. Like *INTEGRAL*, this orbit is optimised to reduced particle background and provide long, interrupted observations of sources.

The goals of the *XMM-Newton* mission are to perform broad band imaging spectroscopy of sources in the 0.5–15 keV band down to a limiting flux of \(10^{-15}\text{ erg s}^{-1}\text{ cm}^{-2}\) as well as perform medium resolution spectroscopy below 2.5 keV in order to investigate both Galactic and extra-galactic compact objects. In order to achieve these goals, *XMM-Newton* carries three high-sensitivity X-ray telescopes as well as a co-aligned optical monitor. Unlike *INTEGRAL*, the instruments on board *XMM-Newton* use X-ray focussing optics in order to collect the photons from observed sources. The principle behind X-ray focussing telescopes is that of grazing incidence, whereby X-rays can be reflected off a metallic surface for small angles of incidence. This reflection is non-dispersive and hence X-rays can be focussed for sufficient configurations of polished metallic surfaces. The angle of incidence required, however, becomes smaller for increasing X-ray photon energy and hence until the ambitious design of *NuSTAR*, focussing X-rays above \(\sim10\text{ keV}\) was considered infeasible. Figure 2.4 shows a schematic of the arrangement of mirrors used to focus X-rays. This arrangement often consists of two sets of concentric circular mirrors with very shallow angles of incidence in order to focus the X-rays onto the focal plane where detectors (in the case of *XMM-Newton* these are CCD detectors) record the arrival of the X-ray photons.

There are three main CCD detectors used by *XMM-Newton* comprising the European Photon Imaging Camera (EPIC). Two of these are Metal Oxide Semi-conductors (MOS) and the other uses pn CCDs and is referred to as the pn camera. A detailed discussion of the workings of these devices is beyond the scope of this thesis though readers are referred to Turner et al. (2001) and Str"uder et al.
Figure 2.4: A schematic diagram of the arrangement of mirrors used to focus X-rays. This arrangement often consists of two sets of concentric circular mirrors with very shallow angles of incidence in order to focus the X-rays onto the focal plane. Image Credit: NASA's Imagine the Universe (2001) for details of MOS and pn, respectively. The EPIC cameras allow XMM-Newton to perform sensitive imaging across the range 0.5-15 keV for a 30’ field of view with an angular resolution of 6’’ (Point spread function, full width half maximum). The CCDs can be operated in either full frame or partial window modes resulting in different segments of the CCD being used to record data. In the case of full frame mode, all the CCD pixels are read out and hence the full field of view is covered. Partial window mode on the other hand restricts the amount of the CCD read out and has two sub-modes - large and small window. In the case of MOS, for small window mode a region of 100×100 pixels is read out, whereas in large window an area of 300×300 pixels is read out. For pn in large window, all 12 of the pn CCDs are utilised, whereas for small window, only one quadrant of the central chip is used. These operating modes have import implications when considered the presence of photon pile-up in an observation of a source as each camera and mode has a different threshold before effects of pile-up become significant. These limits are given by Jethwa et al. (2015). Photon pile-up is the effect whereby a number of independent photons are recorded as a single event in a pixel of a CCD camera due to the difference in arrival times between the photons being shorter than the CCD readout time. Pile-up can affect the spectral shape of an observation by reading multiple lower energy photons as a single high energy photon or result in flux loss due to the CCD detecting a pattern it deems invalid. The effects of pile up are considered in the observations presented in Chapters 3 & 4.

Also part of the suite of instruments located on board XMM-Newton is the Reflection Grating Spectrograph (RGS, den Herder et al. 2001). This instrument provides high resolution spectroscopy in the 0.3–2.1 keV energy range and is optimised to search for spectral lines from elements such as carbon, nitrogen, oxygen, neon, magnesium, and silicon. Due to the high absorbing column densities observed in spectra of SgXRBs and SFXTs, much of the emitted flux from the
Table 2.2: Key parameters of the EPIC-pn and EPIC-MOS instruments located on board *XMM-Newton*. Sensitivity limits are taken from Hasinger et al. (2001) and Brunner et al. (2008). These are the result of combining EPIC-pn and EPIC-MOS, hence here I list the same value for each, though the true sensitivity is less than this for the individual cameras.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EPIC-pn</th>
<th>EPIC-MOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>0.15–12 keV</td>
<td>0.15–12 keV</td>
</tr>
<tr>
<td>Detector Area (cm$^2$)</td>
<td>1550</td>
<td>1550</td>
</tr>
<tr>
<td>Sensitivity (0.2–2 keV, erg s$^{-1}$ cm$^{-2}$)</td>
<td>$1.9 \times 10^{-16}$</td>
<td>$1.9 \times 10^{-16}$</td>
</tr>
<tr>
<td>Sensitivity (2–10 keV, erg s$^{-1}$ cm$^{-2}$)</td>
<td>$9 \times 10^{-16}$</td>
<td>$9 \times 10^{-16}$</td>
</tr>
<tr>
<td>Field of View</td>
<td>30$'$</td>
<td>30$'$</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>6$''$</td>
<td>5$''$</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>$\sim 80$ eV</td>
<td>$\sim 70$ eV</td>
</tr>
</tbody>
</table>

A source below 2 keV is absorbed by material local to the system, as well as the interstellar medium along the line-of-sight, resulting in these sources often being below the detection threshold for this instrument. As a result of this, no RGS data is presented for the *XMM-Newton* observations in this thesis. *XMM-Newton* is also equipped with an optical monitor providing coverage between 170 nm and 650 nm of the central 17 square arcminute region of the field of view, allowing simultaneous UV/Optical observations of sources (Mason et al., 2001). As with RGS, data from the optical monitor is not presented in this thesis. As the results from observations with *XMM-Newton* presented in this thesis are taken from the EPIC-MOS and EPIC-pn cameras exclusively, a summary of key parameters of these can be found in Table 2.2.

While a number of surveys have been carried out by *XMM-Newton*, the main usage of the satellite in understanding accretion processes in HXMBs has been pointed observations lasting between 10 and 100 ks. These types of observations have been used to identify spin periods of neutron stars in HXMBs (e.g Haberl & Pietsch 2004), provide accurate source locations and associations of systems with companion stars (e.g Haberl et al. 2015) as well as study the spectral shapes of these sources in order to gain further insights into the accretion processes at work in SgXRBs, SFXTs and BeXRBs (e.g Hill et al. 2005; Walter et al. 2006; Bozzo et al. 2011; Bartlett et al. 2013; Drave et al. 2013, 2014; Fiocchi et al. 2016). Pointed observations of this type are the main focus of the work presented in Chapters 3 & 4.

While the unparalleled soft X-ray sensitivity of *XMM-Newton* has led to many important discoveries in the field of HXMBs, the over-subscription of the telescope coupled with satellite overheads mean it is ill-equipped for regular monitoring of sources in the soft X-ray band. The next telescope I discuss is *Swift*, which with its combination of instruments and ability to rapidly slew to targets has become the workhorse for monitoring sources in the soft X-ray along with its complementary observing strategies to that of *INTEGRAL* in the hard X-ray.
2.1.3 *Swift* Gamma-Ray Burst Mission

*Swift* is a NASA mission with international participation from the UK and Italy launched in 2004 into a near-circular low Earth orbit at an inclination of 20.6° with perigee and apogee at 586 and 601 km, respectively. The main focus of the *Swift* mission is to categorise Gamma-Ray Bursts (GRBs) by measuring fluxes, spectra and producing light curves of detected events using three instruments covering the EM spectrum from ultra-violet to hard X-ray. A primary requirement of the mission was the ability of the satellite to provide afterglow positions of GRBs within 100 s of the detection by the Burst Alert Telescope (BAT, Barthelmy et al. 2005) with an uncertainty of 5 arcseconds. This requires fast slewing of the satellite which also makes *Swift* ideal for detection and follow-up of transient activity from X-ray binaries.

In order to fulfill these scientific goals, *Swift* is equipped with three instruments. The first of these is the Burst Alert Telescope (BAT) which operates in the 15–150 keV band and uses a D-shaped coded aperture mask with 50% of the mask being open to give a very large field of view of 100° × 60° (half-coded). The large field of view is designed to monitor the sky for GRBs and upon detection BAT is capable of localising the source with a 1-4 arcminute accurate position. The instrument has two modes of operation, the first being a scan-survey mode and the second being burst mode. While BAT is waiting for a GRB to occur in the field of view, the instrument performs a hard X-ray sky survey and monitors for hard X-ray transients. The monitoring of X-ray transients is carried out as part of the BAT Hard X-ray Transient Monitor programme (Krimm et al., 2013) which provides near real-time coverage of the sky in the 15–50 keV band. Due to the short orbital period of *Swift* and the wide field of view of the BAT instrument, approximately 88–90% of the sky is scanned by BAT every day with a limiting flux of ~5 mCrab. The aims of this monitoring have been to detect new transients, track changes in flux of known X-ray sources and produce long base line light curves of sources. Light curves of the list of known sources are made available to the public and are available in two different binnings: one-day averages and *Swift* orbital-averages.

Figure 2.5 shows the *Swift*/BAT 15–50 keV transient monitor light curve of SAX J1818.6−1703 with daily average flux bins. The light curve sampling in this light curve is uniform in time, unlike the INTEGRAL light curve of Figure 2.3, due to the much larger field of view of BAT relative to IBIS allowing the full sky to be covered every day. The trade off for such a large field of view is that the instantaneous sensitivity of BAT is lower than IBIS as well as the fact that a source will spend longer outside the full coded field of view, driving large errors on flux values and as such monitoring short term activity can be hampered. It is also worth noting an apparent ~ 350 day periodicity in the large error bars associated with

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4 https://swift.gsfc.nasa.gov/results/transients/
points. This is likely due to Earth’s orbit bringing the satellite into a higher radiation environment around perihelion every year. A comparison of *INTEGRAL*/IBIS and *Swift*/BAT transient monitor light curves of SAX J1818.6−1703 between MJD 54325 and 54403 is shown in Figure 2.6. This temporal window is chosen to illustrate the differences between the sampling and detection of activity between the different instruments. The IBIS light curve is presented with and without filtering for short exposures and large off axis angles and both the daily and orbital average light curves from the BAT transient monitor are shown. While the BAT light curves (bottom two panels) have more uniform sampling than the IBIS light curves (top two panels) and hence allow a more complete picture of the source activity, the sensitivity of BAT on orbital average time scales is such that the flaring behaviour observed in the source in the IBIS light curves around MJD 54390 is difficult to distinguish. The daily average light curve (second panel from the bottom) shows some hint of the activity being detected, however a point with a large associated error results in this period of activity being less clear in the BAT light curves than the *INTEGRAL* ones. This illustrates the complementary nature of the IBIS and BAT instruments as BAT can be used to monitor the long term behaviour of sources with few gaps in observations while the less uniform observing strategies but higher instantaneous sensitivity of *INTEGRAL* allow for more detailed characterisation of flux evolution in sources, especially fainter examples.

*Swift* also carries the *Swift* X-ray telescope (XRT) to complement the monitoring of BAT. *Swift*/XRT is a sensitive soft X-ray imaging spectrometer operating in the 0.2–10 keV energy band with a field of view of 23.6×23.6 arcminutes. Like *XMM-Newton*, XRT uses the principle of grazing incidence to focus X-rays onto a single CCD originally designed for the EPIC program of *XMM-Newton*. Once a transient event has been detected by BAT, a pointing of XRT within the BAT error circle can refine the positional accuracy of the source to within 2.5 arcseconds in under 100 s for a bright source. XRT can also be used to perform medium resolution spectroscopy of detected objects with a resolution of 130 eV at 6 keV. This spectral capability, combined with that of BAT allows for broad-band studies of GRBs and hard X-ray transients. During operation, XRT has the option of several different readout modes depending on the flux of the source under observation. The first of these is imaging mode that uses the CCD in a manner so as to allow the accumulation of photons on the CCD during a single exposure lasting between 0.1 and 2.5 s. In this mode, there is no spectral capability and hence this mode is only used for localisation of bright events. The second operating mode is timing mode (also known as window timing mode or WT mode). In WT mode, the CCD is operated in a rapid readout mode for bright sources that provides timing resolution of either 0.5 ms if no source location is recorded or 5 ms with a 1-D position. This mode is used for spectroscopy of bright sources in the flux range of $10^{-11}$–$10^{-7}$ erg s$^{-1}$ cm$^{-2}$ and for timing studies of XRBs. The final
Figure 2.5: *Swift/BAT* 15–50 keV light curve of SAX J1818.6–1703 taken from the BAT transient monitor (Krimm et al., 2013). A red line is shown at zero counts cm$^{-2}$ s$^{-1}$ for clarity.
Figure 2.6: Comparison of the INTEGRAL/IBIS and Swift/BAT light curves of SAX J1818.6−1703 between MJD 54325 and 54403 for illustration. In all panels a red line is shown at the zero flux level for clarity. Top panel: Unfiltered 18–60 keV INTEGRAL/IBIS light curve from the catalogue of Bird et al. (2016). Second panel: As for top panel with filtered for large off axis angles and short exposures as in Figure 2.3 bottom panel. Third panel: BAT daily average 15–50 keV transient monitor light curve. Bottom panel: BAT 15–50 keV transient monitor light curve with Swift orbital average binning.
operating mode is photon counting mode (PC mode), in which full spectral and positional information is available. This mode is used for the study of faint to moderate brightness sources with fluxes in the range $10^{-14}$–$10^{-11}$ erg s$^{-1}$ cm$^{-2}$. In its operation in studying GRB afterglows that are rapidly variable over orders of magnitude, XRT can automatically assess and select the readout mode based on source flux, however for targeted observations of known sources, often the readout mode is pre-selected. In most observations PC mode is utilised due to the full spectral coverage and positional information provided, however WT is used in observations where a source is suspected of having a short periodicity and the timing resolution afforded by this mode is required.

The final instrument on board Swift is the ultra-violet/optical telescope (UVOT, Roming et al. 2005). UVOT is similar in design to the optical monitor located on XMM-Newton with a field of view of $17 \times 17$ arcminutes and provides UV/optical coverage in the between 160–60 nm simultaneous with the X-ray data taken by XRT. UVOT also provides sub-arcsecond (down to 0.5 arcseconds) source localisations and spectra of observed sources in the field. As with the XMM-Newton optical monitor and RGS, no data from this instrument is presented in this thesis. A schematic diagram of Swift is presented in Figure 2.7 and the key parameters of XRT and BAT are presented in Table 2.3 as these are the instruments from which main scientific results in this thesis are derived.

With its wide field of view and its high cadence coverage of the whole sky, Swift
Table 2.3: Key parameters of the BAT and XRT instruments located on board Swift. Details taken from https://swift.gsfc.nasa.gov/

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BAT</th>
<th>XRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>15–150 keV</td>
<td>0.2–10 keV</td>
</tr>
<tr>
<td></td>
<td>(15–50 keV transient monitor)</td>
<td></td>
</tr>
<tr>
<td>Detector Area (cm$^2$)</td>
<td>5200</td>
<td>135 @ 1.6 keV</td>
</tr>
<tr>
<td>Sensitivity (erg s$^{-1}$ cm$^{-2}$)</td>
<td>$2 \times 10^{-10}$</td>
<td>$2 \times 10^{-14}$</td>
</tr>
<tr>
<td></td>
<td>(1 day, 3σ, transient monitor)</td>
<td>(in 10$^4$ s)</td>
</tr>
<tr>
<td>Field of View</td>
<td>$100^\circ \times 60^\circ$ (half coded)</td>
<td>$23.6^\prime \times 23.6^\prime$</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>20$^\prime$</td>
<td>15$^\prime$</td>
</tr>
<tr>
<td>Source location</td>
<td>1–4$^\prime$</td>
<td>3–5$^\prime$</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>5 keV @ 60 keV</td>
<td>130 eV @ 6 keV</td>
</tr>
</tbody>
</table>

has been used to survey the hard X-ray sky using BAT, resulting in a source catalogue of 1147 sources, 85 of which are HMXBs, from 70 months of operation (Baumgartner et al., 2013). Data from the BAT transient monitor programme has been used to detect signatures of orbital periods in HXMBs (e.g Jain et al. 2009; Romano et al. 2009; Clark et al. 2010; La Parola et al. 2010, 2013; Cusumano et al. 2013) and provide simultaneous hard X-ray data to complement that of XRT and allow broad-band spectral analyses of these sources (e.g Sidoli et al. 2009c; Tsygankov et al. 2012). Long term monitoring of SFXTs with Swift/XRT has been instrumental in understanding the nature of these sources and has revealed the SFXTs do not exhibit a bi-modal behaviour, being either on or off, and instead typically accrete at a luminosity of $10^{33–34}$ erg s$^{-1}$ making these sources an under-luminous class of SgXRBs (Sidoli et al. 2008; Romano et al. 2011a, 2014a, see also Bozzo et al. 2015). This programme has also allowed the study of these sources in soft X-rays in outburst (Sidoli et al., 2009a,b), revealing spectral shapes characterised by absorbed power laws with high energy cut-offs, typical of the spectral of X-ray pulsars. These observations also revealed a hardening of the spectrum during outburst in IGR J17544−2619, variable absorbing column density in XTE 1739−302 and and a soft thermal component in the case of IGR J08408−4503.

**Swift** also detected the brightest outburst seen in an SFXT, during which IGR J17544−219 reached a peak luminosity of $3 \times 10^{38}$ erg s$^{-1}$, expanding the dynamic range of SFXTs to six orders of magnitude presenting challenges for the current models of SFXT accretion (Romano et al., 2015). Outbursts of SFXT prototypes have also triggered BAT and resulting in further broad-band spectral studies of these sources at peak fluxes in an attempt to disentangle the accretion mechanisms at work (Farinelli et al., 2012).

The high position accuracy of **Swift** has been effective in associating known X-ray sources from previous missions with those detected by new telescopes, as well as associating X-ray sources with counterpart stars (e.g Sguera et al. 2007a, 2011).
Ongoing Swift surveys of the SMC have revealed outbursts of SXP 6.85, SMC X–3 and 3XMM J004855.1–734946 (Kennea et al., 2016a,b,c; Coe et al., 2016). Observations of an outburst from IGR J01217–7257 during this survey are presented in Chapter 5.

The telescopes described above each provide unique and complementary facilities that are crucial to categorise the orbital motions of compact objects in HMXBs, the accretion processes generating the observed X-ray behaviour and understanding fundamental properties of neutron stars. In the next section I discuss temporal analysis techniques used in this thesis to search for periodic signals in the data from these satellites.

### 2.2 Techniques for periodicity searches

Time series analysis has long been a feature of X-ray astronomy since being used to locate pulsations in Cyg X–1 and Cen X–3 (Oda et al., 1971; Giacconi et al., 1971). These techniques can be used to identify the orbital motion of compact objects around companion stars and measure the spin period of neutron stars in binaries. In this section, I outline the three methods for periodicity searches in astronomical time series used in this thesis along with methods for determining the signification and associated uncertainty of a detection.

#### 2.2.1 Lomb-Scargle periodogram

The main technique utilised in this thesis to search data sets for periodic signals is the Lomb-Scargle (LS, Lomb 1976; Scargle 1982) periodogram. The LS periodogram performs a least squares fit of sinusoids over a given frequency range to identify periodic modulation of an unevenly sampled data set. For a data set $X_j$ of $N$ points where $j = 1, 2, 3..., N$, the Lomb-Scargle Periodogram, $P_x(\omega)$, is defined as

$$P_x(\omega) = \frac{1}{2} \left\{ \frac{\left[ \sum_{j=1}^{N} \cos \omega(t_j - \tau) \right]^2}{\cos^2 \omega(t_j - \tau)} + \frac{\left[ \sum_{j=1}^{N} \sin \omega(t_j - \tau) \right]^2}{\sin^2 \omega(t_j - \tau)} \right\}$$  \hspace{1cm} (2.1)

where

$$\tan(2\omega \tau) = \frac{\sum_{j=1}^{N} \sin(2\omega t_j)}{\sum_{j=1}^{N} \cos(2\omega t_j)}$$  \hspace{1cm} (2.2)

The frequency range over which the search is performed is generally limited by the length and sampling rate of the data set. The maximum frequency (and hence minimum period) that can be reliably tested is the Nyquist frequency, which is defined as the $0.5 \omega_s$ where $\omega_s$ is the sampling frequency. Conversely, the minimum
frequency (and hence maximum period) that can be reliably tested is $2/L$ where $L$ is the temporal length of the data set. The advent of long base-line data sets such as those from the IBIS surveys (Bird et al., 2004, 2006, 2007, 2010, 2016) and the BAT transient monitor allow searches for periodicities of years to be undertaken, however increasing the length of the data set being searched also increases the computational time required to calculate the periodogram. Often when using these data sets, the lower bound of the frequency range is restricted based on a priori knowledge of the source type. For example, when testing SFXT light curves for the presence of a signal the maximum period tested is often 200 days as this is long enough to encompass the entire range of orbital periodicities discovered in these sources thus far. For the same reasons, searches in BeXRB light curves are often restricted to a range in period space of between 2 and 1000 days.

The use of an LS periodogram for periodicity searches is required when considering long base line INTEGRAL/IBIS light curves as observations of a given source are not uniform in time (Figure 2.3) due to the observing strategies such as the Galactic Plane Scans. The application of the LS periodogram to the raw light curves of sources is complicated by the algorithm weighting each point equally. This has the effect of suppressing true periodic signals in light curves with short exposure or large off-axis angle data points due to the larger errors associated with these points. In order to correct for this effect, light curve data points with an exposure of less than 200 seconds or an off-axis angle greater than 12$^\circ$ are filtered from the original light curve before computing the periodogram. In this thesis, the Lomb-Scargle periodogram is also calculated for XMM-Newton light curves in searches for neutron star spin periods. These data sets have short temporal binnings that can be unevenly sampled due to filtered for flaring background and other satellite effects. These light curves can also suffer from low fractional exposure, which like the IBIS light curves, increase the errors associated with these points. The filtering of these points involves a more heuristic approach whereby the distribution of fractional exposures are considered and those points significantly different from the majority are excluded. Often it is clear which points should be excluded as they typically have fractional exposures less than 0.5 that drive large errors relative to the rest of the light curve where points have fractional exposures closer to 1.

The periodogram calculates an associated LS power at each frequency tested, and in the presence of a periodic signal will produce a ‘spike’ at the corresponding frequency. Significant power can be generated in frequencies other than the true periodic signal as a result of both systematic and statistical noise in the light curves. These sources of noise can be associated with the observing strategy and dither pattern in the case of long-base line data sets such as the IBIS light curves but also random fluctuations can generate power at a range of frequencies. In the case of noise due to telescope pointings, the associated periodicities are relatively easily identified due to their characteristic values. In order to assess the statistical
significance of a detected periodicity in the presence of random noise, or ‘white noise’, a Monte-Carlo test is undertaken. This process is a randomisation test, where the light curve flux values are randomly reordered and the LS periodogram calculated and the peak LS power recorded for this new data set. The confidence level of detection is set by the number of repetitions of this randomisation process. For example, 100 000 simulations are required in order to assess the 99.99% confidence level of detection, where the chance a detected signal is random is 1 in 10 000, or the detection confidence is \( \sim 3.89\sigma \). The power of this randomisation technique is in the use of the data set itself to create the randomised light curve. By keeping the time stamps the same and randomising the flux locations in the light curve, the new data set retains the statistical properties of the original light curve and hence the sampling and frequencies used across the analysis remain consistent.

Figure 2.8 shows the Lomb-Scargle periodogram of the INTEGRAL/IBIS 18–60 keV light curve from the SFXT SAX J1818.6–1703 taken from the IBIS survey after 1000 orbits (Bird et al., 2016). A clear detection of a periodic signal at 29.969 days is visible with a LS power of 77.08. The 99.99% confidence limit, corresponding to an LS power of 17.92 is marked as a red dashed line. In this periodogram there are significant aliasing effects seen, with many peaks above the 99.99% confidence level. This is likely due to the observation pattern of monitoring Galactic Plane and Bulge sources imposing a window function on the data set. The appearance of significant power in harmonics, as seen by the second highest peak, in LS periodograms is often indicative of non-sinusoidal motion such as elliptical orbits, for which the LS periodogram has to add higher harmonics to compensate. Indeed, using standard supergiant parameters, Zurita-Heras & Chaty (2008) inferred an orbital eccentricity of 0.3–0.4 for this source.

Once a detection of a significant signal is found for a source, the uncertainty associated with the periodicity must be calculated. The periodogram is not calculated for a continuous set of frequencies over the given range, instead it is calculated at discrete frequencies within the range that fundamentally limits the degree of accuracy to which the periodic signal can be known. Observationally, the light curve is subject to statistical and systematic uncertainties in the flux measurements as well as the sub-optimal sampling for detection of the intrinsic periodicity. These issues combine to give an uncertainty in the measured periodicity in which the true signal could be located. In order to calculate the uncertainty associated with a signal, another Monte-Carlo technique is used whereby the flux values in the light curve are randomised within their own error bars using a Gaussian distribution. The LS periodogram is calculated for this ‘blurred’ light curve and the period associated with the peak power recorded. This process is typically carried out 10 000 times in order to acquire a distribution with sufficient statistical quality to accurately constrain the periodicity. The resulting distribution of peak periods is then fit with a Gaussian function with amplitude \( A \), mean, \( \mu \),
Figure 2.8: Lomb-Scargle periodogram of the SAX J1818.6−1703 INTEGRAL/IBIS light curve taken from the catalogue of Bird et al. (2016). A peak at 29.969 days is clearly visible with a significance greater than the 99.99% level from the randomisation tests that is marked with a red-dashed line. The corresponding LS powers of the peak and 99.99% significance level are 77.08 and 17.92, respectively.
Figure 2.9: Distribution of peak periods from 10000 blurring simulations of the IBIS 18–60 keV SAX J1818.6−1703 light curve. The best fit Gaussian function is overlaid with mean and standard deviation 29.987 and 0.007, leading to the reported periodicity being 29.987±0.007 days.

With the determination of a significant periodicity in a data set, the light curve can be ‘phase folded’. The phase of each point in the light curve is calculated using the determined period and a zero reference point, referred to as the ephemeris. This zero point can be chosen arbitrarily and common choices include the first time stamp of the tested light curve or bright outbursts of the source. In BeXRBs, the zero phase point is often chosen to be the centroid of a Type-I outburst as these are expected to occur around periastron. In the case of SFXTs, the situation is less clear as these sources do not necessarily show a phase bias in their outbursts. Hence the common choice of an ephemeris in these systems is the brightest outburst of this source which is more likely to have occurred around periastron in all frameworks describing the SFXT phenomenon. With each point in the light curve having an associated phase value, this phase light curve is grouped into an arbitrary
number of bins (typically 20) by calculating the weighted mean of the points in a
given phase bin. The weighted mean and subsequent standard error associated with
each phase bin are given by

\[
\bar{x} = \frac{\sum x_i \sigma_i^{-2}}{\sum \sigma_i^{-2}} \quad (2.3)
\]

\[
\bar{\sigma} = \frac{1}{\sqrt{\sum \sigma_i^{-2}}} \quad (2.4)
\]

Figure 2.10 shows the phase folded 18–60 keV \textit{INTEGRAL}/IBIS light curve of SAX J1818.6–1703 folded on a period of 29.987 days with an ephemeris of MJD 54540.659. The profile shows significant modulation of X-rays with a strong
preference toward a 4–6-day activity cycle clustered around phase 0. In this case,
the zero phase ephemeris is chosen to be a large flare that is assumed to be the
periastron passage of the putative neutron star. This suggests SAX J1818.6–1703
does in fact have a phase bias in its activity.
subsequently light curve folded on the spin period is known as the ‘pulse profile’.

### 2.2.2 Epoch folding

Another technique used in the searching of astronomical time series is epoch folding. In this method, the data are folded on a given period and grouped into phase bins by the method described above. The resulting phase folded light curve is then tested for the presence of non-uniformity using the $Q^2$ test statistic defined by Davies (1990). Considering a time series of observations divided into $M$ phase bins, with $\bar{x}_i$ and $\sigma_i^2$ being the mean and variance of the $i$th phase bin, the $Q^2$ statistic is defined as

$$Q^2 = \sum_{i=1}^{M} \frac{(\bar{x}_i - \bar{x})^2}{\sigma_i^2}$$

(2.5)

where $\bar{x}$ is the global mean of the light curve being tested. In order to search for unknown periodicities in the light curve, this statistic must be calculated over a wide range of periods, the limitations of which are discussed above. In the presence of a periodic signal the $Q^2$ statistic will have a maximum, the significance of which can be evaluated either by performing a $\chi^2$ test on the anomalously high value of the test statistic or by performing the Monte-Carlo randomisation tests outlined in Section 2.2.1.

Like the LS periodogram, this method can be applied to non-uniformly sampled time series providing the observations are long enough to have sufficient phase coverage such that there are no empty bins. Unlike the LS periodogram, this test makes no assumption about the shape of the periodic signal i.e whether it is sinusoidal or ellipsoidal and instead is merely a diagnostic of the deviation of the folded profile from a constant. This simple measurement of deviation can however be problematic. Folding the light curve on either integer or fractional multiples of a periodicity also results in anomalously high values of the test statistic making it difficult to distinguish the ‘true’ periodicity. This makes epoch folding challenging to use as a method of blindly searching for an unknown periodicity in a new data set, though it is a useful tool when used in conjunction with other methods such as the LS periodogram.

Figure 2.11 shows the $Q^2$ statistic evaluated between 2 and 200 days for the same INTEGRAL/IBIS 18–60 keV light curve used in the temporal analysis above. This illustrates the difficulty in using this test for a blind search as the ~30 day periodicity is clearly seen, however also clear are peaks in the $Q^2$ statistic at ~60, 90 and 120 days resulting from oversampling the true periodic value. In reporting the discovery of this periodicity using a LS periodogram, Bird et al. (2009) also used an epoch folding method to confirm the presence of this signal, however the range over
which the test was performed was limited to 10–50 day hence avoiding this issue.

This technique is most useful where there is prior knowledge of a periodicity in the source and observations are being tested for evolution in the signal over time. An example of this being the change in spin period of accreting neutron stars. The small spin down rates of such systems mean that given an earlier measurement of the spin period, a narrow temporal region around the known periodicity can be searched and any deviations from the known can be found. This approach when implementing the technique is also useful as the algorithm is computationally expensive for blind searches hence a targeted approach is quicker to execute.

### 2.2.3 Discrete fourier transform - DFT

The final temporal analysis technique utilised in this thesis is that of the discrete Fourier transform or DFT. The DFT is the decomposition of a set of discrete time labelled events with a given spacing into its constituent sine waves with discrete frequencies. This is the equivalent of the continuous Fourier transform, however in this case the signal is represented by a series of $N$ points separated by times, $t$. Following the prescription of Horne & Baliunas (1986) and considering a data set $X(t_j)$ where $t_j$ is the $j$th time stamp of the data set, the discrete Fourier transform
is given by

\[ \hat{F}_X(\omega) = \sum_{j=1}^{N} X(t_j)e^{-i\omega t_j} \quad (2.6) \]

The periodogram is the square modulus of this transform normalised by the number of points in the data set and is given by

\[ P_x(\omega) = \frac{1}{N} |\hat{F}_X(\omega)|^2 \]

\[ = \frac{1}{N} \left| \sum_{j=1}^{N} X(t_j)e^{-i\omega t_j} \right|^2 \quad (2.7) \]

(2.8)

When the data is evenly spaced data it is common to take \( \Delta t = t_{j+1} - t_j = 1 \), \( t_j = j \) and \( X(t_j) = X_j \), leading to the periodogram being written as

\[ P_x(\omega) = \frac{1}{N} \left| \sum_{j=1}^{N} X_j e^{-ij\omega} \right|^2 \quad (2.9) \]

This quantity is evaluated across \( N/2 \) evenly spaced frequencies and in the presence of a periodic signal the periodogram ‘spikes’ at the associated frequency and achieves a maximum value.

The uncertainty in the frequency detected by the DFT can be calculated analytically. Assuming the data series contains only one signal and the noise in the light curve is Gaussian, the uncertainty in frequency is given by

\[ \delta\omega = \frac{3\pi\sigma_N}{2(N_0)^{1/2}TA} \quad (2.10) \]

where \( \sigma_N^2 \) is the variance of the noise once the signal has been subtracted, \( N_0 \) is the number of data points used in the DFT, \( T \) is the total length of the data set and \( A \) is the amplitude of the signal. The authors note that the presence of secondary signals and linear trends in the data have the effect of generating shifts in the detected frequencies. The significance of a detected peak in the DFT can again be calculated by performing the randomisation tests described in Section 2.2.1.

As a condition of utilising this tool is the uniformity of spacing in the data series, the DFT cannot be used effectively with INTEGRAL/IBIS data to search for signals indicative of orbital motion of neutron stars. This is a result of the length of pointed observations at a source that are much shorter than the orbital periods of the HMXB subclasses considered in this thesis, with typical observations lasting \( \sim 100 \text{ ks} \) when compared with \( >3 \text{ day} \) orbital periods. Thanks to the daily and orbital binnings of the Swift/BAT transient monitor data, this technique can be applied to these long baseline light curves and such an analysis is performed in
Chapter 5. The application of the DFT to \textit{XMM-Newton} data is complicated by the filtering of events for flaring background in faint sources, as described above. In this case, the observation can be subdivided into sets with even spacing, however this can often reduce the range of possible periodicities to search due to shortening of the light curve. Hence the LS periodogram is preferred in this thesis.

\section*{2.3 Summary}

In this chapter, I have presented an overview of the three main satellites used in this thesis with their unique and complementary facilities for studying the soft and hard X-ray behaviour of HMXBs. I have also outlined a suite of temporal analysis techniques used to investigate data sets provided by these instruments in attempts to categorise key system parameters of these sources such as orbital and spin periods of neutron stars. In the following chapters, I present analyses of observational data from these telescopes and characterise the accretion processes of the sources around the neutron star periastron passage.
Chapter 3

Spectral variation in the SFXT SAX J1818.6–1703 observed by XMM-Newton and INTEGRAL

3.1 Introduction

In this chapter, I present the results of phase targeted temporal and spectral analysis of the prototypical supergiant fast X-ray transient SAX J1818.6–1703, observed with XMM-Newton starting on 2013 March 21 and lasting 30 ks.

SAX J1818.6–1703 was discovered by the BeppoSAX observatory on 1998 March 11 in a short X-ray outburst lasting a few hours (in ’t Zand et al., 1998). Renewed short X-ray activity was subsequently detected by the IBIS/ISGRI telescope on INTEGRAL on 2003 September 9 as two intense short outbursts reaching \( \sim380 \) mCrab in the 18–45 keV energy band (Grebenev & Sunyaev, 2005). The observed activity of SAX J1818.6–1703 by Grebenev & Sunyaev (2005) showed complex time varying behaviour lasting approximately 1 day, with the main flare event lasting 2.7 h. IBIS/ISGRI spectra taken from this observation were fitted well with a thermal bremsstrahlung model, showing signs of spectral evolution through the flaring event. The nature of the system was unknown at the time of this observation, though the authors did rule out changes in accretion through a standard accretion disc as the cause of the behaviour. Other short X-ray outbursts from SAX J1818.6–1703 have been also observed with RXTE (Smith et al., 2012).

The identification of a B0.5Iab supergiant within the error circle of the refined Chandra position of SAX J1818.6–1703 identified the system as an SFXT at a distance of 2.1 kpc (Negueruela & Smith, 2006; Torrejón et al., 2010).
Table 3.1: Log of observations of SAX J1818.6–1703 discussed in this chapter. Phases are calculated using the ephemeris of Bird et al. (2009).

<table>
<thead>
<tr>
<th>Instrument</th>
<th>UTC</th>
<th>MJD</th>
<th>Phase</th>
<th>Exp (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTEGRAL</td>
<td>2013 Mar 12 00:19:37 – 56363.014 – 0.804 – 0.862</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2013 Mar 13 18:15:52 – 56364.761</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2013 Mar 20 11:10:03 – 56371.465 – 0.086 – 0.099</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>2013 Mar 21 12:37:22 – 56372.514 – 0.121 – 0.134</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2013 Mar 21 21:24:54 – 56372.914</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INTEGRAL</td>
<td>2013 Mar 22 09:00:11 – 56373.375 – 0.150 – 0.165</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The source was undetected in a 13 ks observation on 2006 October 8 with XMM-Newton by Bozzo et al. (2008a). The authors placed a 3σ upper limit on the unabsorbed 0.5–10 keV X-ray flux of $1.1 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2}$ ($L_X = 5.8 \times 10^{31} \text{erg s}^{-1}$ at a distance of 2.1 kpc) using data from the EPIC-pn camera. The source was also not detected in a 45 ks observation on 2010 March 21 with XMM-Newton (Bozzo et al., 2012), though due to high flaring background, the effective observation time for EPIC-pn was only 4 ks. This observation placed a 3σ upper limit on the unabsorbed 0.5–10 keV flux of $3 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2}$, consistent with the previous observations.

An in depth study of available INTEGRAL/IBIS data by Bird et al. (2009) revealed a 30±0.1 day orbital period. A period of 30±0.2 days was independently found by Zurita Heras & Walter (2009) and the eccentricity of the orbit was constrained to between 0.3 and 0.4. Using both the orbital period and the ephemeris (MJD 54540.659) from Bird et al. (2009), the previous XMM-Newton observations were found to have been taken at orbital phases of $\phi = 0.51$ and 0.53 (close to apastron) for the 13 and 45 ks observations respectively. Using the same INTEGRAL data set and performing a recurrence analysis of outbursts from SAX J1818.6–1703, Bird et al. (2009) found that the system has a high level of recurrence, showing detectable emission in more than 50% of periastron passages. This high recurrence rate when coupled with the large outbursts as seen by Grebenev & Sunyaev (2005) show the behaviour of SAX J1818.6–1703 is atypical of that found in other SFXTs.

A catalogue of Swift/BAT bright flares from the SAX J1818.6–1703 has been reported by Romano et al. (2014a), while a systematic re-analysis of the INTEGRAL archival data has been reported by Paizis & Sidoli (2014), who found that the distribution of X-ray flare luminosities follow a power-law.
3.2 Data Analysis

3.2.1 XMM-Newton data analysis

A single XMM-Newton/EPIC (Jansen et al., 2001; Turner et al., 2001; Strüder et al., 2001) observation of SAX J1818.6−1703 around the periastron orbital phase of the system was performed between MJD 56372.514 and 56372.914, covering the orbital phase region $\phi = 0.121 – 0.134$ using the ephemeris of Bird et al. (2009) (ObsID: 0693900101). The EPIC-pn camera was operated in small window mode, while the EPIC-MOS cameras were operated in full frame mode. This configuration was chosen to account for the rapid transient nature of this source and reduce pile up in the event of the source experiencing a bright ($\sim 10^{-10}$ erg s$^{-1}$ cm$^{-2}$) outburst.

Data from both EPIC-pn and EPIC-MOS detectors were analysed using the standard XMM-Newton Science Analysis System (SAS v12.0.1; Gabriel et al. 2004) and the most recent instrument calibration files. The standard epproc and emproc tasks were used to produce cleaned event files for EPIC-pn and EPIC-MOS cameras, respectively. The data sets were filtered for flaring particle background and checked for photon pileup using the epatplot tool as described in the XMM-Newton SAS data analysis threads\(^1\). The observation was found not to suffer from photon pile up. We created single-event products (pattern = 0) in the range of 10–12 keV for EPIC-pn and above 10 keV for EPIC-MOS cameras covering the full field of view for each camera and using cut offs of 0.35 and 0.4 counts s$^{-1}$ for EPIC-pn and EPIC-MOS respectively as outlined in the SAS threads. Filtered event files were produced from the resulting good time intervals defined by this filtering.

Optimal extraction regions for all light curve and spectrum generating procedures were generated using the SAS tool eregionanalyse, which yielded extraction regions of 26, 51 and 58 arcsec for EPIC-pn, EPIC-MOS1 and EPIC-MOS2 respectively.

Broad-band 0.2–10 keV light curves from EPIC-pn and EPIC-MOS were extracted with 100 s resolution initially, as shown in Figure 3.2. The properties of the EPIC-pn light curve are discussed in Section 3.3.2.

All spectra reported below were extracted using standard procedures from the XMM–Newton analysis threads and the appropriate response for each spectrum was generated using the SAS tools rmfgen and arfgen. The spectra were fit in the 0.5-15 keV band using xspec version 12.7.1 (Arnaud, 1996) and uncertainties are quoted at the 90% confidence level. The interstellar element abundances for photoelectric absorbing model components are set by the abundances of Wilms et al. (2000). Spectral properties are discussed in Section 3.3.3.

\(^1\)http://xmm.esac.esa.int/sas/current/documentation/threads/

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3.2.2 INTEGRAL data analysis

INTEGRAL/IBIS (Ubertini et al., 2003; Winkler et al., 2003) observed SAX J1818.6−1703 between MJD 56363.014 and 56364.761 as part of Revolution 1271. During this revolution, the source was observed for a total of 10 ks. SAX J1818.6−1703 was also observed by INTEGRAL/IBIS between MJD 56371.465 − 56371.864 and between MJD 56373.375 − 56373.843. These INTEGRAL observations cover the phases $\phi = 0.804 − 0.862$, $\phi = 0.086 − 0.099$ and $\phi = 0.150 − 0.165$ respectively, using the ephemeris of Bird et al. (2009). This archival data were processed and analysed using the INTEGRAL Offline Science Analysis (Goldwurm et al., 2003) software version 10.1. Images were created in the 18–60 keV energy range for each science window (ScW; an individual pointing of INTEGRAL lasting approximately 2 ks) and each observation of the source. Light curves in the 18–60 keV band on ScW and 250 s time-scales and spectra in the 18–500 keV band were also generated following standard procedures. A list of all observations discussed in this work can be found in Table 3.1. I am aware that the low energy threshold of IBIS/ISGRI on-board INTEGRAL has increased since launch and consequently the INTEGRAL Science Data Centre recommend ignoring data below 22 keV for all revolutions after Revolution 1090. I generated images in the 18–60 keV and 22–60 keV bands for both observations in Revolution 1274 and find that there is no significant difference in the detections of the source between the energy bands. In order to compare results in this chapter with previous hard X-ray studies using INTEGRAL, I adopt the 18–60 keV energy band for subsequent analysis.

3.3 Results

3.3.1 INTEGRAL results

SAX J1818.6−1703 was not detected in the earlier observation of the source during Revolution 1271, which was prior to the periastron passage. Figure 3.1 shows the INTEGRAL/IBIS 18–60 keV significance maps for the observations in Revolution 1274 that bracket the XMM-Newton observation of SAX J1818.6−1703. The top panel shows the significance map for the observation taken one day prior to the XMM-Newton observation; SAX J1818.6−1703 is detected at the 10σ level. The bottom panel shows the significance map for the observation taken one day after the XMM-Newton observation. In this map, there is a marginal detection of the source at 6σ, however due to the short exposure time, there is a high level of systematic noise in the map. To look for signatures of fast variability, the 250 s bin light curve of these two observations was analysed. There is evidence of activity and variability through this observation period.
Figure 3.1: Top panel: 18–60 keV INTEGRAL/IBIS significance map from the observation of SAX J1818.6–1703 between MJD 56371.465 and 56371.864. The best X-ray positions of SAX J1818.6–1703 and other sources in the field of view are marked with white circles. Bottom panel: as the left-hand panel for the observation between MJD 56373.375 and 56373.843. Both observations were taken as part of satellite revolution 1274.
3.3.2 Temporal analysis of XMM-Newton data

Figure 3.2 shows the background subtracted 0.2–10 keV EPIC-pn light curve with 100 s time bins and filtered for low fractional exposure (FRACEXP < 0.5). Times in this light curve are given with $t_0 = \text{MJD 56372.530}$ being the first time stamp of the EPIC-pn light curve. For $t<6000$ s, the source shows a low level of X-ray emission with an average flux for this region of the light curve is $0.16\pm0.009 \text{ counts s}^{-1}$ and a minimum count rate of $0.01\pm0.04 \text{ counts s}^{-1}$. Following this, the source then shows an increase in activity up until $t \sim 7500$ s when the source enters a period lasting $\sim 7.5$ ks where 3 small flares occur, reaching up to counts of $2-3 \text{ counts s}^{-1}$. Following the onset of this flaring activity, a large (up to $\sim 8 \text{ counts s}^{-1}$) flare occurs, lasting approximately 7.5 ks after which the source exhibits small-scale flaring activity until the end of the observation. Over the course of the observation, the source exhibits a dynamic range of $\sim 100$ in count rate.

The EPIC-MOS1 and EPIC-MOS2 light curves show similar levels of variability and flaring activity, though due to the lower sensitivity of these instruments and hence lower count rates with respect to the EPIC-pn instrument, I focus our temporal analysis on the EPIC-pn light curves for the remainder of this chapter.
Figure 3.3: Hardness ratio of the 0.5–5 keV and 5–10 keV EPIC-pn light curves of SAX J1818.6–1703 with 400 s binning. As with Figure 3.2, $t_0 = \text{MJD}56372.530$ and is the first time stamp of the EPIC-pn light curve.

Figure 3.4: EPIC-pn 0.2–10 keV 100 s resolution light curve of SAX J1818.6–1703 as shown in Figure 3.2. Regions used for spectral extractions are labelled A–H and the extent of these regions shown by the dot-dashed lines. The hardness ratio for each of the regions labelled at the top of the figure are shown as red circles. The dashed line corresponds to the hardness ratio for the time intervals not covered by the labelled regions.
A filtered light curve with 1 s binning was tested for the presence of periodicities in an attempt to locate the as yet unknown neutron star spin period of SAX J1818.6−1703. A Lomb–Scargle periodogram (Lomb, 1976; Scargle, 1982) was produced using the fast implementation of Press & Rybicki (1989). Significance levels, above which one would consider the detection of a periodic signal to be true, were calculated using Monte Carlo simulations. The method of Hill et al. (2005) was used in order to gain appropriate confidence levels with 100,000 iterations utilised. Using this method when applied to the light curve of the whole observation, no significant peaks in the Lomb–Scargle power in the range 2 s – 4.2 h were found. Searches for periodic signals in temporally selected windows corresponding to low and brighter intensities (t < 8500, 8500 < t < 15000, 15000 < t < 25000, t > 25000) were also carried out in the range of 2–2500 s and yielded no significant signals.

An epoch folding method using the $Q^2$ statistic as defined by Leahy et al. (1983) was also utilised to identify periodic signals. As for the Lomb-Scargle periodogram, 100,000 iterations of a Monte Carlo process were undertaken and confidence levels determined. This method yielded no significant peaks in the range 2s–4.2 h.

### 3.3.3 Spectral analysis of XMM-Newton data

A preliminary, model independent check for spectral variability was performed by calculating the hardness ratio, defined as

$$HR = \frac{H - S}{H + S}, \quad (3.1)$$

where $H$ is the counts in the hard X-ray band (5–10 keV in this work) and $S$ is the counts in the soft X-ray band (0.2–5 keV). The calculated hardness ratio between these two bands is shown in Figure 3.3 with 400 s binning. Given the evident evolution in hardness ratio, I extracted spectra from temporal regions showing similar flux behaviour and constant hardness ratio. The time intervals associated with these extraction regions are listed in Table 4.2 and correspond to the regions specified by dot–dashed lines in Figure 3.4. Region A corresponds to the low flux, early period of the observation. Regions B, C, D, G and H correspond to small flares that occur after the initial low flux interval but either side of the main flare period. Data from these flares were combined to improve the statistical quality of the data products. The mean values of hardness ratio for each of these regions is plotted in Figure 3.4 as red circles. The hardness ratio was also calculated for the periods of intermediate behaviour not covered by regions A–H and is taken to represent the average behaviour of the source. This average hardness ratio is plotted as the red dashed line in Figure 3.4. The hardness ratios calculated for regions A–H show evidence of increasing from a value of approximately 0.25 to 0.7, coinciding with the rise to the main flare (regions E+F).
Table 3.2: Times associated with the regions used for spectral and hardness ratio analysis. $T_{\text{start}}$ and $T_{\text{stop}}$ are given in seconds since beginning of the observation.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>$T_{\text{start}}$</th>
<th>$T_{\text{stop}}$</th>
<th>MJD$_{\text{start}}$</th>
<th>MJD$_{\text{stop}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>6000</td>
<td>56372.530</td>
<td>56372.599</td>
</tr>
<tr>
<td>B</td>
<td>8400</td>
<td>8800</td>
<td>56372.627</td>
<td>56372.632</td>
</tr>
<tr>
<td>C</td>
<td>10200</td>
<td>10500</td>
<td>56372.648</td>
<td>56372.652</td>
</tr>
<tr>
<td>D</td>
<td>12600</td>
<td>13300</td>
<td>56372.676</td>
<td>56372.684</td>
</tr>
<tr>
<td>E</td>
<td>15800</td>
<td>20500</td>
<td>56372.713</td>
<td>56372.767</td>
</tr>
<tr>
<td>F</td>
<td>20500</td>
<td>23800</td>
<td>56372.767</td>
<td>56372.806</td>
</tr>
<tr>
<td>G</td>
<td>25500</td>
<td>25800</td>
<td>56372.825</td>
<td>56372.829</td>
</tr>
<tr>
<td>H</td>
<td>27100</td>
<td>27500</td>
<td>56372.844</td>
<td>56372.848</td>
</tr>
</tbody>
</table>

Figure 3.5: Hardness ratios taken from regions shown in Figure 3.4 plotted against average counts rate for those regions. The point labelled ‘Z’ corresponds to the hardness ratio and average flux for the time intervals not covered the regions labelled A–H.
Figure 3.5 shows the hardness ratio calculated for the spectral extraction regions plotted against average flux for these regions. This shows the often seen ‘harder-when-brighter’ relation in HMXBs (Sidoli et al., 2012, 2013; Odaka et al., 2013; Romano et al., 2014a; Kennea et al., 2014) with spectra A, E and F clearly showing this behaviour. However, in the intermediate intensity range, the situation is somewhat less clear. It is worthy of note that although this relation is often seen in HXMBs, the observed variation in this source is an extreme example of this behaviour.

In order to investigate the hardening of the emission from the source EPIC-pn and EPIC-MOS spectra from the regions shown in Figure 3.4 and Table 4.2 were extracted with a minimum of 15 counts per bin. The pn and MOS spectra were fit simultaneously for each region using xspec in the 0.5–15 keV energy band. In these cases, in order to get values of unabsorbed flux, the models \texttt{cons*phabs*cflux(powerlaw)} and \texttt{cons*phabs*cflux(bbody)} were fit to all spectra, where the constant here is used to account for the difference between the MOS and pn instruments. The model component \texttt{cflux} is a convolution model used to determine the 0.5–10 keV flux of the model it is used in. The position of this component in this model gives the 0.5–10 keV unabsorbed flux. Black body fits to the spectra gave unphysical black body temperatures in the range of 2–4 keV for regions E, F and B+C+D+G+H. The fits of the power-law model to the spectra are presented in Table 3.3 and the power-law fits to regions A, B+C+D+G+H and E are shown in Figure 3.6. The spectrum of region F is similar to that of region E and hence is not shown in Figure 3.6.

The power law model shows variation in both absorbing column density and photon index coinciding with the main period of flaring activity. The variation in photon index covers nearly an order of magnitude from ∼2.5 at early times in the observation to ∼0.36 at the time of the main flaring activity. These variations towards a flatter power law are consistent with the evolution of the hardness ratio shown in Figure 3.4.

More physical models often used in fitting SFXT spectra such as a Comptonising plasma model (\texttt{phabs(compTT)}) or a cut-off power law (\texttt{phabs(cutoffpl)}) were also fit to the spectra of the regions listed in Table 3.3. However, both of these alternative models did not give better fits to the data. Even in the case of a comparable fit, model parameters such as high-energy cut off or seed photon and plasma temperature were highly unconstrained. For example, for region E, the Comptonising plasma model fit has a reduced chi squared, \(\chi^2_{\text{red}} = 1.51\) (300 dof) with kT = 2 ± 31 keV, seed photon temperature \(T_0 = 3.8 ± 1.6\) keV and optical depth \(\tau = 0.01 ± 4\). For the same region, the cut off power-law fit gives the same absorbing column density and photon index as the power-law fit, however the high energy cut off is unconstrained (500 ± 10000 keV).
Figure 3.6: Top Panel: power-law fit and residuals to EMOS (Black and Red) and EPN (Green) spectra from region A. Middle Panel: power-law fit and residuals to EMOS (black and red) and EPN (green) spectra from Region B+C+D+G+H. Bottom Panel: power-law fit and residuals to EMOS (black and red) and EPN (green) spectra from region E.
Due to the unphysical nature of the black body temperature in the fits to regions E, F and B+C+D+G+H, I use the power-law fits throughout to characterise the spectral variability observed over the course of the observation.

The best-fitting values of photon index show significant evidence for spectral evolution over the observation. The 68%, 90% and 99% statistical confidence regions for photon index and $N_H$ in regions A, B+C+D+G+H, E and F are shown in Figure 3.7 and show the evolution of the photon index over the course of the observation. It is clear that the spectra of the low-flux state (region A) and the main flaring activity (regions E+F) occupy distinct regions of the parameter space. By combining data from all the short flares, it is clear that their spectrum is also different to regions A, E and F.

The source shows variation in photon index and when comparing this to the light curve in Figure 3.4, the source evolves from a soft photon index at the onset of the flaring behaviour to hard photon index around the main flare event. Due to the statistical properties of the spectra, investigation the applicability of more complex models in regions E and F by subdividing these regions into smaller intervals is not possible.
**Table 3.3:** Hardness ratios and best-fitting parameters for a power-law model (\(\text{cons*phabs*cflux(powerlaw)}\)) fit to spectra extracted from the regions outlined in Figure 3.4 and Table 4.2. Absorbing column density, \(N_H\) is in units of \(10^{22}\) \(\text{cm}^{-2}\), the 0.5–10 keV unabsorbed flux is in units of \(\times 10^{-10}\) \(\text{erg s}^{-1}\) \(\text{cm}^{-2}\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A</th>
<th>E</th>
<th>F</th>
<th>B+C+D+G+H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness Ratio</td>
<td>0.30±0.06</td>
<td>0.66±0.01</td>
<td>0.68±0.02</td>
<td>0.54±0.02</td>
</tr>
<tr>
<td>(N_H)</td>
<td>(56^{+12}_{-10})</td>
<td>(43^{+2}_{-2})</td>
<td>(51^{+3}_{-3})</td>
<td>(53^{+4}_{-4})</td>
</tr>
<tr>
<td>(\Gamma)</td>
<td>(2.4^{+0.6}_{-0.5})</td>
<td>(0.36^{+0.1}_{-0.1})</td>
<td>(0.57^{+0.1}_{-0.1})</td>
<td>(1.86\pm0.2)</td>
</tr>
<tr>
<td>Unabsorbed Flux</td>
<td>(0.27^{+0.38}_{-0.13})</td>
<td>(1.49^{+0.07}_{-0.07})</td>
<td>(1.66^{+0.16}_{-0.16})</td>
<td>(1.82^{+0.50}_{-0.37})</td>
</tr>
<tr>
<td>(\chi^2_{\text{red}}) (dof)</td>
<td>1.07 (68)</td>
<td>1.34 (302)</td>
<td>1.39 (242)</td>
<td>1.02 (163)</td>
</tr>
</tbody>
</table>

### 3.3.4 INTEGRAL and Combined Spectral Analysis

With the aim of better constraining the spectral model of the source, an average INTEGRAL/IBIS spectrum was extracted from the ScWs with the greatest significance detections of the source in the first observation in Revolution 1274. This spectrum was fitted in the 18–60 keV range with a power-law model, yielded a photon index of \(\Gamma = 3.15^{+1.15}_{-0.99}\) with \(\chi^2_{\text{red}} = 0.80\) (2 dof) and a model flux of \(2.879 \times 10^{-10}\) \(\text{erg s}^{-1}\).

Simultaneous fits of the INTEGRAL spectrum with the XMM-Newton MOS and pn spectra were performed in the 0.5–50 keV range. Fits of an absorbed power-law model described in Section 3.3.3 yielded good fits and best-fitting parameters consistent with those presented in Table 3.3 for the XMM-Newton data only. The statistics of the INTEGRAL spectrum are such that they do not constrain the hard X-ray spectral shape well and consequently the much better statistics in the XMM-Newton energy range cause it to dominate when fitting over the full spectral range. As a result, combining XMM-Newton and INTEGRAL spectra does not allow us to better constrain the spectral model achieved with XMM-Newton data alone.

### 3.4 Discussion

I have presented the results of a 30 ks XMM-Newton observation of the SFXT, SAX J1818.6–1703. This is the first in-depth soft X-ray investigation of the source located around the peak in the INTEGRAL/IBIS phase folded light curve (Figure 3 of Bird et al. 2009), likely located near periastron. I have also presented the results of contemporaneous archival INTEGRAL/IBIS observations spanning 115 ks with 25 ks on-source exposure.

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3.4.1 *INTEGRAL* Context

Previous studies of this source with *INTEGRAL* have revealed a long (30 days), eccentric ($e \sim 0.3–0.4$) orbit and shown detections in more than 50% of neutron star periastron passages.

SAX J1818.6–1703 was not detected by *INTEGRAL* in an observation carried out between MJD 56363.014 and 56364.761 during Revolution 1271, at a time that corresponds to an orbital phase of 0.804–0.862. During this region of a long eccentric orbit, the stellar wind, through which the neutron star passes, is not expected to be sufficiently dense or structured so as to produce detectable emission from accretion.

A bright flare from SAX J1818.6–1703 detected by *Swift*/BAT on MJD 56368 (corresponding to phase, $\phi = 0.970$) was reported by Romano et al. (2014a). During this flare the source reached a peak flux of 146 mCrab (15–50 keV), clearly showing that the source exhibited enhanced X-ray emission a few days prior to the *XMM-Newton* observation reported here.

The source was also detected by *INTEGRAL* during Revolution 1274 at a significance of $\sim 13\sigma$. A more detailed analysis of this revolution shows that the source was first observed between MJD 56371.465 and 56371.864, corresponding to orbital phases $\phi = 0.086–0.099$, with a total source exposure of 7.5 ks. During this observation, the source was detected with an average count rate of 2.17$\pm$0.22 counts s$^{-1}$ (18–60 keV) or $\sim$10 mCrab. The source was subsequently observed between MJD 56373.375 and 56373.843, corresponding to orbital phases $\phi = 0.150–0.165$, again with a total source exposure of 7.5 ks. The average count rate in this observation was 1.27$\pm$0.22 counts s$^{-1}$ (18–60 keV). In order to compare these fluxes to previous periastron passages, I performed the recurrence analysis of Bird et al. (2009) using an *INTEGRAL*/IBIS light curve of SAX J1818.6–1703 from the first 1000 revolutions of *INTEGRAL*. The mean flux detected by *INTEGRAL* during a 4-day period centred on periastron was calculated and from this, I find that during the first observation of Revolution 1274, the source is brighter than 80% of periastron passages observed by *INTEGRAL*. The flux detected between MJD 56373.375 and 56373.843 is consistent with fluxes observed by *INTEGRAL* during the majority of periastron passages. However, it is different from the distribution of apastron flux measurements and still represents a significant detection of the source. When considering the *Swift*/BAT bright flare on MJD 56368 and the observations during Revolution 1274, it is clear that SAX J1818.6–1703 was in an atypically active state during the periastron passage covered by the *INTEGRAL* and *XMM-Newton* observations presented in this chapter.
3.4.2 Source Distance

Knowledge of the source distance is critical in order to calculate associated luminosities and hence disentangle the accretion processes generating the observed dynamic X-ray behaviour. A number of source distances have been suggested for SAX J1818.6−1703, though the distance is still one of the best constrained for an SFXT. Using near infra-red spectroscopy Torrejón et al. (2010) inferred a distance of 2.1±0.1 kpc. More recently, Coleiro & Chaty (2013) inferred a distance of 2.7±0.28 using a similar method. For the subsequent discussion, I adopt the better constrained distance estimate of 2.1±0.1 kpc from Torrejón et al. (2010). The range of possible distances to the source is such that the luminosities calculated assuming a distance of 2.1 kpc could be a factor of 1.3 larger if the source is located at 2.7 kpc.

3.4.3 Observed Luminosity

In order to critically evaluate the accretion processes taking place over the course of the XMM–Newton observation, the pn count rates shown in Figure 3.4 were converted to X-ray luminosities. To convert from count rate to luminosity, I assumed an absorbed power-law spectral model with photon index Γ = 1.9, an absorbing column density of $N_H = 5 \times 10^{23} \text{cm}^{-2}$ and a source distance of 2.1±0.1 kpc. These spectral parameters are consistent with the fits to regions A and B+C+D+G+H. Although these are not consistent with regions E and F, the same model is applied to these sections of the light curve so as not to introduce discontinuities in the luminosity light curve scale factor. The resulting luminosity light curve is shown in Figure 3.8.

During the first 6 ks of the XMM-Newton observation, the source exhibits low level persistent emission with luminosities of $\sim 10^{34} \text{erg s}^{-1}$. This corresponds to low level accretion of material from the stellar wind, however the light curve shows no flaring behaviour during this interval. This was further investigated by estimating the 0.5–10 keV luminosity for the INTEGRAL observation of the source between MJD 56371.465 and 56371.864. Using an INTEGRAL/IBIS source count rate of 2.17 counts s$^{-1}$ and the cut-off power law of Sidoli et al. (2009c) and the absorbing column density measured in this work of $5 \times 10^{23} \text{cm}^{-2}$, I calculate an XMM-Newton count rate of 4.45 counts s$^{-1}$ (0.5–10 keV). Assuming the same absorbed power-law used to produce Figure 3.8, this corresponds to a luminosity of $3.3 \times 10^{35} \text{erg s}^{-1}$. This suggests that the initial 6 ks of the XMM-Newton observation is a low flux interval between periods of higher activity.

One possible explanation for initial low flux observed by XMM-Newton could be the obscuration of the emitting region by circumstellar material. However, the spectral analysis of Section 3.3.3 rules out this scenario as the values of absorbing column density for this region are consistent with the regions showing flaring activity.
**Figure 3.8:** The *XMM–Newton* light curve shown in Figure 3.4 with count rate converted into luminosity using an absorbed power law with photon index $\Gamma = 1.9$, absorbing column density, $N_H = 5 \times 10^{23} \text{ cm}^{-2}$ and a source distance of $2.1 \pm 0.1 \text{kpc}$. The red dashed line corresponds to the critical luminosity for transition between the radiatively cooled to Compton-cooled regimes in Shakura et al. (2013)
Excluding the obscuration of the source by a dense clump, other possibilities are often discussed in the literature to explain these ‘dips’ or ‘off-states’ sometimes observed in supergiant HMXB pulsars. These include a transition to a less effective accretion regime likely triggered by a mild variability in the wind properties. If this is the case, the initial dip could be explained by either a transition to the subsonic propeller regime where the low luminosity is produced by means of matter penetrating the magnetosphere by the Kelvin-Helmholtz instability (e.g. Doroshenko et al. 2011) or by a cooling regime switch (Shakura et al., 2013). In this latter scenario, an accretion regime transition from a Compton cooling dominated regime (implying a higher accretion rate through the magnetosphere) to a radiative dominated regime (producing a lower X-ray luminosity) is produced in the equatorial plane of the neutron star magnetosphere, due to a switch from a fan beam to a pencil beam geometry (Shakura et al., 2013).

Following the method of Doroshenko et al. (2011) and Drave et al. (2013), I apply the framework of Bozzo et al. (2008b) to explain this low activity region seen in the first 6 ks of the XMM-Newton observation. Within this framework, the accretion luminosity in the subsonic propeller regime is given by

\[ L_{KH} = 1.8 \times 10^{35} \eta_K H P_{23}^{-1} R_{M10}^3 \dot{M} a_{10d}^{-2} \eta_{KH}^{-1} \]

\[ \times \left[ 1 + 16 R_{a10}^2/(5 R_{M10}) \right]^{3/2} \frac{\sqrt{\rho_i/\rho_e}}{(1 + \rho_i/\rho_e)} \text{erg s}^{-1} \]  

(3.2)

where \( R_{a10} \) and \( R_{M10} \) are the accretion and magnetospheric radii in units of 10\(^{10}\) cm and \( \rho_i, \rho_e \) are the plasma densities inside and outside the magnetosphere respectively. Here \( \eta_{KH} \sim 0.1 \) is an efficiency factor taken from Burnard et al. (1983). In this regime, the magnetospheric radius is given by:

\[ R_M = 2 \times 10^{10} a_{10d}^{4/7} \dot{M}^{-2/7} v_8^{8/7} \mu_{33}^{4/7} \text{cm} \]  

(3.3)

where \( \mu_{33} \) is the magnetic moment in units of 10\(^{33}\) G cm\(^3\). I assume three possible values for the ratio of densities inside and outside the magnetospheric boundary \( \rho_i/\rho_e = 1, 0.5 \) and 0.1 with \( \rho_i/\rho_e = 1 \) giving an upper limit for the neutron star spin period. A magnetic field strength of 10\(^{12}\) G is also assumed for the neutron star, in line with measurements of other field strengths in HMXBs and the SFXT, IGR J17544–2619 (Kreykenbohm et al., 2002; Bhalerao et al., 2015).

In order to calculate stellar wind velocities, I follow previous works (e.g. Ducci et al. 2009; Romano et al. 2012; Drave et al. 2013) and adopt the Castor et al. (1975) velocity law to describe the stellar wind velocity at a given orbital separation. This
is given by

\[ v(r) = v_{\infty} \left(1 - \frac{R_\star}{r}\right)^\beta \]  

(3.4)

where \( v_{\infty} \) is the terminal wind velocity, found to lie in the range 800–1300 km s\(^{-1}\) by modelling of flare luminosity distributions and \( \beta \) is a power law index with a value between 0.8 and 1.3 (Romano et al., 2012). \( R_\star \) is the radius of the supergiant and \( r \) is the orbital separation.

For supergiant stellar parameters, I adopt a stellar mass and radius of 25 \( M_\odot \) and 30 \( R_\odot \) respectively and a stellar mass loss rate \( \dot{M}_w = 5 \times 10^{-7} M_\odot \text{yr}^{-1} \). With these stellar parameters, the wind velocity at this orbital separation lies in the range 450–730 km s\(^{-1}\) for terminal wind velocities between 800 and 1300 km s\(^{-1}\) and a power law index of 1.

Using an average luminosity of \( 1 \times 10^{34} \text{erg s}^{-1} \), Equation 3.2, the range of wind velocities and plasma density ratios, the corresponding neutron star spin periods fall between 50 and 90 s. These values are comparable with the majority of known spin periods in SFXTs (see Table 1.1) and hence the subsonic propeller regime could be invoked to explain this low activity period if the neutron star is slowly rotating with a magnetic field strength of \( 10^{12} \text{Gauss} \).

Given the low luminosities associated with region A, the quasi-spherical accretion theory of Shakura et al. (2012) can also be applied. In this framework, for luminosities below \( \sim 3 \times 10^{35} \text{erg s}^{-1} \), the source inhabits a region where plasma held above the magnetosphere cools by thermal bremsstrahlung before entering the magnetosphere by the Rayleigh Taylor instability (Shakura et al., 2013). The low luminosity interval at the beginning of the XMM-Newton observation can be explained as lower density plasma entering the magnetosphere during this time.

Recently, hydrodynamic simulations of Vela X–1, taking into account ionisation of the stellar wind by the central X-ray source, by Manousakis & Walter (2015) have shown that off-states lasting between 300 s and 7.2 ks can be generated by lower density ‘bubble’ structures forming in the wind around the neutron star. The density of these bubbles is approximately one tenth that of the time-averaged density of the plasma surrounding the neutron star causing a corresponding luminosity drop of the same factor. Therefore, the presence of one of these low density bubbles could also explain the first 6 ks of this XMM-Newton observation.

The increase in luminosity following the low activity region can also be explained within the framework of quasi-spherical accretion as increases in the amount of material entering the magnetosphere while still in the radiative cooling regime. The main flare event (regions E and F) at approximately 17 500 ks exceeds the critical luminosity value of \( \sim 3 \times 10^{35} \text{erg s}^{-1} \) (shown as a red dashed line in Figure 3.8) for
a transition between the radiative and Compton cooling regimes (Shakura et al., 2013). This occurs at approximately the same time as the evolution to a harder photon index in the spectral fits.

After the period of enhanced soft X-ray emission, the source decreases in luminosity and appears to return to the radiatively cooled regime, again with flaring behaviour. Using the second \textit{INTEGRAL} observation of SAX J1818.6−1703 during Revolution 1274, we can infer the soft X-ray behaviour of the source after the \textit{XMM-Newton} observation. During the \textit{INTEGRAL} observation, an average source flux of 1.27 counts s$^{-1}$ was detected. Using the same method as for the previous \textit{INTEGRAL} observation between MJD 56371.465 and 56371.864, an \textit{XMM-Newton} 0.5–10 keV count rate of 2.6 counts s$^{-1}$ can be inferred. Assuming an absorbed power law with absorbing column density, $N_H = 5 \times 10^{23}$ cm$^{-2}$ and photon index, $\Gamma = 1.9$, this corresponds to a luminosity of $1.9 \times 10^{35}$ erg s$^{-1}$. This is consistent with continued flaring behaviour following the \textit{XMM-Newton} observation of SAX J1818.6−1703.

It is worth noting that although the distribution of orbital eccentricities of SFXTs is not well known (see Paizis & Sidoli 2014 and references therein), short-period systems are likely to have more circular orbits. The high eccentricity of SAX J1818.6−1703 and resulting wind density variation along the orbit experienced by the compact object is likely to be an additional factor and acting alongside the mechanisms discussed above driving the atypical variability seen in this source.

### 3.4.4 Spectral Variation

The analysis of the hardness ratio evolution shows that SAX J1818.6−1703 undergoes clear spectral evolution, shown in Figure 3.7, during the development of the flaring behaviour. The ‘harder-when-brighter’ relation often seen in HMXBs is also seen in this observation, as shown in Figure 3.5. Spectra A, E and F clearly show this behaviour, however in the intermediate intensity range, this relationship is less clear. One explanation for this could be that the average source count rate is not representative of source luminosity as the spectral extraction regions contain both flare peaks and lower intensity portions of the light curve. Changes in absorption caused by circumstellar material could also mask or distort the ‘harder-when-brighter’ relation, but there is no evidence for that here.

A more detailed analysis (see Table 3.3) revealed variations in the photon index. The source shows significant variation in photon index and when comparing this to the EPIC-pn light curve of Figure 3.4, it is clear that the source evolves from a soft spectrum at the onset of the flaring episode to a harder spectrum around the main flare event. From Figure 3.7, using a power law fit, it is evident that this is a true variation within this model and not a result of the correlation of the fit parameters as the parameters are seen to be only weakly correlated. However, using a more
realistic absorption model could change the observed relationship between the absorption and spectral slope. Although the evolution shown in Figure 3.7 is model-dependent, evolution in the hardness ratio shows that higher energy photons are being detected for periods of higher flux. An absorbed power law is one method of characterising this change which gives reasonable fits to the data.

It can be seen from Table 3.3 that the photon index of the underlying continuum varies from 0.3 to 2.5 on a time-scale of approximately 10 ks. The absolute values of absorbing column density are among the highest ever observed in an SFXT and are comparable with the observed \((6 \pm 1) \times 10^{23} \text{ cm}^{-2}\) in IGR J16465−4507 (Walter et al., 2006). Previous soft X-ray observations of an outburst of this source around periastron by Sidoli et al. (2009c) with \textit{Swift} did not reveal any spectral variability in either photon index or absorbing column density; however, the source was in outburst for the duration of the observation. Those observations did reveal a high absorbing column density of \((5 \pm 7) \times 10^{22} \text{ cm}^{-2}\) and a photon index of \(\Gamma = 0.3 \pm 0.2\) for a cut-off power-law fit to \textit{Swift}/XRT and BAT data. This absorption is still an order of magnitude less than that measured in this observation, while the photon index is consistent with that measured here. Such large values of absorbing column density are more in line with those measured in the highly obscured persistent HMXBs discovered by \textit{INTEGRAL} (Walter et al., 2003; Filliatre & Chaty, 2004). Given the line of sight absorption to SAX J1818.6−1703 \((N_{H} = 1.42 \times 10^{22} \text{ cm}^{-2}; \text{Dickey & Lockman 1990})\), it is clear that this increased absorption is intrinsic to the system.

3.4.5 Temporal Studies

Spin periods of neutron stars in SFXTs are known for less than half of the known sources and range from \(\sim 5 \text{ s}\) in AX J1841.0-0536 (Bamba et al. 2001, see also Romano et al. 2011b for further discussion) to \(\sim 1212 \text{ s}\) in the case of IGR J16418–4532 (Sidoli et al., 2012). Previous observations of SAX J1818.6−1703 with \textit{XMM-Newton} and \textit{Swift} have failed to find a periodic signal that could be interpreted as a neutron star spin period (Sidoli et al., 2009c; Bozzo et al., 2012).

Searching for a neutron star spin period in this system using a both a Lomb-Scargle periodogram and an epoch folding method as described in Section 3.3.2, no significant periodicities are detected in the range of 2s–4.2h. This period range is the range over which the data set would allow for a periodic signal to be detected with confidence and covers the spread in known neutron star spin periods in SFXTs (Paizis & Sidoli, 2014). Since spin periods in some systems have only been detected in certain accretion states, time windows corresponding to periods of lower and higher intensity were selected from the EPIC-PN light curve \((t<8500, 8500<t<15000, 15000<t<25000, t>25000)\) and tested for the presence of neutron
star spin periods; however, no significant signal was detected.

A possible explanation for the lack of a neutron star spin period detection comes from the nature of the behaviour during this observation. The source exhibits flaring activity, with 5 flares each lasting $\sim$1 ks and a main flare event, seen to occur approximately 17.5 ks after the start of the observation. The rapidly changing nature of the flux could have masked any periodic modulation due to the rotation of the neutron star.

Another explanation for the non-detection could be that the spin period value lies outside the range probed in this work. This would imply the neutron star is either a faster or slower rotator compared to other neutron stars hosted in SFXTs. Currently, the longest known neutron star spin period in an HMXB is 36 200±100 s found in AX J1910.7+0917 (Sidoli et al., 2017). If the neutron star in SAX J1818.6−1703 were to have such a slowly rotating neutron star, it would be located at the extreme end of the spin period distribution for HMXBs (Figure 1 of Enoto et al. 2014; catalogue: Liu et al. 2006).

One further possibility to explain the lack of pulsations would be a geometric effect such as low inclination of the binary plane or the existence of a small angle between rotation and magnetic field axes as suggested by Reynolds et al. (1999) for the HMXB 4U 1700–37.

The non-detection of a spin period allows the possibility that the compact object could be a black hole. However, there are currently no candidate black hole systems amongst SFXTs and only a handful in the entire population of HMXBs e.g Cyg X−1, LMC X−3 and MWC 656 (Bolton, 1975; Cowley et al., 1983; Casares et al., 2014).

There is a hint of ‘quasi-periodic’ flaring in the light curve, on a time-scale of about 2 ks. This could be explained by a number of models of HMXB accretion (see for example, the discussion in Sidoli et al. 2012 regarding quasi-periodicity in X-ray flaring of the SFXT, IGR J16418–4532). The explanations that seem to better apply to SAX J1818.6–1703 include the quasi-spherical settling accretion model (Shakura et al., 2012), where convective motion at the base of the shell located above the magnetosphere can produce X-ray flares on a quasi-periodic time scale, or the effects seen in hydrodynamic simulations of the accretion flow in the vicinity of the neutron star (Manousakis & Walter 2015 and references therein), where low-density bubbles forms and are accreted by the neutron star in a sort of ‘breathing mechanism’, alternating between low- and higher density matter.
3.5 Conclusions

In this chapter I have presented, for the first time, soft X-ray observations of SAX J1818.6–1703 around periastron. The observed luminosities seen in both INTEGRAL and XMM-Newton place this source in a highly active state with periods of fast flaring followed by a longer duration flare event reaching a peak luminosity of $\sim 6 \times 10^{35}$ erg s$^{-1}$. The large increase in activity is coincident with a significant hardening of the source spectrum from a photon index $\Gamma \sim 1.9$ to $\Gamma \sim 0.3$, suggesting a change in accretion mechanism compared to the earlier flaring activity. Although other mechanisms cannot be ruled out, we note that the luminosity of the main flare period exceeds the critical luminosity required for a transition between the radiative and Compton cooling regimes in the theory of quasi-spherical accretion proposed by Shakura et al. (2012). We also report an initial lower luminosity state with $L_X \sim 10^{34}$ erg s$^{-1}$ that could be generated either by the source entering a subsonic propeller regime as outlined by Bozzo et al. (2008b) or by a decrease in density of material accreting on to the neutron star.

Spectral analysis indicates high intrinsic absorbing column densities of $N_H \sim 5 \times 10^{23}$ cm$^{-2}$; an order of magnitude higher than previous observations of the source. These column densities are amongst the highest measured in an SFXT and comparable to those found in highly obscured HMXBs discovered by INTEGRAL (Walter et al., 2006).

Further detailed investigation of this source relies upon a determination of the neutron star characteristics, principally its spin period and magnetic field strength, as has recently been demonstrated by NuSTAR observation of IGR J17544–2619 (Bhalerao et al., 2015). Observations with these aims in mind are instrumental to disentangle the accretion processes generating the observed X-ray behaviour in this prototypical SFXT.
Chapter 4

Observations of the SFXT IGR J18450−0435 with INTEGRAL and XMM-Newton around periastron

4.1 Introduction

In this chapter, I present the results of two periastron-targeted XMM-Newton of the intermediate SFXT, IGR J18450−0435 with simultaneous hard X-ray data from INTEGRAL. This is the first time that such observations have been performed for this source.

IGR J18450−0435 was first discovered as AX J18450−0433 during ASCA observations of the Scutum Arm between 1993 October 18–24. Initially found with an unabsorbed flux of $\sim 3 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, the source reached a peak flux of $\sim 10^{-9}$ erg s$^{-1}$ cm$^{-2}$ in under 1 hour (Yamauchi et al., 1995). INTEGRAL first observed the source as part of a survey of the Sagittarius Arm during 2004 (Molkov et al., 2004) and later associated with AX J18450−0433 (Halpern & Gotthelf, 2006) before being confirmed by during a Swift/XRT observation by Sguera et al. (2007a).

Using optical/IR spectroscopy Coe et al. (1996) suggested the counterpart to be an O9.5I supergiant at a distance of approximately 3.6 kpc. The associated error on this distance estimate was suggested to be large due to the uncertainty in the reddening law used, though an exact value could not be calculated. Subsequent work by Negueruela et al. (2008a), using broad-band spectroscopy and the more complicated reddening law of Cardelli et al. (1989), resulted in a source distance of 7 kpc. This estimate has since been refined and constrained to $6.4\pm0.76$ by Coleiro & Chaty (2013) using SED fitting of Optical/Near IR data from the Two Micron...
Table 4.1: Log of observations of IGR J18450−0435 discussed in this work. Phases are calculated using the ephemeris of Goossens et al. (2013) (MJD 52708.43297 as phase=0, which leads to a peak in the phase folded light curve at $\phi = 0.65$).

<table>
<thead>
<tr>
<th>Instrument</th>
<th>UTC</th>
<th>MJD</th>
<th>Phase</th>
<th>Exp (ks)</th>
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<td>56944.026</td>
<td>0.553−0.924</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>2014 Oct 16 03:35:15</td>
<td>56946.150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>2014 Oct 13 23:29:03</td>
<td>56943.978</td>
<td>0.545−0.591</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>2014 Oct 14 05:50:43</td>
<td>56944.244</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>2014 Oct 15 16:20:00</td>
<td>56945.681</td>
<td>0.842−0.882</td>
<td>18 (pn)</td>
</tr>
<tr>
<td></td>
<td>2014 Oct 15 21:50:00</td>
<td>56945.910</td>
<td></td>
<td>13 (MOS)</td>
</tr>
</tbody>
</table>

All Sky Survey point-source catalogue.

Previous observations of IGR J18450−0435 using INTEGRAL and Swift by Sguera et al. (2007a) showed fast flaring behaviour on time scales of tens of minutes. A spectral analysis of the Swift/XRT data revealed absorbing column densities of $2.3\pm0.7$ and $1.6\pm0.18\times10^{22}\text{cm}^{-2}$, consistent with the line-of-sight galactic absorption, and photon indices between 0.75 and 0.85. The XRT spectrum was also adequately fit with a black body model with $kT = 2.4\pm0.2$.

Subsequent observations by using XMM-Newton and INTEGRAL by Zurita Heras & Walter (2009) showed variability by a factor of 50 on times scales of a few hundred seconds. The broad band spectrum (0.4−100 keV) was described by a hard continuum with a soft X-ray excess below 2 keV, a high energy cut off at $\sim16$ keV and an absorbing column density of $2.6\pm0.2\times10^{22}\text{cm}^{-2}$. The authors suggested that the flaring behaviour was consistent with the accretion of clumps of mass $M \sim 10^{22}\text{g}$ forming within the supergiant stellar wind.

Using INTEGRAL/IBIS data, Goossens et al. (2013) found a periodicity of $5.7195\pm0.0007$ days, which they attributed to the orbital period of the system. Knowledge of this orbital period allowed the authors to place upper limits of $<27R_\odot$ and $e<0.37$ on the supergiant radius and orbital eccentricity as well as show that outbursts detected from this source cluster around periastron.

### 4.2 Data Analysis

#### 4.2.1 INTEGRAL data analysis

IGR J18450−0435 was observed by INTEGRAL (Ubertini et al., 2003; Winkler et al., 2003) between MJD 56944.026 and 56946.150 for a total on-source exposure of 41 ks covering phases $\phi = 0.553−0.924$. This observation was processed using the INTEGRAL Offline Science Analysis software (OSA) version 10.1. Images were created at science window resolution (ScW, a single pointing of INTEGRAL lasting

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approximately 2 ks) in the 22–60 keV energy band and a mosaic of all ScW images (Figure 4.1).

4.2.2 XMM-Newton data analysis

IGR J18450–0435 was also observed by XMM-Newton in two ~20 ks observations simultaneous with the INTEGRAL observations discussed above. The first observation (hereafter Obs 1) occurred between MJD 56943.978 and 56944.244, covering phase range $\phi = 0.545 - 0.591$ with a total exposure of 21 ks. The second (hereafter Obs 2) was taken between MJD 56945.681 and 56945.910, covering phase range $\phi = 0.842 - 0.882$ with a total exposure of 18 ks. During both observations the EPIC-pn camera was operated in small window mode, while the EPIC-MOS cameras were operated in full frame mode. Table 3.1 lists all observations of IGR J18450–0435 discussed in this chapter and all phases are calculated using the orbital period and ephemeris of Goossens et al. (2013) ($P = 5.7195 \pm 0.0007$ days, MJD 52708.43297).

All XMM-Newton observations were analysed using the XMM-Newton Science Analysis System (SAS) Version 14.0.0. Cleaned event files were produced using the standard epproc and emproc for the EPIC-pn and EPIC-MOS cameras respectively. All data sets were filtered for flaring particle background and checked for pile-up using the standard analysis pipeline as outlined in the SAS Data Analysis Threads.

Due to high radiation during Obs2, the EPIC-MOS cameras shut down leading to a reduced exposure time in the EPIC-MOS cameras for this observation. Due to the interruption in observation and the increased radiation background during this observation, we neglect the EPIC-MOS data for Obs2 and instead restrict our analysis to the EPIC-pn data as this camera is much less affected by the high background radiation.

Calibrated events files were created, filtered using patterns 0–4 and 0–12 (corresponding to single and double events) for EPIC-pn and EPIC-MOS respectively. Optimal extraction regions for spectra and light curves were found using the SAS tool eregionanalyse, however due to the nearby, unidentified XMM-Newton X-ray source 2XMMi J184505.0–043351, these regions were revised to avoid contamination. Extraction radii of 26, 34, and 21 arcseconds were utilised for EPIC-pn, EPIC-MOS1 and EPIC-MOS2 respectively during Obs1, while an extraction radius of 10 arcseconds was used for the EPIC-pn camera during Obs2.

Light curves in the 0.2–10 keV energy range were initially extracted from EPIC-pn and EPIC-MOS at 100 s resolution and the light curves from Obs1 and Obs2,

\footnote{http://xmm.esac.esa.int/sas/current/documentation/threads/}
binned such that each point represents a $3\sigma$ detection, are shown in Figure 4.2.

All spectra were extracted using standard procedures described in the XMM-Newton Data Analysis Threads with detector responses generated using the SAS tools rmfgen and arfgen. Extracted spectra were grouped with a minimum of 20 counts per bin using the SAS tool specgroup and fit in the 0.5–12 keV band using xspec version 12.8.2 (Arnaud, 1996). All uncertainties related to the spectral fits are quoted at the 90% confidence level and elemental abundances are set by the abundances of Wilms et al. (2000) for all absorption models.

4.3 Results

4.3.1 INTEGRAL results

Figure 4.1 shows the 22–60 keV INTEGRAL IBIS mosaic of the observation listed in Table 4.1. IGR J18450−0435 was not detected in the IBIS/ISGRI 22–60 keV map leading to a $3\sigma$ upper limit on the flux of $1.04 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, corresponding to a luminosity of $5.10 \times 10^{34}$ erg s$^{-1}$. Examination of individual ScW images occurring simultaneously with the XMM-Newton observations also reveals no detections of the source in the 22–60 keV energy band. We note that the brightest source in this image is the nearby SFXT, IGR J18483−0311 undergoing an outburst. Analysis and discussion of this source in outburst is beyond the scope of this work - for a recent broad-band study of this source during outburst see Sguera et al. (2015).

4.3.2 XMM-Newton Results

XMM Temporal Analysis

Figure 4.2 shows the broad-band 0.2–10 keV EPIC-pn light curves for the XMM-Newton observations of IGR J18450−0435 referred to as Obs1 and Obs2 above with each point representing at least a $3\sigma$ bin. The left-hand panel shows the light curve for Obs1 with $t_0 = \text{MJD} 56943.994$ as the first time stamp. This light curve shows fast (∼400 s) flaring behaviour, with the main flares in the observation reaching peak count rates of $21.17 \pm 0.61$ and $21.93 \pm 0.62$ counts s$^{-1}$ for the first and second flares respectively. Outside of this flaring behaviour, the source shows a low level of X-ray emission, with an average count rate of $0.18 \pm 0.01$ counts s$^{-1}$. The right-hand panel shows the light curve of Obs2, the XMM-Newton observation of IGR J18450−0435 taken ∼2 days after Obs1, with $t_0 = \text{MJD} 56945.696$. The source behaviour in this observation is similar to that of the low flux state seen in
Figure 4.1: 22–60 keV INTEGRAL/IBIS significance map of the observations of IGR J18450–0435 taken between MJD 56944.026 and 56946.150. The best X-ray positions of IGR J18450–0435 the SFXTs IGR J8410–0535 and IGR J18483–0311 as well as the SgH-MXB XTE J1855–026 are shown in white circles.
Figure 4.2: Left-hand Panel: EPIC-pn 0.2–10 keV light curve of the observation of IGR J18450−0435 taken between MJD 56943.978 and 56944.244 (Obs1) with each point representing at least a 3σ bin. In this panel $t_0 = \text{MJD 56943.994}$. Right-Hand Panel: EPIC-pn 0.2–10 keV light curve of the observation of IGR J18450−0435 taken between MJD 56945.681 and 56945.910 (Obs2) with each point representing at least a 3σ bin. In this panel, $t_0 = \text{MJD 56945.696}$

Obs1 with an average count rate of 0.157±0.006 counts s$^{-1}$ and not showing any flaring behaviour.

Temporal analysis for all observations is restricted to the EPIC-pn light curves due to the higher sensitivity and hence higher count rates with respect to the EPIC-MOS detectors.

Broad band 0.2–10 keV light curves for all observations were extracted at 1 second resolution in order to search for a periodic signal indicative of the presence of an accreting neutron star. A Lomb–Scargle periodogram (Lomb, 1976; Scargle, 1982) was produced using the fast implementation of Press & Rybicki (1989). Adopting the method of Hill et al. (2005), Monte-Carlo simulations were used with 100,000 trials to generate significance levels, above which one would consider a signal to be true. Searching the whole light curves of observations Obs1 and Obs2 revealed no significant periodic signals in the range 2 s–7 ks. Temporal regions, selected for low and high X-ray intensities, were also searched. For Obs1, the low intensity region corresponds to the times $t-t_0 < 7800, 12800 < t-t_0 < 18900$ and $t-t_0 > 19200$,......
while a higher intensity region corresponds to \(7800 < t - t_0 < 11900\). Searches in these temporal windows revealed no significant signals in the range 2\(s\) to 2.5\(ks\). Obs2 was not subdivided for temporal analysis as the activity during this observation is all low level emission, similar to that of the low flux periods of Obs1.

**XMM Spectral Analysis**

The hardness ratio through the observation was calculated using the definition of Equation 3.1 as an initial, model-independent diagnostic of spectral variability. Due to the strong absorption present around periastron in SFXTs, the hard and soft bands were defined as \(H = 5–10\) keV and \(S = 0.2–5\) keV to overcome photon loss below 2 keV. There is no clear evidence of hardness ratio evolution over the course of the *XMM-Newton* observations analysed in this chapter. Rebinning the hardness ratio light curve may result in smoothing out short time scale variability, hence we only calculate hardness ratios for temporal regions used for spectral extraction henceforth.

Given the lack of obvious spectral variability over the course of all the observations, spectra were selected based on the light curve morphology. These regions are labelled A–F and are shown in Figure 4.3 with the associated extraction times given.
Table 4.2: Times associated with the regions used in the spectral analysis of Obs1. Times are given in seconds as $t-t_0$, where $t_0 = \text{MJD 56943.994}$ - the first time stamp in the PN light curve.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>$T_{\text{start}}$</th>
<th>$T_{\text{stop}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>7800</td>
</tr>
<tr>
<td>B</td>
<td>7800</td>
<td>10400</td>
</tr>
<tr>
<td>C</td>
<td>10800</td>
<td>11900</td>
</tr>
<tr>
<td>D</td>
<td>10400</td>
<td>10800</td>
</tr>
<tr>
<td>E</td>
<td>12000</td>
<td>18900</td>
</tr>
<tr>
<td>F</td>
<td>18900</td>
<td>19200</td>
</tr>
<tr>
<td></td>
<td>19200</td>
<td>21300</td>
</tr>
</tbody>
</table>

in Table 4.2. Spectra from Regions A, D and F (the low flux regions) were combined due to the similarity in light curve morphology and in order to improve the statistical quality of the data products.

Pile Up

During Obs1, the source exhibits both bright flaring periods (Regions C and E) and lower level flaring (Region B). The bright flare peak count rates in the EPIC-pn camera approach a rate at which spectral distortions and flux loss due to pile up may become important\(^2\). These effects were accounted for during the creation of response matrices for EPIC-pn spectra extracted from these temporal regions using the `correctforpileup` flag with the `rmfgen` tool.

In the case of the EPIC-MOS detectors, due to their operation in Large Window mode, the count rate threshold for pile is significantly lower than that of EPIC-pn. Subsequently, count rates for Regions B, C and E exceed the threshold for significant spectral distortion and flux loss. Correcting EPIC-MOS spectra for pile up effects using the `rmfgen` tool is not possible at the time of writing. The usual procedure for pile up correction in this case involves excising the core of the point spread function, where the source is most piled up, and evaluating the pile up using the `epatplot` tool. However, due to the short exposure and low count rates in this interval, the statistical approach taken by the `epatplot` tool is not a reliable measure of pile up. As a result of this, and coupled with the fact that excision of any core region will lower the statistical quality of the resulting spectra, spectral analyses of Regions B, C and E are restricted to spectra taken from the EPIC-pn camera.

\(^2\)Limits for both EPIC-pn and EPIC-MOS are given by Jethwa et al. (2015)
Spectral Results

Spectra extracted from the selected regions of Obs1 and the average spectrum of Obs2 were fit with absorbed power law and black body models ($\text{tbabs*cf}lux(\text{powerlaw})$ and $\text{tbabs*cf}lux(\text{bbodyrad})$ in xspec notation) in the 0.5–12 keV range. In the case of the average Obs2 spectrum and A+D+F where EPIC-pn and EPIC-MOS data were fit simultaneously, a constant model component was added to account for the systematic differences between the cameras. The $\text{cflux}$ model component was utilised in this way to calculate the 0.5–10 keV unabsorbed flux of the models.

Best fit parameters of the power law fits to spectra extracted from Obs1 and Obs2 are found in Table 4.3 and the spectra are shown in Figure 4.4. The hardness ratio, as calculated by the method described above, is also presented as well as the average counts of these temporal regions. Luminosities associated with the spectra are calculated assuming a distance to the source of 6.4±0.76 kpc (Coleiro & Chaty, 2013). This choice of source distance is justified in Section 4.4.2.

The power law model fits show all spectra have high absorbing column densities with values of $N_H \sim 10^{23} \text{cm}^{-2}$ for Obs1 spectra and $N_H \sim 7 \times 10^{22} \text{cm}^{-2}$ for Obs2. Given the line of sight absorption to IGR J18450−0435 is $1.52 \times 10^{22} \text{cm}^{-2}$ (Dickey & Lockman, 1990), this enhanced absorption is intrinsic to the system. Spectrum E also shows greater absorption than the line-of-sight value, however the magnitude of absorption is roughly half that seen in other spectra taken from this observation. Coincident with this drop in column density, a significant hardening of the photon index to $\Gamma = 0.61$ is also seen. Other spectra from Obs1 and Obs2, however have photon indices consistent with those of accreting X-ray pulsars. It is of note that while the initial hardness ratio analysis did not reveal any clear variations when computing the average hardness ratio for each spectral extraction region, we see that there is evidence of evolution, however the harder photon index seen in spectrum E does not correspond to the greatest value of the hardness ratio.

Best fit parameters of the black body fit to spectra taken from Obs1 and Obs2 are shown in Table 4.4. Again, hardness ratios, average counts and 0.5–10 keV fluxes and luminosities are presented for comparison. As with the power law fit, enhanced local absorption is seen with a decrease coinciding with spectrum E however the magnitudes of this absorption in all spectra are approximately half that seen in Table 4.3. Spectrum E also sees an increase in black body temperature to 2.67 keV which is equivalent to the harder photon index seen in the power law fits. The other black body temperature fits for Obs1 are broadly consistent around 2 keV, while the fit for Obs2 shows a much cooler black body of 1.64 keV which is again consistent with a much soften spectrum as seen in the hardness ratio and power law fit.

More complex models often used to described SFXT spectra such as
Figure 4.4: Power law spectral fits to spectra extracted from the XMM-Newton observation of IGR J18450–0435 between MJD 56943.978 and 56944.244.
Table 4.3: Hardness ratios, average counts and best fit parameters of TRABS*CFLUX(Powerlaw) model fits to the spectra outlined in Table 4.2 and also Obs2. Absorbing column density, $N_H$ is given in units of $10^{22}$ cm$^{-2}$, the 0.5–10 keV flux is given in units of $10^{-11}$ erg s$^{-1}$ cm$^{-2}$. Luminosities are calculated using a source distance of 6.4$^{+0.76}_{-0.76}$ and are given in units of $10^{35}$ erg s$^{-1}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C</th>
<th>E</th>
<th>B</th>
<th>A+D+F</th>
<th>Obs2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>-0.10$^{+0.02}_{-0.02}$</td>
<td>-0.05$^{+0.02}_{-0.02}$</td>
<td>0.02$^{+0.02}_{-0.02}$</td>
<td>-0.04$^{+0.02}_{-0.02}$</td>
<td>-0.22$^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>Avg Cts</td>
<td>8.48$^{+0.17}_{-0.17}$</td>
<td>3.85$^{+0.13}_{-0.13}$</td>
<td>1.14$^{+0.02}_{-0.02}$</td>
<td>0.18$^{+0.01}_{-0.01}$</td>
<td>0.16$^{+0.01}_{-0.01}$</td>
</tr>
<tr>
<td>$N_H$</td>
<td>9.75$^{+0.98}_{-0.88}$</td>
<td>4.86$^{+0.87}_{-0.77}$</td>
<td>10.04$^{+1.00}_{-0.90}$</td>
<td>9.62$^{+0.87}_{-0.80}$</td>
<td>7.00$^{+0.91}_{-0.81}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>1.45$^{+0.14}_{-0.13}$</td>
<td>0.61$^{+0.16}_{-0.15}$</td>
<td>1.17$^{+0.12}_{-0.12}$</td>
<td>1.30$^{+0.12}_{-0.12}$</td>
<td>1.61$^{+0.17}_{-0.16}$</td>
</tr>
<tr>
<td>$\chi^2_{\text{red}}$ (d.o.f)</td>
<td>1.30 (95)</td>
<td>1.11 (86)</td>
<td>0.95 (107)</td>
<td>1.17 (220)</td>
<td>1.15 (108)</td>
</tr>
<tr>
<td>Flux</td>
<td>28.8$^{+3.20}_{-2.50}$</td>
<td>17.7$^{+1.00}_{-0.90}$</td>
<td>3.74$^{+0.30}_{-0.25}$</td>
<td>0.62$^{+0.05}_{-0.04}$</td>
<td>0.46$^{+0.07}_{-0.05}$</td>
</tr>
<tr>
<td>L</td>
<td>14.1$^{+2.80}_{-2.70}$</td>
<td>8.68$^{+1.54}_{-1.52}$</td>
<td>1.83$^{+0.34}_{-0.33}$</td>
<td>0.30$^{+0.06}_{-0.05}$</td>
<td>0.22$^{+0.05}_{-0.05}$</td>
</tr>
</tbody>
</table>

Comptonisation of soft photons due to hot plasma (COMP+-TT in XSPEC) and a cut-off power law (CUTOFFPL) were also fit to spectra extracted from Obs1 and Obs2. These fits however did not give improved fits relative to the more simple models described above. In all cases, the Comptonisation model, the seed photon and plasma temperatures along with the plasma optical depth are highly unconstrained. In the case of the cut-off power law fits, the photon index and high energy cut off are often unconstrained. In order to illustrate this, the model parameters for fits of these models to spectrum B, which shows flaring behaviour, are compared. The best fit parameters of the Comptonisation model are: seed photon temperature $T_0 = 1.40 \pm 0.60$ keV, plasma temperature $kT = 52 \pm (1 \times 10^5)$ keV and optical depth $\tau = 0.89 \pm 2579$. The best fit photon index of the cut-off power law for this spectrum is found to be unconstrained at $\Gamma = -0.53^{+0.79}_{-0.70}$ and $E_{\text{cut}} = 3.89^{+3.33}_{-1.22}$ keV for the high energy cut off. This best fit value is likely due to lack of hard X-ray data to constrain any spectral cut off as such features are usually present around 15–20 keV. While the black body model is a good fit to all the spectra considered in this work, black body temperatures greater than 2 keV, as found in spectra B and E, are often interpreted to be unphysical in SFXT spectra. To this end, the power law model is utilised as a non-physical characterisation of spectral shape for the rest of this chapter. It is worthy of note that the black body model when fit to spectrum A+D+F is very good with a reduced chi-squared value of 1, however the uncertainty on the derived flux and hence luminosity result in consistent values with power law fit to this spectral region. As a result, the discussion and conclusions presented below are unaffected by the choice of a power law fit over black body as an adequate description of the underlying spectra. It is also noted that while the absorbing column densities from the black body model are all significantly different to those found in the power law fits, the trend in the best fit parameters is the same and hence does not change any interpretation presented in Section 3.4.
Table 4.4: Hardness ratios, average counts and best fit parameters of \texttt{tbabs*cflux(bbodyrad)} model fits to the spectra outlined in Table 4.2 and also Obs2. Absorbing column density, $N_H$ is given in units of $10^{22}$ cm$^{-2}$, the 0.5–10 keV flux is given in units of $10^{-11}$ erg s$^{-1}$ cm$^{-2}$. Luminosities are calculated using a source distance of 6.4±0.76 and are given in units of $10^{35}$ erg s$^{-1}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C</th>
<th>E</th>
<th>B</th>
<th>A+D+F</th>
<th>Obs2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR</td>
<td>-0.10±0.02</td>
<td>-0.05±0.02</td>
<td>0.02±0.02</td>
<td>-0.04±0.02</td>
<td>-0.22±0.03</td>
</tr>
<tr>
<td>Avg Cts</td>
<td>8.48±0.17</td>
<td>3.85±0.13</td>
<td>1.14±0.02</td>
<td>0.18±0.01</td>
<td>0.16±0.01</td>
</tr>
<tr>
<td>$N_H$</td>
<td>5.27$^{+0.56}_{-0.50}$</td>
<td>2.18$^{+0.57}_{-0.45}$</td>
<td>5.23$^{+0.57}_{-0.52}$</td>
<td>4.85$^{+0.49}_{-0.45}$</td>
<td>3.02$^{+0.50}_{-0.44}$</td>
</tr>
<tr>
<td>kT (keV)</td>
<td>1.89$^{+0.09}_{-0.09}$</td>
<td>2.67$^{+0.24}_{-0.21}$</td>
<td>2.19$^{+0.11}_{-0.10}$</td>
<td>1.98$^{+0.09}_{-0.08}$</td>
<td>1.64$^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td>$\chi^2_{\text{red}}$ (d.o.f)</td>
<td>1.19 (95)</td>
<td>1.27 (86)</td>
<td>0.86 (107)</td>
<td>1.00 (220)</td>
<td>0.92 (112)</td>
</tr>
<tr>
<td>Flux</td>
<td>17.6$^{+0.70}_{-0.70}$</td>
<td>14.9$^{+0.70}_{-0.70}$</td>
<td>2.58$^{+0.09}_{-0.08}$</td>
<td>0.40$^{+0.14}_{-0.14}$</td>
<td>0.26$^{+0.01}_{-0.01}$</td>
</tr>
<tr>
<td>L</td>
<td>8.63$^{+1.49}_{-1.49}$</td>
<td>7.30$^{+1.27}_{-1.27}$</td>
<td>1.26$^{+0.22}_{-0.22}$</td>
<td>0.20$^{+0.34}_{-0.34}$</td>
<td>0.13$^{+0.02}_{-0.02}$</td>
</tr>
</tbody>
</table>

The 68%, 90% and 99% statistical confidence regions for absorbing column density and photon index taken from fits to spectra extracted from Obs1 are shown in Figure 4.5. While there is some degree of degeneracy between the two parameters, it is clear that spectrum E inhabits a distinctly different region of parameter space compared with the other spectra taken from Obs1.

From this analysis, a significant variation in photon index during Obs1 can be seen. While this variation is coincident with a bright flare, a temporal region with similar morphology earlier in the observation (region C) does not have a similar spectral shape. This suggests that the two bright flares may be the result of different accretion processes.

### 4.4 Discussion

In this chapter I have presented the results of two ∼20 ks \textit{XMM-Newton} observations of the intermediate SFXT, IGR J18450−0435. The first of the observations is targeted at periastron, while the second occurred approximately one quarter of an orbital cycle later. Simultaneous \textit{INTEGRAL} observations spanning 144 ks with a total of 41 ks of on-source exposure are also presented. Below I clarify the source distance and use this information to discuss implications of these observations in building up a picture of the accretion phenomena at work in IGR J18450−0435 during these observations.

#### 4.4.1 \textit{INTEGRAL} context

A previous study of IGR J18450−0435 by Goossens et al. (2013) using long base-line \textit{INTEGRAL}/IBIS data revealed this source to be a short period system...
Figure 4.5: Confidence contours for the best fitting spectral parameters to spectra extracted from Obs1 using an absorbed power law model (tbabs*cflux(powerlaw)) with the 68%, 90% and 99% statistical confidence regions marked. Regions B, C, E and A+D+F are marked it green dot-dashed, red dashed, magenta dotted and solid blue lines respectively.
with $P_{\text{orb}} = 5.7195 \pm 0.0007$ days with evidence of slight eccentricity of the orbit present in the folded light curve. A recurrence analysis performed 0.75 days either side of periastron (leading to a total phase coverage of $\sim 25\%$ of the orbit) also showed a mild orbital phase bias in detected emission with $\sim 12\%$ of periastron passages showing $\geq 3\sigma$ detections compared with 0.9\% for apastron. This phase bias is also indicative of orbital eccentricity, however it does suggest a somewhat less eccentric orbit than that of the prototypical SFXT, SAX J1818.6–1703 with $e = 0.3–0.4$ and 50\% of periastron passages showing detectable emission with a significance greater than $3\sigma$ (Bird et al., 2009). Goossens et al. (2013) constrained the eccentricity of IGR J18450–0435 by assuming the orbit is such that the star does not fill its Roche Lobe and derive an upper limit of $e < 0.37$ based on this. Comparing the *INTEGRAL* observations of IGR J18450–0435 reported in this work covering the phase range $\phi = 0.553–0.924$ (periastron phase $\sim 0.65$) with the analysis of Goossens et al. (2013), we can see that this observation appears to be typical of periastron passages of this source observed by *INTEGRAL*, with no detectable emission around periastron. The recurrence analysis is particularly suited for detection of longer periods of activity as the significance of each periastron passage is the weighted mean of the flux in a time period $\pm 0.75$ d either side of periastron. As such *INTEGRAL* observations with similar temporal structures as those seen in the *XMM-Newton* light curves of this work would be counted as non-detections due to averaging effects.

This picture is somewhat complicated by the presence of the bright flaring periods observed in the *XMM-Newton* data. The lack of detection in the *INTEGRAL* mosaics is not surprising as short period flaring activity on time scales of a few hundred seconds can be averaged out during the mosaicing process. However, the lack of detection of IGR J18450–0435 at the ScW level in pointings simultaneous with the soft X-ray flaring behaviour suggest that the temporal duration of the flares ($\sim 400$ s) is such that any hard X-ray emission is below the sensitivity limit of *INTEGRAL*/IBIS, there is a sharp spectral cut-off outside the *XMM-Newton* energy range resulting in any hard X-ray emission being below the sensitivity limit of IBIS or a combination of these factors. Simple extrapolation of the power law spectra for Regions C and E to the 22–60 keV energy band results in IBIS/ISGRI source count rates of 5.72 and 10.16 counts s$^{-1}$, respectively. The analytical formula for the $5\sigma$ limiting sensitivity of *INTEGRAL* in the 17–60 keV energy band is given by Krivonos et al. (2010) as $F_{\text{lim}}^{5\sigma} = 0.77(T/\text{Ms})^{-1/2}$ mCrab, where $T$ is the on-source exposure of the source. Assuming on-source exposure durations equal to the flare lengths as observed by *XMM-Newton* of 400 s, the subsequent sensitivity limit is 38.5 mCrab, which corresponds to $\sim 9.21$ counts s$^{-1}$. This implies any detection of these flares by *INTEGRAL*/IBIS would be considered marginal, assuming the soft X-ray spectral shape is also valid in the hard X-ray band. However, it is known that spectra of SFXTs can possess high energy cut-offs in their
spectra, typically at energies between 10–20 keV (Sidoli et al., 2009a,c; Ducci et al., 2010) and hence it is likely the combination of the short flare durations and spectral cut-off resulting the non-detection of flares in the INTEGRAL/IBIS observations.

Examining the long base-line 15–50 keV Swift/BAT light curves of IGR J18450–0435 taken from the BAT transient monitor (Krimm et al., 2013) at the daily average level shows that the source was not detected at a significance greater than 2σ during the INTEGRAL observation reported here or in a 100 day period centred on this observation. As with the INTEGRAL mosaicing process, averaging effects can suppress the presence of short term flaring behaviour however inspection of the orbital average BAT light curve in the same 100 day period around the INTEGRAL observation reveals only one detection with a significance greater than 3σ on MJD 56959.9 with the rest of the light curve showing detections less than 2σ. When considering the non-detection of IGR J18450–0435 during the INTEGRAL observation reported here, coupled with the BAT transient monitor data, I suggest the source is exhibiting typical SFXT behaviour in the hard X-ray band, spending the majority of the time below detection thresholds for both INTEGRAL/IBIS and Swift/BAT.

4.4.2 Source Distance

Observed SFXT behaviour is often ascribed to changes between different accretion regimes, each with their own characteristic luminosities. In order to distinguish between the different accretion mechanisms it is critical to know the distance to the source. In the case of IGR J18450–0435, a number of possible source distances have been discussed in the literature. For the calculation of luminosities in this chapter the constrained distance estimate of 6.4±0.76 kpc from Coleiro & Chaty (2013) is adopted.

4.4.3 Accretion luminosity

The spectral analysis of Section 4.3.2 shows that for the majority of Obs1, the source spend its time in an intermediate luminosity states as seen in SFXTs (Sidoli et al., 2008; Romano et al., 2011a) with an average luminosity of $3 \times 10^{34}$ erg s$^{-1}$. From Figure 4.2 that during the first 7 800 s (region A) of Obs1 the source has a lower average flux than the other non-flaring times (regions D and F) and also reaches a flux minimum. The average and minimum luminosities associated with region A are $(1.5 \pm 0.3) \times 10^{34}$ and $(4.3 \pm 4.0) \times 10^{33}$ erg s$^{-1}$ respectively, assuming the same spectral shape as the combined power law fit to regions A+D+F. Previous observations of IGR J18450–0435 with XMM-Newton reported a ‘quiescent’ luminosity of $1.4 \times 10^{35}$ erg s$^{-1}$ and a minimum of $1.1 \times 10^{34}$ erg s$^{-1}$ at a similar phase to Obs2 (Zurita Heras & Walter, 2009), however the authors used the source
distance of 3.6 kpc reported by Coe et al. (1996). Rescaling these luminosities to 6.4 kpc as discussed above, the subsequent average and minimum luminosities are $4.4 \times 10^{35}$ and $3.5 \times 10^{34}$ erg s$^{-1}$ respectively suggesting the low flux intervals observed in Obs1 and Obs2 represent the lowest luminosity states seen in this source around periastron. The presence of small scale flaring behaviour during these low flux periods also suggests accretion onto the neutron star has not been halted but instead the accretion rate is reduced relative to the rest of the observation. Outside the low flux periods, the source exhibits rapid flaring behaviour with characteristic time scales of $\sim 400$ s with average luminosities of $1.8 \times 10^{35}$ erg s$^{-1}$ in the case of flares occurring in region B and $\sim 1 \times 10^{36}$ erg s$^{-1}$ in the case of spectra C and E. Comparing regions C and E with the flaring behaviour seen in observations of IGR J18450–0435 by Zurita Heras & Walter (2009) with XMM-Newton, it can be seen that the flares observed in Obs1 are typically shorter in duration ($400$ s for regions C and E compared with $\sim 1$ ks for Zurita Heras & Walter 2009) and lower in luminosity ($\sim 1 \times 10^{36}$ erg s$^{-1}$ for regions C and E compared with $5.7 \times 10^{36}$ erg s$^{-1}$ for Zurita Heras & Walter (2009) when using $D = 6.4$ kpc). The peak luminosities of the flares observed in Regions C and E are $(2.8 \pm 0.5) \times 10^{36}$ and $(1.8 \pm 0.3) \times 10^{36}$ erg s$^{-1}$ respectively, suggesting these flares are bright flares observed in the SFXT class.

One possible explanation for the observed low flux periods is obscuration of the neutron star by increased density of stellar wind material. However, the lack of variation in the absorbing column density between the spectra during flaring periods (regions B and C) relative to the low flux intervals rules this out.

The hydrodynamic simulations of Manousakis & Walter (2015) have shown that the influence of the neutron star on the stellar wind via gravitational focussing and photo-ionisation can generate a non-stationary shock front that moves toward and away from the neutron star. This ‘breathing mechanism’ can generate global luminosity variations of up to three orders of magnitude on time scales of $300$ s–$7$ ks. These time scales and luminosity variations match the observed behaviour during Obs1, with periods of low flux lasting $\sim 7$ ks and short flaring behaviour. In this framework, the low flux periods are generated by the non-stationary shock standing off from the neutron star and lower density material behind the shock (closer to the neutron star) being accreted. The large flares, conversely are generated by rapid variation in the shock front toward the neutron star and the accretion of denser material.

Other possible scenarios often discussed in the literature to explain periods of low X-ray activity seen in HMXBs, sometimes referred to as ‘off-states’, include the invocation of magnetic and centrifugal barriers as a means to dampen the accretion rate on to the neutron star or transitions to less effective accretion regimes as a result of variations in the stellar wind parameters. The low flux periods seen in this
observation (regions A, D and F) could possibly be explained by either the neutron star inhabiting the subsonic propeller regime as outlined by Bozzo et al. (2008b) or by transition of the source to the radiative cooling regime in the theory of quasi-spherical accretion (Shakura et al., 2012; Shakura et al., 2013).

In the case of the subsonic propeller regime, matter cannot penetrate the magnetosphere at the rate it is captured by the neutron star gravitational field as the energy input to the matter above the magnetosphere is too great, instead this matter penetrates the magnetosphere by means of the Kelvin-Helmholtz Instability. Following the method of Doroshenko et al. (2011) and Drave et al. (2013), the possibility of the subsonic propeller regime generating the observed low X-ray activity can be evaluated. Recent studies of the stellar companion of the prototypical SFXT IGR J17544−2619 (Giménez-García et al., 2016) allow the use accurate parameters in this calculation due to the similar spectral types of the companion stars in IGR J17544−2619 and IGR J18450−0435. A stellar mass and radius of 25.9 $M_\odot$ and 20 $R_\odot$ respectively are adopted, with stellar mass loss rate $\dot{M}_w = 1.58 \times 10^{-6} M_\odot$ yr$^{-1}$ and terminal wind velocity of 1500 km s$^{-1}$. As the neutron star magnetic field strength of this source is currently unknown, a canonical value of $10^{12}$ G, in line with that detected in IGR J17544−2619 (Bhalerao et al., 2015) is assumed. Using the average luminosity taken from the spectral fit of a power law to Regions A+D+F and the range of plasma densities used by Drave et al. (2013) as parameters in equation 21 of Bozzo et al. (2008b), the corresponding neutron star spin periods fall in the range 0.8–1.4 s. Such a neutron star spin period breaks the assumption of the subsonic propeller regime that the corotation radius of the neutron star is outside the magnetospheric radius. Increasing the neutron star magnetic field to $10^{13}$ G results in neutron star spin periods in the range 320–565 s suggesting that a slowly rotating neutron star with a strong magnetic field would be required to magnetically inhibit accretion in IGR J18450−0435 and produce the observed low luminosity periods. However, magnetic fields of order $10^{13}$ G have not been observed in SFXTs and indeed the prototype SFXT IGR J17544−2619 was found to have a magnetic field more in line with that expected for supergiant binaries. Detailed, high sensitivity hard X-ray studies would be required to evaluate the magnetic field strength of the neutron star in IGR J18450−0435. The flaring behaviour seen in Obs1 can also be explained in the framework of Bozzo et al. (2008b) by transition of the source from the subsonic propeller to the direct accretion regime. In this case, the flaring behaviour observed is the result of accretion of the stellar wind directly with the flares representing inhomogeneities accreted by the neutron star.

The low flux intervals of Obs1 can also be interpreted within the framework of quasi-spherical accretion (QSA). In this model, source luminosities of less than $\sim 3 \times 10^{35}$ erg s$^{-1}$ are the result of plasma held above the magnetosphere in a quasi-static shell, being cooled by thermal bremsstrahlung before entering the
magnetosphere via the Rayleigh-Taylor Instability (Shakura et al., 2013). Above this threshold luminosity, the source inhabits the Compton cooling regime whereby material is cooled more efficiently by Compton processes and enters the magnetosphere at a higher rate than the radiative regime. Transitions between these two regimes can be generated by changes in local stellar wind density and velocity. Shakura et al. (2014) subsequently developed this model to explain the occurrence of bright ($>10^{36}$ erg s$^{-1}$) flares in SFXTs. In the case of these bright flares, the entry rate into the magnetosphere is enhanced by the sporadic accretion of magnetised elements of the supergiant winds. Within this framework, the low luminosity periods corresponding to regions A, D, F and Obs2 can be attributed to the source inhabiting the radiative cooling regime while region B corresponds to the source transitioning into the Compton cooled regime with the caveat that the neutron star magnetic field is $\sim 5 \times 10^{12}$ G. Such a magnetic field reduces the critical transition luminosity to that observed in region B. The presence of a bright flare corresponding to region C during this period in the Compton cooling regime could either be interpreted as an increase in entry rate into the magnetosphere due to increased density at the base of the shell or as the accretion of a magnetised element of stellar wind effectively opening the magnetosphere and allowing a temporary large increased in accretion rate. Region E is also a bright flare however unlike region C, before and after the flare event the source can be considered to be in the radiative cooling regime. Within the QSA theory, this is most comfortably explained as accretion of magnetised stellar wind and unrelated to the Compton cooling regime. Interpreting the observed luminosity during the XMM-Newton observations using QSA does not require neutron star magnetic fields far in excess $10^{12}$ G in order to generate the observed behaviour, unlike the model of Bozzo et al. (2008b). Hence, we favour this scenario to explain the accretion processes at work in these observations.

Over the course of Obs1 the source exhibits a dynamic range of $\sim 600$, an order of magnitude greater than previous observations, and extends the observed dynamic range in this source. While this still categorises the source as an 'intermediate' SFXT, the observation of luminosities of order $10^{33}$ erg s$^{-1}$ around periastron suggest that the true dynamic range could be more akin to those observed in typical SFXTs, but we currently lack information about the apastron luminosity.

### 4.4.4 Spectral Evolution

An initial model-independent investigation for possible spectral evolution during Obs1 and Obs2 based on hardness ratio did not show any clear signatures of changing spectral shape coincident with any temporal features. The subsequent spectral analysis of morphological features in the EPIC-pn light curve presented in Section 4.3.2 revealed that all of the extracted spectra, with the exception of one,
show consistent, large absorbing column densities of approximately $9 - 10 \times 10^{22} \text{ cm}^{-2}$ for the power law fit. These large absorbing column densities do not show any correlation with flux and are far in excess of the line of sight absorption to IGR J18450–0435, suggesting that this is the result of localized stellar wind material along the line of sight. Large absorbing column densities as seen in these observations have been observed many times in the X-ray spectra of SFXTs (Romano et al., 2011a; Sidoli et al., 2012). The spectral analysis of Region E, however, reveals a spectrum with significantly lower line of sight absorption ($\sim 5 \times 10^{22} \text{ cm}^{-2}$) coupled with a hardening of the spectrum to $\Gamma \sim 0.6$. A reduction of the line of sight absorption coincident with increasing flux could be interpreted as the accretion of stellar wind material that had previously been obscuring the line of sight. However, despite the differences in absorbing column density, the morphological similarity of Regions C and E suggest these events are not generated by accretion of a clump of stellar wind and instead the variation seen is due to motion of the stellar wind material itself. Previous observations of IGR J18450–0435 with XMM-Newton occurring at orbital phase $\phi = 0.855 - 0.894$, approximately a quarter of the orbit later than Obs1, revealed an absorbing column density four times less than those observed in regions B, C and A+D+F and half that of region E. Hence, the observations presented here represent the highest observed absorbing column density in this source.

A large change in photon index similar to that reported in this chapter has previously been observed in the SFXT SAX J1818.6–1703 (Boon et al. (2016), the subject of Chapter 3), where the photon index varied by an order of magnitude coincident with increasing flux. These observations of IGR J18450–0435 however do not appear to show the ‘harder-when-brighter’ relation of HMXBs (Sidoli et al., 2012, 2013; Odaka et al., 2013; Romano et al., 2014a; Kennea et al., 2014). This suggests that, while the generated morphology of the light curve may be similar in the cases of regions C and E, another accretion process is potentially generating a harder spectrum in the case of region E. While the hardening of the photon index is a model-specific effect, the calculated hardness ratio for Region E shows evidence of hardening relative to the other spectra extracted from Obs1, suggesting increased production of hard photons. To account for the hardening of the spectrum during this period, the black body spectral fit results in a black body with higher characteristic temperature relative to the other fits. We use a simple absorbed power law as a non-physical method for characterising the overall shape of the spectrum. The XMM-Newton observation of IGR J18450–0435 reported by Zurita Heras & Walter (2009) also presented spectra with hard photon indices with $\Gamma \sim 0.7 - 0.9$ for low and high flux periods, however these were consistent to within errors.

Spectral analysis of Obs2 revealed reduced intrinsic absorption in the system of $7 \times 10^{22} \text{ cm}^{-2}$ and a softer photon index of $\Gamma = 1.6$, relative to those of Obs1.
These changes, coupled with the lack of flaring behaviour and lower average luminosity relative to Obs1, are consistent with the model of accretion whereby the neutron star accretes from lower density stellar wind material as it moves away from periastron around the orbit. The small change in absorbing column density is also consistent with the orbit being short period and only mildly eccentric as such orbits would not expect to encounter dramatic changes in average stellar wind density one quarter of an orbit past periastron. The observations of Zurita Heras & Walter (2009) were taken at the same orbital phase as Obs2, however the absorbing column density of Obs2 is a factor of \( \sim 3 \) higher than that previously seen at this phase. Such an enhancement could be the result of the source being observed through structures in the stellar wind not present in the previous observation, through focussed stellar wind material due to the influence of the neutron star or a combination of both effects.

**4.4.5 Temporal Analysis**

In Section 4.3.2, we performed a temporal analysis of the EPIC-pn light curves of Obs1 and Obs2 using a Lomb-Scargle periodogram to identify any periodic modulation in the range 2s–7ks. This analysis did not reveal any significant signals in this range that covers the entire spin period distribution of SFXTs (see Table 1.1). We also searched temporal regions corresponding to both low and high flux as in the case of some systems, spin periods have only been detected in certain accretion states, however no significant signals were detected in the range 2s–2.5ks. This is in line with previous observations of IGR J18450–0435 with XMM-Newton that also failed to detect pulsations in the range 0.1s–5ks in both low and high flux states (Zurita Heras & Walter, 2009). The lack of pulsations detected in the EPIC-pn light curves is not unique as under half of known SFXTs have associated spin periods and in some cases (such as the 71.49s pulse period of IGR J17544–2619 reported by Drave et al. 2012), prior detections have not been confirmed by subsequent observations with more sensitive X-ray instruments (Bhalerao et al., 2015; Bozzo et al., 2016b).

Possible explanations for the lack of pulsations detected in these observations include observational, geometric and physical effects. One possible explanation is that the spin period of the neutron star lies outside of the range of periodicities searched in the temporal analysis. This would require the neutron star to possess a spin period far outside the currently known distribution of SFXTs and in the case of the spin period being greater than 7ks, would make the neutron star one of the slowest rotators of any known HMXB (Corbet et al., 1999; Enoto et al., 2014; Sidoli et al., 2017). If the spin period is shorter than 2s then this system would lie outside the parameter space inhabited by wind fed SgXRBs in the Corbet Diagram (Corbet, 1986) and instead occupy the same region as systems fed by Roche Lobe
overflow. We suggest that IGR J18450−0435 is not a RLOF fed system due to its transient behaviour and while there has been some discussion as to whether this source is persistent, the characteristic luminosity exhibited is of magnitude below that of a typical RLOF SgXRB. While the lack of pulsations detected does not rule out the presence of a neutron star as the accreting body, it could suggest that the compact object is in fact a black hole. This scenario is however unlikely as currently there are no black hole candidate systems amongst the SFXTs and only a small number of confirmed black hole systems amongst HMXBs (Liu et al., 2006).

Geometrically, misalignment of the neutron star rotation and spin axes could be small enough that the ‘lighthouse’ effect required to observe pulsations does not cross the line-of-sight to the source (as suggested by Reynolds et al. (1999) for 4U 1700−37) as well as the binary inclination being of low enough such that any ‘lighthouse’ effect is out of the line-of-sight.

The EPIC-pn light curve shows potential quasi-periodic flaring during the temporal regions covered by Spectra B and C with small flares and the large flare comprising Spectrum C being separated by approximately 2 ks. Such behaviour has previously been seen in other SFXTs (XTE 1730−302, Ducci et al. (2010); IGR J16418−4532, Sidoli et al. 2012; SAX 1818.6−1703, Boon et al. 2016) and other HXMBS (EXO 2030+375) with explanations for this phenomenon including formation of transient accretion discs (Parmar et al., 1989), the flare recurrence time being a product of the large stellar wind speeds of the supergiant (Taam et al., 1988), and the beginning of Roche Lobe overflow of the supergiant atmosphere (Bhattacharya & van den Heuvel, 1991; Sidoli et al., 2012). Other mechanisms invoked include hydrodynamic effects in the stellar wind when influence by the neutron star generating low- and high density ‘bubbles’ that are formed in the vicinity of the neutron star and then accreted (Manousakis & Walter, 2015) and also convective motions in the quasi-static shell held above the magnetosphere in the theory of quasi-spherical accretion (Shakura et al., 2012; Shakura et al., 2013). In this chapter, the theory of quasi-spherical accretion is favoured as the origin of this phenomenon as when coupled with the discussion surrounding the observed luminosities during this period, the model of Shakura et al. (2012) provides a consistent explanation for the observed behaviour.

### 4.5 Conclusions

In this chapter I have presented, for the first time, simultaneous XMM-Newton and INTEGRAL observations of the intermediate SFXT IGR J18450−0435 around periastron. Over the course of the first XMM-Newton observation located close to periastron, the source exhibits a dynamic range of ∼600, spending the majority of the time with an average luminosity of $3 \times 10^{34}$ erg s$^{-1}$ with short (400 s), sharp
flaring activity reaching a peak luminosity of $(2.8 \pm 0.5) \times 10^{36}$ erg s$^{-1}$. Comparing the minimum luminosity of $(4.3 \pm 4.0) \times 10^{33}$ erg s$^{-1}$ observed during the first XMM-Newton observation with previous studies, it is clear that this is the lowest luminosity state observed in this source. Interpreting the luminosity evolution over the course of this observation within the framework of quasi-spherical accretion, it is suggested that the source spends the majority of the observation in the radiative cooling regime and transition to the Compton cooling regime generates flaring behaviour. The presence of two bright flares with peak luminosities of $\sim 10^{36}$ erg s$^{-1}$, potentially suggest the sporadic accretion of magnetised stellar wind elements in this framework. The second XMM-Newton observation is located approximately a quarter of the orbit later than the first and has an average luminosity of $2 \times 10^{34}$ erg s$^{-1}$, showing no significant flaring behaviour. During this observation, it is suggested that the source inhabits the radiative cooling regime. Observations of IGR J18450$-$0435 by INTEGRAL simultaneous with those by XMM-Newton result in the source not being significantly detected in either mosaics of the whole observation of at science window resolution. This is likely due to the combination of the short flare durations and the presence of a spectral cut-off between 10–20 keV.

Spectral analysis during both observations with XMM-Newton reveal high intrinsic absorption of $\sim (7 - 9) \times 10^{22}$ cm$^{-2}$ - up to a factor of 5 greater than previously observed in this source. There is evidence for spectral evolution coinciding with the second large flare event seen in the first XMM-Newton observation (region E) with both a drop in photon index and absorbing column density from $\Gamma = 1.3$ and $N_H = 9.62 \times 10^{22}$ cm$^{-2}$ during the preceding low luminosity phase, to $\Gamma = 0.61$ and $N_H = 4.86 \times 10^{22}$ cm$^{-2}$. This suggests the accretion mechanism generating the second observed flare differs from that generating the low luminosity state and also the first large flare, where for a similar morphology and luminosity, the spectrum is more absorbed and softer.

Confirming the nature of the accretion processes at work in this source requires further knowledge of intrinsic properties of the system, such as the neutron star spin period and magnetic field along with further examples of variability in source behaviour and spectra. To this end, further, high sensitivity studies of this source in both active and quiescent states are highly encouraged.
Chapter 5

Multi-wavelength observations of the BeXRB IGR J01217–7257 (=SXP 2.16) during outburst

5.1 Introduction

It has been found that the Small Magellanic Cloud (SMC) hosts a population of HMXBs comparable in size to our Galaxy. All but one of the known SMC HMXBs are BeXRBs, making the SMC a rich target for monitoring these sources, as they provide a population at known distance (62 kpc, Haschke et al. 2012) with low Galactic obscuration and likely similar ages. Discovery and monitoring of the HMXB population in the SMC based on emission from BeXRBs during outburst was performed by RXTE in the decade from 1999. More recently, the SMC has been regularly monitored by INTEGRAL as part of a Large Programme since 2008. Over the course of each observation period (one year), the SMC was observed for a total of ~1 Ms. This programme has had major success in the discovery and classification of new X-ray binaries in the SMC (Coe et al., 2010, 2015a; McBride et al., 2010).

IGR J01217–7257 was first discovered by INTEGRAL during observations of the SMC between 2014 January 11 and 2014 January 12 (Coe et al., 2014). The authors also suggested a potential orbital period of ~84 days based on visible recurrent outbursts in the $I$-band light curve of the 14th magnitude star SMC732.03.3540 from the Optical Gravitational Lenses Experiment (OGLE) Phase IV. Unfortunately, this observation was the last of the SMC during the year-long INTEGRAL monitoring campaign. However, the source went into outburst again during the following campaign and it is this outburst that is the main driving force behind the work presented in this chapter. Using data from OGLE Phase IV,
Schmidtke et al. (2014) confirmed the presence a periodicity of 84.03 days using a phase dispersion minimisation technique and attributed this to the orbital period of the compact object.

During \textit{INTEGRAL} monitoring of the SMC in 2015, IGR J01217$-$7257 was detected in outburst between 2015 October 29 and 2015 October 30 (Coe et al., 2015b). Follow-up observations with \textit{XMM-Newton} associated the source with the transient X-ray pulsar, SXP2.16 and found the 0.2–10 keV spectrum well described by a multi-temperature disk with a power law tail model (Haberl et al., 2015). Subsequent analysis of \textit{Swift}/BAT data by Corbet et al. (2015) revealed a peak in the X-ray power spectrum at 83.4 days.

**5.1.1 IGR J01217$-$7257 = SXP 2.16**

SXP 2.16 was first identified during \textit{RXTE}/PCA observations on 2003 January 5 in which a transient X-ray pulsar with a periodic signal of 2.1652$\pm$0.0001 s and pulsed flux of 0.625 mCrab (2–10 keV) was detected in the direction of the SMC. Pulsations were not detected in a previous observation on 2002 December 13 or follow-up observations on 2003 January 17 (Corbet et al., 2003). Coe & Gaensicke (2003) suggested the optical counterpart to SXP 2.16 was the emission-line star Lin 526 using spectroscopy from the SAAO 1.9m telescope and searching in the XTE error box, however more recent work has revealed the optical counterpart to be AzV 503, an emission-line star with spectral type B0-5IIe (Coe et al., 2014; Haberl et al., 2015).

The association between SXP 2.16 and IGR J01217$-$7257 was not immediately clear. Using the spin period as a unique identifier, the same signal was detected in an \textit{XMM-Newton} observation by Haberl et al. (2015) at RA = 01:21:40.5, Dec = -72:57:32 with an error circle of 5 arcsec. This signal position is consistent with the best determined X-ray position of RA = 01:21:40.6, Dec = -72:57:21.9 (error circle = 1.5 arcmin) from the \textit{INTEGRAL}/JEM-X detection between MJD 56668.038 and 56669.192, which confirmed the association of these two sources. Figure 5.1 shows the 0.3–10 keV image taken by \textit{Swift}/XRT during a 1 ks observation in PC mode on MJD 57329. The best X-ray positions of IGR J01217$-$7257 for \textit{INTEGRAL}/JEM-X and \textit{XMM-Newton} are shown as white and red circles respectively (Coe et al., 2014; Haberl et al., 2015), while the \textit{RXTE} position of Corbet et al. (2003) is marked as a green box. From this image it is clear why SXP 2.16 and IGR J01217$-$7257 were not initially associated as the same source. The source position and error box determined from the detection observations of SXP 2.16 by \textit{RXTE} on 2003 January 5 are likely incorrect. This is due to the non-imaging nature of \textit{RXTE} requiring positions and uncertainties to be inferred from dithering of the satellite. The detection of the 2.16 second spin period at a

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Figure 5.1: 0.3–10 keV image taken by Swift/XRT during a 1 ks observation in PC mode on MJD 57329. Best X-ray source positions of IGR J01217–7257 for INTEGRAL/JEM-X and XMM-Newton are shown as red and white circles respectively while the best source position from RXTE is marked as a green box. Inset panel: Zoom of the best source positions for INTEGRAL/JEM-X and XMM-Newton.

location consistent with the INTEGRAL/JEM-X and XMM-Newton source position of IGR J01217–7257 firmly associates the two sources and rules out the RXTE position as the location of this signal.

Figure 5.2 shows the 20–40 keV INTEGRAL/IBIS significance map of the SMC from the observation between MJD 57324.774 and 57325.874 with known SMC pulsars marked as white circles. The image is centred on the BeXRB IGR J01054–7253 and has a radius of 2 degrees. The best X-ray position for IGR J01217–7257 from INTEGRAL is marked as a white circle. The incorrect source position as determined by RXTE is shown as a green circle. This image shows the large number of X-ray sources in a small region of the sky as well as the proximity of IGR J01217–7257 to SMC X–1, which is the brightest source in the field of view. In the case of the derived position from RXTE, SXP 2.16 lies approximately 20 arcminutes from SMC X–1. The implications of this close proximity on observations with RXTE that had a non-imaging field of view of 1° (FWHM) are discussed in Sections 5.2.3 & 5.3.3. The derived X-ray positions of IGR
Figure 5.2: IBIS/ISGRI 20–40 keV significance map of the SMC from the observation between MJD 57324.774 and 57325.874 centred on IGR J01054−7253 with 2 degree radius. Known SMC pulsars are marked in white with their associated spin periods. The best X-ray position for IGR J01217−7257 from INTEGRAL is marked as a white circle. The incorrect source position as determined by RXTE is shown as a green circle. The bright source in the field of view is SMC X–1. This map is also presented as part of Figure 5.4.
J01217–7257 from INTEGRAL/JEM-X and XMM-Newton (the true position of the source) lie approximately 35 arcminutes from SMC X–1. An edited version of this significance map is also presented in Figure 5.4 and science results are outlined and discussed in Sections 5.3.1 and 5.4.1.

In this chapter, I present analysis of INTEGRAL, OGLE and Swift data taken during the 2014 and 2015 outbursts of IGR J01217–7257, archival RXTE observations from the discovery of SXP 2.16 and Swift observations of the source during a new outburst in 2016.

5.2 Observations

Details of all observations of IGR J01217–7257 used in this chapter are provided in Table 5.1. The data reduction methods are described below.

5.2.1 INTEGRAL data analysis

IGR J01217–7257 was detected by INTEGRAL/IBIS (Ubertini et al., 2003; Winkler et al., 2003) during observations of the SMC taken between MJD 56668.038 and 56669.192 during Revolution 1373 (Coe et al., 2014). This observation is referred to as the 2014 Outburst for the remainder of this chapter. The source was subsequently detected in further monitoring of the SMC nearly 2 years later between MJD 57324.774 and 57347.281 during Revolutions 1604–1612. I refer to this as the 2015 Outburst henceforth. The data were processed from these two detected outbursts using the Offline Science Analysis (OSA, Courvoisier et al. 2003) software version 10.2. Images were created at the Science Window level as well as mosaic images on a revolution-by-revolution basis. Light curves for each outburst were produced at science window resolution.

5.2.2 Swift data

The observations of IGR J01217–7257 were taken from the Swift/BAT transient monitor\(^1\) (Krimm et al., 2013) and cover the energy range 15–50 keV. The time range covered by the observations of IGR J01217–7257 with Swift/BAT is from MJD 56679 to 57674. The transient monitor data are provided with time resolutions of one orbit and daily averages; the orbit light curve were used for period searches, and the one day averages for plotting the light curve.

Data were selected and analysed in a way similar to that described in Corbet & Krimm (2013): only data for which the quality flag (‘DATA_FLAG’) was set to 0,\(^1\)https://swift.gsfc.nasa.gov/results/transients/
Table 5.1: Log of observations discussed in this work. The OGLE data used here covers both the OGLE–III and OGLE–IV observation campaigns. Phases are calculated using the ephemeris and orbital period of MJD 56995 and 82.5 days derived in this work using Swift/BAT observations. The duration of the S-CUBED survey data is listed here, each exposure during this period is 60 seconds. S-CUBED data of IGR J01217−7257 are shown in Figure 5.11 and discussed in Section 5.3.2. Phases and exposures are not listed for either Swift/BAT, OGLE or S-CUBED observations as they cover all binary phases. The RXTE observation on MJD 51309.668 is a pre-discovery detection of SXP 2.16 found through analysis of archival SMC observations as discussed in Section 5.2.3.

<table>
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<td>INTEGRAL (Rev 1608) 2015 October 29 18:34:33 – 57324.774 – 0.997 – 0.011 21</td>
</tr>
<tr>
<td>INTEGRAL (Rev 1609) 2015 November 20 10:36:28 – 57346.442 – 0.260 – 0.270 16.5</td>
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<td>INTEGRAL (Rev 1604) 2014 January 01 09:34:00 0.267 4</td>
</tr>
<tr>
<td>INTEGRAL (Rev 1601) 2014 January 01 09:34:00 0.267 4</td>
</tr>
<tr>
<td>INTEGRAL (Rev 1608) 2014 January 01 09:34:00 0.267 4</td>
</tr>
<tr>
<td>INTEGRAL (Rev 1605) 2014 January 01 09:34:00 0.267 4</td>
</tr>
<tr>
<td>INTEGRAL (Rev 1602) 2014 January 01 09:34:00 0.267 4</td>
</tr>
</tbody>
</table>
indicating good quality, was used and also points with low count rates and extremely small nominal uncertainties were excluded.

The transient monitor data were extended by re-analysing data collected from BAT from the start of the mission until MJD 56679, when IGR J01217−7257 was added to the monitor catalogue. The back-processed light curve differs from the transient monitor in that only daily averages were produced. In addition, the errors on the fluxes are only statistical and do not include systematic errors that are included in the full transient monitor data. The back-processed light curve covers MJD 53407 to 56708 and so overlaps the transient monitor light curve by approximately 30 days.

The Swift SMC Survey (S-CUBED) is a wide area/short exposure survey of the SMC in X-rays performed by the Swift X-ray Telescope (XRT) (Kennea et al., 2016a). The survey consists of 142 x 60 second exposure tiled pointings covering the SMC performed approximately weekly. Observations for S-CUBED began on MJD 57547 and IGR J01217−7257 was detected on MJD 57575, 57579 and 57584. The journal of these observations can also be found in Table 5.1.

5.2.3 RXTE data

The region of the SMC containing SXP 2.16 was observed four times (MJD 51309, 52621, 52644, 52656) by RXTE as part of the long-term SMC X-ray monitoring programme (Galache et al., 2008). Since the RXTE PCA telescope (Jahoda et al., 1996, 2006) had a large non-imaging field of view (1° FWHM) there was always the possibility of other sources contributing to the resulting signal. However, the identification of a pulsed signal is unique to a specific source and a clear indication of identification - even if the pulse fraction is difficult to determine. Hence, because the best determined X-ray position of SXP 2.16 from RXTE lies approximately 20 arcminutes from the bright persistent source, SMC X−1, after the initial discovery observations on MJD 52644 and subsequent follow up on MJD 52656 no further pointings were attempted.

5.2.4 OGLE data

Data from the Optical Gravitational Lenses Experiment (OGLE) Phases III and IV (Udalski et al., 2008, 2015) were downloaded from the XROM website2 and used to compare the long-term I-band behaviour of the companion star with the long-term hard X-ray activity as monitored by Swift/BAT. Time stamps and magnitudes of the OGLE observations were converted to Modified Julian Date and Jansky (Jy)

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2http://ogle.astrouw.edu.pl/ogle4/xrom/xrom.html
respectively. The light curves from the combined OGLE–III and OGLE–IV data sets spanning nearly 15 years are shown in Section 5.3.4.

In order to search for the presence of sub-seasonal variations, the combined OGLE light curves were detrended using polynomial fits. The entire OGLE IV data set (MJD 55347.427 –57647.221) cannot be adequately described by a single polynomial fit. The data were divided into two sections, the first from MJD 55347.427 to 57434.033 and the second from MJD 57560.425 to 57647.221. The first section is well described by a quartic polynomial, while the second is well described by a linear fit. These functional forms are used as adequate descriptions of the overall behaviour of the companion star and decretion disc during these epochs. The OGLE III (MJD 52090.42954 – 54873.06695) data also cannot be well described by a single polynomial fit. As a result, each season of OGLE III data was fit with separate polynomials to remove seasonal trends.

5.3 Results

5.3.1 INTEGRAL results

The results of the INTEGRAL analysis detailed above are summarised in Table 5.2 and the 20–40 keV significance maps for the 2014 and 2015 outbursts are shown in Figures 5.3 and 5.4, respectively. The bright object in the top right of Figure 5.3 is the BeXRB RX J0059.2−7138 (also known as SXP 2.76) detected in outburst during this observation, as reported by Coe et al. (2014a). Orbital phases of these observations are calculated using the orbital period and ephemeris derived from X-ray data in Section 5.3.2. Conversion of the source intensity from IBIS/ISGRI counts s$^{-1}$ to flux was obtained by processing an observation of the Crab taken during Revolution 15973 in the 20–40 keV band and using the conversion factors of Bird et al. (2016). Luminosity calculations were performed assuming a distance to the SMC of 62 kpc from Haschke et al. (2012).

In order to quantify the variability within the science window light curves, the Bayesian Blocks method of Scargle et al. (2013) was adopted using a Python implementation4 (Hill, 2016). The Bayesian blocks method is a way of characterising local variability in a given time series, with the aim of locating statistically significant variations in flux. The method evaluates a given time series and seeks to identify periods of statistically constant flux by optimally segmenting the light curve into a step function where each step has statistically constant flux. In essence, the algorithm attempts to evaluate if the time series is consistent with a single constant flux level up to a given significance level (usually 3σ). If the light

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3Observations used in this work were taken between MJD 57305.334 and 57305.894
4https://zenodo.org/record/57750#.V-qBXYqMrK37
Figure 5.3: IBIS/ISGRI 20–40 keV significance map of IGR J01217−7257 observed between MJD 56668.038 and 56669.192. The source is detected at 6.3σ with a 24 ks exposure. The best X-ray positions of IGR J01217−7257, SMC X−1 and SMC X−2 are shown in white circles. The bright object in the top right is the BeXRB RX J0059.2−7138 (also known as SXP 2.76) detected in outburst during this observation, as reported by Coe et al. (2014a).
Figure 5.4: IBIS/ISGRI 20–40 keV significance maps of IGR J01217−7257 observed during the 2015 Outburst. Again, the best X-ray positions of IGR J01217−7257, SMC X−1 and SMC X−2 are shown in white circles. Top left-hand panel: Revolution 1604 Top right-hand panel: Revolution 1606 Bottom left-hand panel: Revolution 1608 Bottom right-hand panel: Revolution 1612. Refer to Table 5.1 for observations dates and orbital phases and Table 5.2 for associated results.
Figure 5.5: IBIS/ISGRI science window level 20–40 keV light curve of IGR J01217−7257 observed between MJD 56668.038 – 56669.192. The source is detected with an average count rate of $0.59 \pm 0.09$ counts s$^{-1}$. The red line denotes the average flux of the block as determined by the Bayesian Blocks analysis. The analysis shows that there is no evidence of source variability during this observation i.e the light curve is consistent with a constant poissonian rate.

The light curve is not consistent with a flat line additional steps will be included in order to minimise any significant deviations. The significance at which a change is determined to have occurred is set by the false alarm probability i.e the probability that the change is not a real feature of the light curve. The false alarm probability was set to be 0.003 such that an approximately 3σ change is required before the algorithm accepts there is significant variation between points in the time series.

Figure 5.5 shows the 20–40 keV ScW level light curve of IGR J01217−7257 during the 2014 Outburst with the average flux in regions of statistically constant flux shown by the red line. In this observation, the Bayesian Blocks analysis suggests that there is no significant variation at the ScW level as the behaviour is characterised by a step function with a single interval.

Figure 5.6 shows the ScW light curves for the 2015 Outburst with the average flux for the regions of significant variability again marked with red lines. The layout of this figure is identical to that of Figure 5.4 with the light curves of the Revolutions 1604, 1606, 1608 and 1612 arranged top-left to bottom right. The analysis of Revolution 1604 suggests there are 8 separate, statistically different flux regions during this observation. However, one of these is driven by a large negative flux in
Table 5.2: Results from the IBIS/ISGRI analysis of the 2014 and 2015 Outbursts of IGR J01217–7257. The 20–40 keV flux is given in units of mCrab (F_{Crab}) and $10^{-11}$ erg s$^{-1}$ cm$^{-2}$ (F$_{-11}$). Conversion between counts and mCrab was obtained using an observation of the Crab taken during Revolution 1597 between MJD 57305.334 and 57305.894 and the conversion factors of Bird et al. (2016). Luminosities are calculated using a distance of 62 kpc (Haschke et al., 2012) and given in units of $10^{37}$ erg s$^{-1}$.

<table>
<thead>
<tr>
<th>Rev.</th>
<th>Intensity (cts s$^{-1}$)</th>
<th>Sig</th>
<th>Exp (ks)</th>
<th>F_{Crab}</th>
<th>F$_{-11}$</th>
<th>L_{X}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1373</td>
<td>0.59±0.09</td>
<td>6.3</td>
<td>24</td>
<td>4.21±0.67</td>
<td>3.19±0.51</td>
<td>1.43±0.23</td>
</tr>
<tr>
<td>1604</td>
<td>1.56±0.10</td>
<td>15.2</td>
<td>21</td>
<td>11.79±0.76</td>
<td>8.92±0.58</td>
<td>4.10±0.27</td>
</tr>
<tr>
<td>1606</td>
<td>0.77±0.08</td>
<td>9.1</td>
<td>25</td>
<td>5.83±0.60</td>
<td>4.41±0.45</td>
<td>2.03±0.21</td>
</tr>
<tr>
<td>1608</td>
<td>1.13±0.09</td>
<td>12.4</td>
<td>21</td>
<td>8.50±0.67</td>
<td>6.43±0.51</td>
<td>2.96±0.24</td>
</tr>
<tr>
<td>1612</td>
<td>0.57±0.10</td>
<td>5.7</td>
<td>16.5</td>
<td>4.29±0.76</td>
<td>3.25±0.58</td>
<td>1.50±0.28</td>
</tr>
</tbody>
</table>

The light curve. This negative ‘spike’ is of order the same magnitude as the two positive ‘spikes’ - suggesting knowledge of the errors associated with the light curve is insufficient to comment on the short term variability in this revolution. The analysis of Revolution 1606 suggests the observation can be broken into six different blocks. Three of these blocks are low flux regions with points consistent with zero, while the other blocks have observed fluxes significantly above zero - suggesting that during this revolution, the source exhibits short (10–20 ks) periods of variability. The observation of Revolution 1608 in the bottom left panel can be broken into a number of blocks. However, a negative point approximately halfway through the observation drives a break in the first block. Omission of this point would likely result in a single flat line as a description of the source behaviour. In this case, it is not possible to comment on short term variability in this window and the results suggest it is likely that during this observation the source flux is consistent with a constant Poissonian rate. The observation of Revolution 1612 is shown in the bottom right panel and the variability analysis in this case suggests that for the majority of the observation the source flux is statistically consistent, with only 1 science window observation significantly different from this average behaviour - suggesting during this observation the source experiences a single short period of increased flux activity.

This analysis shows that in general, IGR J01217–7257 shows very little sub-10 ks variability and for the most part, shows a statistically constant flux during an INTEGRAL revolution. However, the source does in general exhibit a decrease in average luminosity between revolutions. It is notable that the luminosities and orbital phases of Revolution 1373 and 1612 are approximately equal, suggesting that Revolution 1373 is in fact the tail end of an outburst. The peak of this outburst was not observed by INTEGRAL or reported by any other missions.
Figure 5.6: IBIS/ISGRI 20–40 keV ScW level light curves of IGR J01217−7257 observed during the 2015 Outburst. The red line indicates the weighted average flux in regions of statistically different flux derived from a Bayesian blocks analysis with a false positive rate of 0.003 (3σ). Top left-hand panel: Revolution 1604 (MJD 57324.774 – 57325.874, φ=0.954–0.967). Top right-hand panel: Revolution 1606 (MJD 57330.042 – 57331.335, φ=0.017–0.033). Bottom left-hand panel: Revolution 1608 (MJD 57334.465 – 57335.717, φ=0.070–0.097). Bottom right-hand panel: Revolution 1612 (MJD 57346.442 – 57347.281, φ=0.214–0.224).
5.3.2 Swift results

Swift/BAT Transient Monitor Results

To search for and quantify periodic modulation of the hard X-ray data, the power spectrum of the BAT light curve was calculated. This was obtained by calculating the discrete Fourier transform (DFT) of the orbital light curve with the contribution of each data point weighted using the ‘semi-weighting’ method that accounts for both the error on each data point and the excess variance of the entire light curve (Corbet et al., 2007a,b).

The period range searched was from 0.07 days to the length of the data set (994 days) oversampling the power spectrum by a factor of 5 compared to the nominal Fourier resolution of $1/994$ days$^{-1}$. The resulting power spectrum is shown in Figure 5.7. The largest peak in the power spectrum is at a period of 82.5±0.7 days, where the uncertainty is derived from the prescription of Horne & Baliunas (1986). There is also a smaller peak at a frequency consistent with the second harmonic of the 82.5 day modulation.

The BAT light curve folded on the derived period is shown in Figure 5.8. Figure
Figure 5.8: Swift/BAT transient monitor light curve of IGR J01217−7257 folded on the proposed 82.5 day orbital period with phase zero at MJD 56995.

5.20 shows the Swift/BAT rebinned and smoothed along with the times of the predicted maxima from the 82.5 day period. It is noted that although outbursts can be directly observed at the predicted outburst times, there is cycle to cycle variability in the peak flux and morphology.

**Back-processed BAT Observations**

The DFT was calculated of the back-processed light curve alone, covering a period range from 2 days to the length of the data set (3302 days) This did not show the presence of any modulation at the 82.5 day period. A direct inspection of the light curve also did not directly reveal large outbursts at the expected times.

Next the combined transient monitor and back-processed light curve was investigated. For consistency only the one day resolution transient monitor data was used and only statistical errors were considered. Back-processed data that overlapped with the transient monitor data were excluded. The power spectra for periods longer than 2 days were then calculated and the height of modulation near 82.5 days compared to the mean power level. The light curves used for this always had the same end time of MJD 57674 but differing start times i.e light curves of increasing length were generated by starting at the last time stamp of the BAT combined transient monitor and back-processed data light curve and adding in data.
Figure 5.9: Relative height of periodic modulation in power spectra of Swift/BAT light curves of IGR J01217−7257. The light curves used have end dates of MJD 57674. The start date is MJD 57674 minus the light curve length. The vertical dashed blue line indicates the length of light curve that corresponds to the BAT transient monitor light curve i.e the light curve being tested at the blue dashed line is the BAT transient monitor light curve.

from earlier times. The aim of this investigation was to examine the effect of adding data into the periodicity search and evaluate the contribution of the back-processed BAT data to any signal. The top panel of Figure 5.14 shows the combined transient monitor and back-processed light curve. The transient monitor light data starts at approximately the first red vertical stripe, corresponding to the first INTEGRAL detection of IGR J01217−7257 and its inclusion in the transient monitor source list, while the historic back-processed light curve is all data preceding this red interval.

From Figure 5.9 it can be seen that the relative height of the modulation initially increased as the start time of the light curve was moved earlier. A maximum in the relative height is found that coincides with the start of the transient monitor data. The relative height then generally declines, with a more significant drop for times starting earlier than 1950 days before the end date. (i.e. for light curves with start times before ∼ MJD 55274 = 2010 March 19). As the start time is moved earlier there is a modest increase for a start time of ∼3800 days before the end date (i.e. for a light curve with start time of ∼MJD 53874) suggesting possible activity at that time.
Figure 5.10: Period of the strongest peak in power spectra of Swift/BAT light curves of IGR J01217−7257. The light curves used had end dates of MJD 57674. The start date is that date minus the light curve length. The vertical dashed blue line indicates the start of the transient monitor data. The horizontal dashed line indicates the period determined from OGLE observations in Section 5.3.4.
In Figure 5.10 the apparent period determined for light curves of different lengths is plotted, all with the same end time as above. It is noted that the inclusion of data from before the transient monitor data results in an apparently somewhat longer period of approximately 83 days, that is closer to that determined from the OGLE light curve in Section 5.3.4.

**Swift/XRT Results**

One of the sources detected in outburst during the S-CUBED monitoring campaign was SXP 2.16. Figure 5.11 shows the light curve history for this source with clear detections on MJD 57575, 57579 and 57584. This outburst peaked at a flux of \((4.4 \pm 1.2) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}\) in the energy range 0.3–10 keV, that corresponds to \(L_x = (2.0 \pm 0.5) \times 10^{37} \text{ erg s}^{-1}\) for a source in the SMC at a distance of 62 kpc (Haschke et al., 2012). The XRT count rate was too low to justify triggering a longer WT observation hence there is no measurement of the pulse period during this outburst. The duration of the outburst (\(\sim 9\) d) and the lack of a detection on either side, strongly suggests this is a typical Type-I outburst from this system. Calculating the phase of the outburst based on the period and ephemeris determined in Section 5.3.2 gives a phase range of \(\phi = 0.030–0.139\), confirming the Type-I nature of this outburst.

**5.3.3 RXTE results**

The RXTE observations of the SMC on MJD 52644 revealed the presence of a new periodic signal at 2.165 s. This was identified as a previously unknown X-ray pulsar and given the designation XTE J0119-731 (Corbet et al., 2003). Other observations, 3 weeks before (MJD 52621) and 2 weeks afterwards (MJD 52656), failed to detect the pulsations. However, it is worth noting that the strong signal at 0.7 s from the nearby source SMC X−1 significantly reduced the sensitivity as harmonics of this signal mask the presence of the 2.16 s periodicity of SXP 2.16. Figure 5.12 shows the power spectrum obtained from the RXTE observation on MJD 52644. There is a clear strong peak at the fundamental period of 2.1652±0.0001 s, with significant power also present in the harmonics. This immediately suggests a complex pulse profile and that is confirmed by folding the data at the fundamental period - see Figure 5.13, bottom panel for this profile. This complexity in the pulse profile was commented upon by Haberl et al. (2015) from their XMM observations during the recent outburst. It is possible that the profile is more complex during the 2015 Outburst than the 2003 one because those authors report more power in the harmonics of the power spectrum than in the fundamental. However, it is also possible that the complexity seen in the XMM-Newton observation is due to the increased S/N in the data. These complex
Figure 5.11: 0.3–10 keV light curve of IGR J01217–7257 as observed by Swift/XRT as part of the S-CUBED survey. There are clear detections on MJD 57575, 57579 and 57584. The peak flux during this outburst is \((4.4\pm1.2)\times10^{-11}\) erg s\(^{-1}\) cm\(^{-2}\) corresponding to a luminosity of \((2.0\pm0.5)\times10^{37}\) erg s\(^{-1}\) at 62 kpc.
Figure 5.12: Lomb-Scargle periodogram of data taken by RXTE during an observation of the SMC on MJD 52644.399. The peak in the power spectrum is at 0.4618 Hz, corresponding to a period of 2.165 s. The red dashed line indicates the 95% confidence level of detection.
Figure 5.13: Top panel: pulse profile of SXP 2.16 from the observation of the SMC taken on MJD 51309.668 by RXTE. The data are folded on a period of 2.164971 s. Bottom panel: pulse profile of SXP 2.16 from the observation of the SMC taken on MJD 52644.399 by RXTE. The data are folded on a period of 2.165 s and show a complex pulse profile.

pulse profiles presumably arise from several emission regions contributing to the X-ray signal.

Subsequent reanalysis of archival RXTE data using the PUMA/ORCA pipelines revealed a periodic signal of $2.16497 \pm 0.00014$ s (see Galache et al. 2008 for details of the algorithms used) at the 99% significance during an earlier observation of the SMC on MJD 51309.668. This detected period is consistent with that found in the initial discovery observations on MJD 52644. Details of this observation can be found in Table 5.1. SXP 2.16 was not identified during this observation as a blind period search is heavily affected by the presence of SMC X−1 in the RXTE field of view. Only with prior knowledge of the periodicity can the signal be found in the archival data. The pulse profile obtained from this observation is shown in the top panel of Figure 5.13. It is noted that the count rate in this profile is much greater than that observed in the lower panel, taken from the observation on MJD 52644. This is almost certainly due to the presence of SMC X−1 in the field of view and the fact RXTE was not an imaging telescope. The pulse profile, however, should be unaffected by the presence of the 0.7 s pulse period of SMC X−1. Comparing the
Figure 5.14: Top panel: *Swift/BAT* 15–50 keV light curve of IGR J01217−7257. The light curve is a combination of the transient monitor data and the back-processed data as outlined in Section 5.2.2. The red vertical shaded regions represent the dates of the 2014 and 2015 outbursts as detected by *INTEGRAL* and the green shaded region is the outburst detected between MJD 57575 – 57584 as part of the S-CUBED *Swift/XRT* monitoring. Bottom panel: OGLE–III and IV combined *I*-band light curve of the optical counterpart of IGR J01217−7257 from MJD 52090.430 – 57647.221. The blue triangle represents the *RXTE* observation on MJD 52644.399 during which the spin period of 2.165 s was first detected. Inset panel: zoom of OGLE–III and IV light curve between MJD 56400 – 57500, detrended for seasonal variations. The red vertical regions correspond to the detected *INTEGRAL* outbursts. The ~84 day variation is clearly seen.

Two profiles, it can be seen that the depth of modulation of the observation on MJD 51309.668 is ~0.8 counts s$^{-1}$, compared with ~0.3 counts s$^{-1}$ for the discovery observation on MJD 52644. Unfortunately, due to the presence of SMC X−1, any potential variation in pulse fraction between the two observations cannot be quantified.

5.3.4 OGLE results

Figure 5.14 shows the OGLE Phase III and IV combined *I*-band light curve of the optical counterpart of IGR J01217−7257 spanning almost 15 years from MJD 52090.430 to 57647.221. In this plot, the light curve time stamps and magnitudes have been converted to MJD and mJy respectively. The *RXTE* detection of the
2.165 s spin period is shown as a blue triangle, the *INTEGRAL* detected outbursts in 2014 and 2015 are marked with red intervals and the 2016 outburst observed as part of the S-CUBED survey is shown as a green interval. The counterpart shows large variations over the course of the 15 year observations of approximately 4 mJy, corresponding to $\sim$1 magnitude. The large optical variations seen in this figure appear to have an approximately 4000 day cycle. This is discussed further in Section 5.4.3. On top of this behaviour, recurrent outbursts occurring every $\sim$84 days can be seen during brighter epochs, for example around MJD 53000 and MJD 56500 onwards.

The combined OGLE III and OGLE IV detrended light curve was tested for the presence of periodicities in the range 2–200 days by calculating the Lomb-Scargle periodogram using the fast implementation of Press & Rybicki (1989). Significance levels, above which a detection would be considered to be true, were calculated using Monte Carlo simulations and adopting the method of Hill et al. (2005) with 100 000 iterations to assess the confidence levels of a signal detection. The resulting periodogram is shown in Figure 5.15 with a peak in the Lomb-Scargle power at $P = 83.67$ days with a significance greater than 99.99% shown by the red dashed line. In order to ascertain the uncertainty of this signal, we created 10 000 simulated light curves using the bootstrapping method and calculated the periodogram for each. The peak period was recorded for each and the resulting distribution of peak periods was fit using a Gaussian distribution, of which, the standard deviation is taken to be the error on the periodic signal. From this analysis, the derived period and associated error are found to be $P = 83.67 \pm 0.05$ days. The phase folded light curve of the combined OGLE III and OGLE IV detrended light curve folded on this period with a zero phase of MJD 56579.9 is presented in Figure 5.16.

Each season of data across OGLE III and IV observing campaigns was also searched for the presence of periodicities such as non-radial pulsations (NRPs) as have been seen previously in optical companions in BeXRBs. Schmidtke et al. (2014) reported the detection of a 1.173 day periodicity in the OGLE-IV light curve of IGR J01217−7257 that they attributed to the presence of NRPs in the Be companion star. Hence, the same Lomb-Scargle analysis detailed above was carried out, though the range over which periodicities were tested was changed from 2–200 days to 1–200 d. As the OGLE data are not evenly sampled, defining a Nyquist frequency is difficult, though the approximate sampling is $\sim$1 day leading potentially to strong aliasing effects in the periodogram. Significant detections of signals are found in Seasons 1, 10 and 11 of the combined OGLE III and IV observations.

The Lomb-Scargle periodogram of OGLE observations was taken between MJD 52090.429 and 52303.095 as part of the OGLE III campaign and reveals a peak at 1.167 days with a detection significance greater than 99.9% along with a strong aliasing feature at 6.851 days. Due to the strong aliasing effects, it is impossible to
Figure 5.15: Lomb-Scargle periodogram of combined OGLE III and OGLE IV detrended light curve searched in the range 2–200 d. The peak in the Lomb-Scargle power is located at 83.67 d. The red dashed line indicates the 99.99% confidence level of detection.
claim with any certainty which periodicity is the true sub-orbital signal. Focus is restricted to the signal at 6.851 days to derive an error and evaluate any evolution in these signals. A bootstrapping analysis, as detailed above, was carried out to evaluate the uncertainty of this signal at 6.851 days, resulting in a period of $P = 6.851 \pm 0.024$ days.

Running the same analysis on data taken as part of the OGLE IV campaign between MJD 55699.404 and 55993.014 results in periodic signals at 1.171 and 6.801 days with significances greater than 99.99%. A Bootstrapping analysis of this observation period leads to a distribution of peak peaks with mean, $\mu = 6.880$ and standard deviation $\sigma = 0.024$. Therefore, I report the periodic signal as 6.880 ± 0.024 days for this observing season.

The resulting periodogram of observations taken between MJD 56083.432 and 56353.022 reveals periodic signals at 1.158 and 7.237 days detected with a significance greater than 99.99%. Bootstrapping analysis of the 7.237 day signal results in a distribution with standard deviation $\sigma = 0.008$ days. I therefore report a signal of $7.237 \pm 0.008$ days from this observation period. The periodograms of the three seasons with significant detections and appropriate confidence levels are shown in Figure 5.17 and light curves folded on the two detected periodicities for each season are shown in Figure 5.18. The phase folds show sinusoidal behaviour in
Figure 5.17: Top panel: The Lomb-Scargle periodogram of OGLE data taken between MJD 52090.429–52303.095. The resulting periodogram shows signal at 1.167 days with a detection significance greater than 99.9% (red dashed line) and also a strong aliasing feature at 6.851 d. Middle panel: as top panel for observations taken between MJD 55699.404–55993.014, periodic signals at 1.171 and 6.801 days are detected with significances greater than 99.99%. Bottom panel: as top panel for observations taken between MJD 56083.43167–56353.022, periodic signals at 1.158 and 7.237 days are detected with significances greater than 99.99%
Figure 5.18: Phase folded light curves of OGLE observing seasons showing non-radial pulsations. Each row is a separate season of OGLE data folded on both the ~1 and 6 day periods with zero phase set as the first time stamp of the season being folded. Top left panel: Phase fold of observations between MJD MJD 52090.429 and 52303.095 with $P = 1.167$ days. Top right panel: As for top left panel with $P = 6.851$ days. Middle left panel: Phase fold of observations between MJD 55699.404 and 55993.014 with $P = 1.171$ days. Middle right panel: As for middle left panel with $P = 6.880$ days. Bottom left panel: Phase fold of observations between MJD 56083.432 and 56353.022 with $P = 1.158$ days. The number of bins has been reduced to 10 in this plot due to insufficient phase coverage for 20 bins. Bottom right panel: As for bottom left panel with $P = 7.237$ days.
Table 5.3: Results of the Lomb-Scargle analysis of subsections of observations taken between MJD 55699.404 – 55993.014. In the case of the first three subsections, two periodicities are significantly detected, one around 1 days, the other around 6 days. The fourth subsection does not show a significant periodicity around 1 day and hence we restrict uncertainty calculations to the 6 day periodicities for all subsections. Where two significance values are given, their order denotes their associated periodicity.

<table>
<thead>
<tr>
<th>Section</th>
<th>MJD</th>
<th>Periodicity (d)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55699 − 55803</td>
<td>1.17, 6.77±0.04</td>
<td>99%</td>
</tr>
<tr>
<td>2</td>
<td>55803 − 55853</td>
<td>1.02, 6.57±0.05</td>
<td>99.9, 90%</td>
</tr>
<tr>
<td>3</td>
<td>55854 − 55905</td>
<td>1.17, 6.78±0.04</td>
<td>99.9%</td>
</tr>
<tr>
<td>4</td>
<td>55906 − 55993</td>
<td>6.91±0.05</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

both the longer and shorter periodicities, as expected if the signals are NRPs and one is an alias of the other. In the bottom left hand panel, where data from between MJD 56083.432 and 56353.022 are folded on a period of $P = 1.158$ days, the number of bins used in the fold is reduced to 10 due to insufficient phase coverage for the standard 20 bins used in the other folds.

In order to investigate a possible evolution of the short term periodicities over the course of the observations between MJD 55699.404–55993.014 towards the detected period observations between MJD 56083.43167 – 56353.022, the former observation period was subdivided into four sections with equal numbers of observations in each. The same Lomb-Scargle analysis of these sections was performed as described above, though in this case, due to the much shorter total observation time in each section, the period search was restricted to 1–25 days. The results of this analysis can be found it Table 5.3. In the first three subsections, two periodicities are significantly detected, the first at around 1 day and the other between 6 and 7 days. In the fourth subsection, a periodicity of 6.873 days is detected, though no significant signals around 1 day are found. Therefore for consistency, uncertainty calculations are limited to the $\sim$6 days periodicities that are also given in Table 5.3. Figure 5.19 shows the detrended light curves of the four sections folded on the $\sim$6 day periods. As with the folds in Figure 5.18, the ephemeris used in each case is the first time stamp of the section being folded. In the case of the top two panels (Observations between MJD 55699 − 55803 and MJD 55803 − 55853, sections 1 and 2 respectively), the phase folded light curves show clear sinusoidal behaviour indicative of NRPs. The bottom two panels (Observations between MJD 55854 − 55905 and MJD 55803 − 55853, sections 3 and 4 respectively) show similar behaviour, however the picture is slightly complicated by spikes around phases 0.5 and 0.8 for sections 3 and 4, respectively. These features are generated by the lack of consistent phase coverage of the detected periodicities resulting in phase bins containing only one or two points.
Figure 5.19: Phase folded light curves from subsections of OGLE observations taken between MJD 55699–55994. In each case the zero phase point is the first time stamp of the section being folded. Top left panel: Folded light curve of data from between MJD 55699–55803 (Section 1 from Table 5.3) folded with $P = 6.77$ days. Top right panel: Folded light curve of data from between MJD 55803–55853 (Section 2) folded with $P = 6.57$ days. Bottom left panel: Folded light curve of data from between MJD 55854–55905 (Section 3) folded with $P = 6.78$ days. Bottom right panel: Folded light curve of data from between MJD 55906–55993 (Section 4) folded with $P = 6.91$ days.
5.4 Discussion

5.4.1 Outburst History

The first reported outburst of IGR J01217−7257 detected by RXTE coincides with a period of high optical flux and the non-detections three weeks prior and two weeks after suggest that this is a Type-I outburst. Unfortunately, there is limited diagnostic information about the pre-discovery outburst from 1999 and so we cannot draw firm conclusions about the nature of this period of activity.

IGR J01217−7257 was identified as a transient object during INTEGRAL observations of the SMC between MJD 56668.038 and 56669.192. During this period the source reached a luminosity of $(1.43 \pm 0.23) \times 10^{37} \text{ erg s}^{-1}$ in the 20–40 keV band and subsequent INTEGRAL observations revealed no detectable emission from the source.

The following year, the source was again detected by INTEGRAL during four observations between MJD 57324.774 and 57347.281. Over the four observations, there is clear evolution in the average luminosity of the source. Initially, between MJD 57324.774 and 57325.874, the source was detected with a luminosity of $(4.10 \pm 0.27) \times 10^{37} \text{ erg s}^{-1}$ and shows a general trend of decreasing luminosity. Using the orbital period and ephemeris of Section 5.3.2, both outbursts reported here occurred during periastron as determined from the X-ray data and had luminosities of $\sim 10^{37} \text{ erg s}^{-1}$, consistent with Type-I X-ray outbursts in Be/X-ray binaries (Reig, 2011).

The Swift/BAT transient monitor light curve of IGR J01217−7257 is shown in Figure 5.20 with the times of the flux maxima predicted by the orbital period and ephemeris of Section 5.3.2 marked with dashed red lines. From the light curve apparent Type-I outbursts can clearly be seen during most periastron passages, as well as a potential unreported Type-II outburst occurring around MJD 56850. It is worth of note that although outbursts can be directly observed at the predicted outburst times, there is cycle-to-cycle variability in the peak flux and morphology.

The observed outburst detected by Swift/XRT during the S-CUBED survey also has phase, duration and luminosity consistent with being a Type-I outburst.

5.4.2 Temporal Analysis

Spin Period

In Section 5.3.3, I present the detection of SXP 2.16 during an observation of the SMC on MJD 52644. A periodic signal of $P = 2.1652 \pm 0.0001 \text{ s}$ is detected that is interpreted as modulation of X-rays by a rotating neutron star. I also present the
Figure 5.20: *Swift/BAT* light curve of IGR J01217−7257. The lightcurve is a rebinned and smoothed version of the BAT Transient Monitor one-day resolution light curve. The dashed red lines indicate the times of predicted flux maximum from the 82.5 day period.

Results of archival observations of the SMC on MJD 51309 where, thanks to knowledge of the spin period as detected in 2003, a periodicity of 2.164971 s is now detected at the 99% significance level. Comparing this spin period with the sample of SMC pulsars used by Klus et al. (2014) in their study of spin period change in BeXRBs, it is clear that SXP 2.16 has one of the fastest spin periods in the SMC (It is noted that SMC X−1 has a spin period of 0.72 seconds, however this is the only known example of a Roche lobe filling supergiant system in the SMC).

Comparing this initial detection with the recent measurement of the spin period at $2.16501 \pm 0.00001$ s by Haberl et al. (2015) suggests a very small possible spin-up of the pulsar, $\dot{P} \sim 1.7 \times 10^{-5}$ s yr$^{-1}$. However, it is worth noting that the recent spin period detection of Haberl et al. (2015) is only 2σ different from the discovery detection period and hence I suggest that this measurement of spin-up is tentative. Such a small change in spin period over the course of $\sim 12.8$ years could suggest the neutron star is in spin equilibrium. However, the lack of reported outbursts between the *RXTE* detections and the association with IGR J01217−7257 suggests the neutron star could have experienced a protracted spin down phase and the inferred spin-up has only occurred since the outburst detected by *INTEGRAL* between MJD 56668.038 and 56669.192. In this case, a lower bound can be set of the value of $\dot{P} \sim 1.85 \times 10^{-4}$ s yr$^{-1}$ for the possible spin-up rate.
Orbital Period

Using long base-line hard X-ray data taken from the Swift/BAT transient monitor signal with period, $P = 82.5 \pm 0.7$ days is detected. This is similar to the periodic signal of $P= 83.67 \pm 0.05$ days detected in Section 5.3.4 from a systematic temporal analysis of the light curve taken from both the OGLE III and IV campaigns. While the quoted uncertainties on these detected signals suggest they are different, they are consistent at the 2$\sigma$ level, this is largely driven by the uncertainty in the X-ray period. There are a number of BeXRB systems where there are significant discrepancies between the X-ray and optical periods (see Table 2 and references therein of Bird et al. 2012). This difference is likely due to the origin of the modulation in each waveband. The X-ray emission and its modulation trace the accretion of material on to the neutron star that in the case of BeXRBs is when the neutron star is close to the Be decretion disc. The optical modulation, however, is likely due to a combination of the orbital motion of the neutron star around the companion star and the rotation of the decretion disc. The difference in the periodicities here, when compared with other examples of Bird et al. (2012), is relatively small, suggesting that the contribution to the signal from the decretion disc motion is small. In this case the X-ray periodicity is favoured as the binary period of this system.

With the association of SXP 2.16 and IGR J01217$-$7257, the source can be placed in the $P_{\text{spin}}$–$P_{\text{orb}}$ parameter space. Figure 5.21 shows the $P_{\text{spin}}$–$P_{\text{orb}}$ diagram of HMXBs (Corbet, 1986) with period data taken from Liu et al. (2006) and Bodaghee et al. (2007) and IGR J01217$-$7257 marked as a green triangle, assuming the orbital period determined from the X-ray data. The source lies on the bottom side of the Be/X-ray binary track. However, the track is quite broad and hence I do not suggest that this system is peculiar with respect to other systems of the same class.

Short period oscillations

The detection of short period optical oscillations in BeXRBs are often associated with non-radial pulsations (NRPs) of the companion star. In this case, short period oscillations are significantly detected in three epochs of combined OGLE–III and OGLE–IV data. The three epochs all have a similar flux of 5–6 mJy and occur prior to the onset of flaring behaviour seen in the companion light curve. NRPs have been invoked to explain the formation of the decretion disc in BeXRBs (Cranmer 2009 and references therein) and hence the onset of Type-I outbursts. Schmidtke et al. (2014) also detected short period pulsations ($P = 1.173$ d) in the OGLE-IV light curve searching between outburst times over the whole campaign, in contrast to the approach outlined in this chapter, where individual OGLE observing seasons are searched. Their derived sub-orbital periodicity is consistent with that found.
Figure 5.21: $P_{\text{spin}}$–$P_{\text{orb}}$ diagram of HMXBs (Corbet, 1986). Be/X-ray binaries are denoted by blue crosses, wind-fed supergiant X-ray binaries (SgXRBs) by red circles and Roche Lobe Overflow (RLOF) supergiant X-ray binaries by black squares. IGR J01217−7257 is marked by a green triangle and lies just below the BeXRB track. Period data are taken from Liu et al. (2006) and Bodaghee et al. (2007).
during the observations spanning MJD 55699.404 to 55993.014.

Timing analysis of epochs spanning MJD 55699.404 to 55993.014 and MJD 56083.43167 – 56353.022 of the OGLE data suggests an evolution of the NRP between the seasons. In the case of the \( \sim 1 \) days signal, a shortening of the periodicity is seen, whereas the converse is true for the signals around 6-7 days. This behaviour is expected if one of the signals is an alias of the other. I suggest that this is tentative evidence for periodicity evolution in NRPs driving the growth of a decretion disc to a critical size, such that periastron passages of the neutron star generate Type-I X-ray outbursts.

Sub-division of the observations between MJD 55699.404 and 55993.014 does not reveal monotonically decreasing/increasing signals and the inferred periodicities are broadly consistent with the periodicity found for the season as a whole.

5.4.3 X-ray – Optical Behaviour

Figure 5.14 shows the Swift/BAT light curve for both the transient monitor and the back-processed data in the top panel. The bottom panel shows the combined OGLE–III and IV light curves spanning \( \sim 15 \) years. In both panels, the INTEGRAL and Swift detected outbursts are marked with red and green regions respectively. There is clear association between the detected X-ray and optical outbursts. This is, again, consistent with Type-I outbursts from BeXRBs where X-ray outbursts are caused by the interaction of the neutron star with the decretion disc. From the OGLE light curve, orbital modulation from the neutron star-decretion disc interactions is clear between the detected INTEGRAL outbursts. This suggests that due to the observing strategy employed in monitoring the SMC with INTEGRAL, a number of X-ray outbursts were not observed during the peak in \( I \)-band flux. The observing strategy employed during the monitoring of the SMC is not optimised for the detection of given sources and is instead designed to have observations at regular intervals, restricted slightly by satellite scheduling.

The 11 year period between the RXTE detection of the source as SXP 2.16 on MJD 52644 and the re-discovery as IGR J01217−7257 coincides with a protracted low-flux period for the companion star. The lack of X-ray outbursts reported during this time or seen in the Swift/BAT light curve, coupled with the decrease in optical flux suggests that during that phase we are seeing either a reduced decretion disc size, a lack of a decretion disc around the star or observations of the SMC during this period were unfortunately timed. In the first case, the disc has retreated below the radius at which the binary orbital of the neutron star brings it into contact with the decretion outflow. The flux minimum seen in the OGLE light curve around MJD 54000 is then the flux of the companion star combined with that of the decretion disc at its minimum radial extent from the stellar photosphere. In
the second case, the flux minimum seen would correspond with the flux from the companion star with no decretion disc. The third case regarding observing strategy, I believe is unlikely, due to the fact that a similar observing strategy to that used during the flux minimum resulted in the observation of two outbursts in as many years. The apparent 4000 day super-orbital modulation present in the OGLE light curve is a common feature of BeXRBs. Rajoelimanana et al. (2011) studied long base-line OGLE and MAssive Compact Halo Objects (MACHO) light curves of SMC pulsars and found that all sources showed quasi-periodic super-orbital modulation between 200 and 3000 days and also found a linear correlation between orbital and super-orbital periods. Comparing the orbital period and ∼4000 day super-orbital modulation seen in IGR J01217−7257 with the Figure 44 of Rajoelimanana et al. (2011) it can be seen that this source, while lying on the top edge of the linear fit, does indeed follow the observed relation between orbital and super-orbital periods. The authors also find in the case of most BeXRBs a correlation between optical brightness and outburst strength that again this source appears to follow i.e when the source is optically bright, outbursts are seen.

The Swift outburst detected during the S-CUBED survey favours the idea that a circumstellar disc is still present at a sufficient size to interact with the neutron star. This X-ray outburst is observed during a period of decreasing $I$-band flux, suggesting that during this phase the decretion disc has not sufficiently decreased in size so as to inhibit Type-I outbursts. Comparing the behaviour of the companion with the activity seen around MJD 53700, we appear to be seeing the onset of a second flux minimum of the companion star with an apparent recurrence time of 10.2 years. Further monitoring of IGR J01217−7257 during the S-CUBED survey will reveal whether or not X-ray outbursts continue during the expected flux minimum. Detection of any Type-I outbursts during this time will confirm the presence of a decretion disc.

While Figures 5.14 and 5.20 show clear X-ray outbursts during the period when the source is optically bright, the picture is more difficult to see during periods of optical minimum. The analysis shown in Figure 5.9 shows that including hard X-ray data into the periodicity search from periods of low optical flux weakens the detection of the X-ray periodicity. This further suggests that the Type-I outbursts cease or are of low enough luminosity not to be detected by Swift/BAT during the period of low optical flux. Including this portion of the Swift/BAT light curve does not enhance the detection of the orbital modulation in the hard X-ray.

### 5.5 Conclusions

In this chapter, I have presented multi-wavelength observations of the Small Magellanic Cloud Be/XRB, IGR J01217−7257, also known as SXP 2.16, during
three outburst epochs as well as the original RXTE discovery data for the first time. Initially detected on 2003 January 05 during RXTE scans of the SMC with a periodicity of 2.1562±0.0001 s, the source was not subsequently detected for 11 years (corresponding with a minimum in flux activity from the companion star) until January 2014 when it was detected by INTEGRAL. Further X-ray outbursts were detected by INTEGRAL between 2015 October 29 and 2015 November 21 and by Swift/XRT as part of the S-CUBED survey between 2016 July 06 and 2016 July 15. Temporal analyses of long base line Swift/BAT and OGLE light curves reveals a small discrepancy between inferred orbital periods of 82.5±0.7 and 83.67±0.05 days, respectively. Interpreting the X-ray periodicity as indicative of binary motion of the neutron star, the outbursts detected by INTEGRAL and Swift between 2014 and 2016 are consistent with Type-I outbursts seen in BeXRBs, occurring around periastron. Comparing these outbursts with the OGLE data, there is a clear correlation between outburst occurrence and increasing I-band flux. A periodic analysis of subdivisions of OGLE data reveals three epochs during which short periodicities of ∼1 days are significantly detected that are suggested are NRPs of the companion star. These seasons immediately precede those exhibiting clear outburst behaviour, suggesting an association between the NRPs, decetration disc growth and the onset of Type-I outbursts as has been suggested before.
Chapter 6

Conclusions

The focus of this thesis has been the characterisation of accretion processes during periastron passages of neutron stars in high mass X-ray binaries. To this end, I have presented the results of phase targeted XMM-Newton observations of two supergiant fast X-ray transients and a multi-wavelength study of a BeXRB in the Small Magellanic Cloud. In this chapter, I summarise the findings of these studies and comment on potential future developments that may help to further illuminate accretion processes in high mass X-ray binaries.

In Chapter 3, I presented the results of a single 30 ks observation of the SFXT, SAX J1818.6–1703 along with contemporaneous INTEGRAL data. These observations place the source in an active state with a peak luminosity in the 0.5–15 keV energy range of $\sim 6 \times 10^{35}$ erg s$^{-1}$ and also show the presence of lower luminosity flaring behaviour. The first 6 ks of the XMM-Newton observation show the source in a low state with an average luminosity of $\sim 10^{34}$ erg s$^{-1}$. While disentangling the accretion processes generating this behaviour was not possible due to lack of knowledge of fundamental system parameters, such as neutron star spin period and magnetic field strength, possible explanations for this low luminosity phase include inhibition of accretion by means of a subsonic propeller (Bozzo et al., 2008b) or transition of the source into the radiative cooling regime in quasi-spherical accretion (QSA, Shakura et al. 2013). Following the initial low luminosity period, the source exhibits flaring behaviour before entering a long duration flare event that coincides with the critical luminosity for transition between the radiative and Compton cooling regimes in QSA. Spectral analysis reveals significant hardening of the spectrum coincident with this long duration flare event with evolution of the photon index from $\Gamma \sim 1.9$ to $\Gamma \sim 0.3$, suggesting a change in accretion mechanism compared to the earlier flaring activity. Spectra extracted also show strong intrinsic absorption with column densities of $N_H \sim 5 \times 10^{23}$ cm$^{-2}$, attributed to the strong stellar wind of the companion. These absorbing column densities are an order of magnitude higher than previously
observed in this system and indeed among the highest measured in an SFXT.

In Chapter 4, I presented the results of two 20 ks XMM-Newton observations of the intermediate SFXT, IGR J18450−0435 located either side of system periastron, and of simultaneous INTEGRAL observations spanning a total of 41 ks. During the first XMM-Newton observation, the source spends the majority of the time in an intermediate accretion state with an average luminosity of $3 \times 10^{34}$ erg s$^{-1}$ punctuated by short flares lasting $\sim$400 s reaching a peak luminosity of $(2.8 \pm 0.5) \times 10^{36}$ erg s$^{-1}$. Comparison of the average and minimum luminosities seen in this XMM-Newton observation with previous works reveals that this constitutes the lowest luminosity state seen in this source. The second XMM-Newton observation is located approximately one quarter of an orbit after the first and shows the source in a intermediate luminosity state with average luminosity $2 \times 10^{34}$ erg s$^{-1}$.

Spectral analysis reveals absorbing column densities up to five times greater than previously observed with values of $N_H = 7 - 10 \times 10^{22}$ cm$^{-2}$ and there is evidence of spectral evolution from $\Gamma = 1.3$ and $N_H = 9.62 \times 10^{22}$ cm$^{-2}$ during the intermediate luminosity phase to $\Gamma = 0.61$ and $N_H = 4.86 \times 10^{22}$ cm$^{-2}$ during a bright flare event in the first XMM-Newton observation.

Attempting to invoke the subsonic propeller to explain the observed intermediate luminosity state assuming a canonical magnetic field of $10^{12}$ Gauss breaks the key assumption of this regime, that the corotation radius lies outside the Alfvén radius. Only by assuming a magnetic field strength of $10^{13}$ Gauss can the subsonic propeller be invoked. The luminosity evolution observed during this observation can also be explained by invoking transitions between the radiative and Compton cooling regimes in the theory of quasi-spherical accretion and within this framework, the observed bright flares can be explained by the capture of magnetised stellar wind by the neutron star. The framework of quasi-spherical accretion is the favoured explanation as it does not require neutron star magnetic fields far in excess $10^{12}$ G in order to generate the observed behaviour and also provides a natural explanation for the quasi-periodic flaring during the first XMM-Newton observation. The simultaneous observations of IGR J18450−0435 by INTEGRAL result in the source not being significantly detected in either mosaics of the whole observation or at science window resolution. This is likely due to the combination of the short flare durations and the presence of a spectral cut-off between 10–20 keV.

In Chapter 5, I present the results of multi-wavelength observations of the BeXRB IGR J01217−7257, located in the Small Magellanic Cloud. I present for the first time the initial discovery of the source during RXTE scans of the SMC in 2003 as an X-ray pulsar with a 2.1562 s periodicity. The source was not detected for a period of 11 years before being rediscovered as part of INTEGRAL monitoring of the SMC during January 2014. Further observations as part of this programme in October
and November 2015 as well as monitoring of the SMC with Swift/XRT as part of the S-CUBED survey in July 2016 also detected activity from IGR J01217−7257. Using temporal analysis techniques outlined in Chapter 2, a periodicity of 82.5±0.7 day was found using long base-line Swift/BAT light curves and attributed to the orbital period of the neutron star around the companion in this system.

A temporal analysis of long base-line $I$-band light curves from the Optical Gravitational Lensing Experiment (OGLE) spanning almost 14 years reveals a periodicity of 83.67±0.05 days. The possible difference in X-ray and optical periods could be attributed to the combined effect of the neutron star and decretion disc orbital periods on the optical modulation. Using the X-ray derived orbital period, all reported outbursts occur at periastron, are consistent with Type-I outbursts and reach luminosities of $\sim 10^{37}$ erg s$^{-1}$ and show clear correlation with increasing optical flux. The detection of short periodicities in subdivisions of OGLE data preceding outburst behaviour suggests an association between the NRPs, decretion disc growth and the onset of Type-I outbursts.

The sources presented in this thesis span a large range in orbital periods and geometries. IGR J18450−0435 is the shortest period system presented in this work, with a 5.7 day period and an eccentricity upper limit of $e < 0.37$ which, when using the stellar parameters discussed in Chapter 4, result in periastron and apastron distance limits of $1.3 R_\star$ (lower limit) and $2.8 R_\star$ (upper limit) respectively. A similar calculation for SAX J1818.6−1703 with an orbital period of 30 days and eccentricity range of 0.3–0.4 gives periastron and apastron distances of 5.5–6 $R_\star$ and 2.5–3 $R_\star$. For periastron distances of $\sim 2 R_\star$ the neutron star is expected to experience a dense stellar wind, generate increased X-ray activity and hence suggests that eccentric systems should show a phase bias in outbursts for sufficiently long period systems.

In the case of SAX J1818.6−1703, this phase bias toward periastron was demonstrated by Bird et al. (2009) in their recurrence analysis of INTEGRAL data and outbursts of this source seem to cluster around periastron in behaviour reminiscent of BeXRBs. While the recurrence analysis of IGR J18450−0435 shows evidence of a mild eccentricity of the orbit, the upper limit apastron distance of $2.8 R_\star$ is small enough such that it is still expected that the neutron star will experience a similar stellar wind environment to periastron and hence outbursts could be generated at any orbital phase.

A phase bias in outbursts is expected in the case of IGR J01217−7257 due to its BeXRB nature and the analysis presented in Chapter 5 does indeed show recurrent flux maxima in the hard X-ray band around the proposed periastron likely due to interaction with the Be decretion disc. This picture is somewhat complicated by the lack of hard X-ray detections of the source during the 11 years coincident with a decrease in optical flux from the companion which suggests a change periastron
environment experience by the neutron star during this time, possibly due to the recession of the decretion disc below the L1 point or total depletion of the disc. The picture is further complicated by the detection of activity consistent with a Type-I outburst by Swift/XRT as the companion star appears to be entering another flux minimum. This suggests that during the optical flux minimum, the decretion disc is still present albeit reduced in size but still sufficient to interact with the neutron star. In this case, the paucity of hard X-ray detections during the 11 year optical minimum is likely due to outbursts lacking sufficient signal-to-noise to be identified as such.

This picture is not true in the case of all sources. It is worth noting that the prototypical BeXRB, A0538−66 (and a few others e.g SXP 25.5) in fact displays the opposite behaviour to that observed in the majority of sources, including IGR J01217−7257. During the super-orbital minimum, A0538−66 shows its strongest orbital outburst behaviour. Rajjoelimanana et al. (2011) suggested that this is due to the inclination of the decretion disc relative to the observer. Changes in the decretion disc size on the super-orbital time scale lead to a greater opening angle of the decretion disc resulting in greater obscuration of the Be star itself. This larger decretion disc interacts with the neutron star and generates the stronger outburst behaviour during optical minimum. The continuation of Type-I outbursts seen in IGR J01217−7257 during a superorbital minimum could be due to a flaring of the decretion disc increasing the opening angle presented to the observer and obscuring the Be star. Unlike A0538−66, the decretion disc of IGR J01217−7257 would not be edge on. Instead it would be at moderate enough inclination to allow for changes in the opening angle on time scales of ~4000 days to obscure the Be star but outside of these times, the full decretion disc and star would be visible - leading to an optical maximum.

The spectral analyses of both SAX J1818.6−1703 and IGR J18450−0435 presented in Chapters 3 and 4 show strong intrinsic absorption far in excess of that previously observed in both systems that is attributed to the presence of the dense stellar winds of the supergiant companion. The lack of variation in absorbing column density over the course of the XMM-Newton observation of SAX J1818.6−1703 suggests that there is no significant change in the periastron environment experienced by the neutron star and any structure in the winds is stable on time scales of 10 ks. In the observations of IGR J18450−0435, the absorbing column density is broadly consistent throughout the observations with the only exception being during a bright flare where the column density reduces by a factor of 2. This evolution could be attributed to the accretion of a clump of material along the line-of-sight or by the motion of stellar wind structures out of the line of sight. However, such a change in line-of-sight absorption is insufficient to account for the observed luminosity of \( \sim 9 \times 10^{35} \text{erg s}^{-1} \) and hence this change is likely due to the motion of a small structure in the stellar wind out of the line-of-sight. Observations
a quarter of an orbit later show reduced but still enhanced intrinsic absorption that is consistent with the picture discussed above, that the NS orbit in IGR J18450–0435 does not take it sufficiently far from the supergiant such that the neutron star experiences drastically different stellar wind environments.

Both analyses also show large changes in photon index coincident with flaring behaviour, suggesting that during these observation the accretion mode of the neutron star has changed. The picture is however not uniform across both sources, with the photon index change in SAX J1818.6–1703 occurring during a $\sim 8$ ks period with characteristic luminosity $\sim 6 \times 10^{35}$ erg s$^{-1}$ while the change in IGR J18450–0435 occurs during a 400 s long bright flare with a luminosity of $\sim 9 \times 10^{35}$ erg s$^{-1}$. This suggests that the mechanisms generating the hardening emission from the sources are different and that the observed behaviour in SFXTs may be the result of a number of physical processes that produce similar spectral shapes and/or luminosities.

The spectral analyses presented in this thesis suggest that the periastron environment experienced by the neutron stars in SFXTs, while characterised by a dense stellar wind, do not show large variations in absorbing column density. This could be the result of any shell or clumping structures (as discussed in Chapter 1) being of sufficient size such that their motion along the line-of-sight occurs on time scales greater than the observations lengths or that the total stellar wind environment along the line-of-sight, despite being comprised of a number of clumps or shells, is broadly stable and not rapidly varying.

In this thesis, no spectral analysis of IGR J01217–7257 during periastron passage is presented due to the proprietary 18 ks XMM-Newton observation reported by Haberl et al. (2015) being better able to constrain the spectral shape of the source than the publicly available Swift/XRT 1 ks snapshots. In their spectral analysis, Haberl et al. (2015) find no evidence of increased absorption along the line-of-sight to the source, which is consistent with the notion that Be star stellar winds are sufficiently weak so as not to affect the source X-ray spectrum and also that the source is not viewed at low inclination such that any accretion disc would appear edge on.

In all HMXB systems presented in this thesis, observations in both soft and hard X-ray show significant activity around periastron. In the case of the SFXTs, dynamic ranges of $\sim 100$ and 600 are observed over the course of the observations suggesting there is a moderate variation in accretion rate on to the neutron star as observed in the soft X-ray band. This is consistent with the idea that variations in the ambient stellar wind material surrounding the neutron star result in a variable accretion rate and hence luminosity.

In the theory of QSA, the observations presented here show the sources spending
the majority of their time in the radiative regime and flaring behaviour during these is the result of density variations in the quasi-static shell arising from the stellar wind inhomogeneities. Transition of sources into the Compton cooling regime as a result of an increased magnetospheric entry rate of plasma generates brighter flaring behaviour than that of the radiative regime. In the case of IGR J18450–0435 there is tentative evidence of the accretion of magnetised stellar wind resulting in a large flare. The behaviour of the SFXTs presented here can naturally be explained within the framework of quasi-spherical accretion assuming standard properties of neutron stars in SgXRBs, however measurements of the neutron star spin period and magnetic field are required to confirm this theory.

In the case of IGR J01217–7257, the hard X-ray observations presented in Chapter 5 show no evidence of variability on time scales shorter than 10 ks suggesting that the accretion onto the neutron star in this case is more stable than that of the wind accretors. The QSA framework has been applied to explain the behaviour of a number of BeXRBs and the peculiar system γ Cas (e.g Postnov et al. 2015, 2017) and can be utilised as the decretion disc appears as a region of enhanced stellar wind to the orbiting neutron star with a scale height greater than the size of the neutron star. Interpreting the INTEGRAL observations of IGR J01217–7257 within this model it can be seen that the associated luminosities $\sim 10^{37}$ erg s$^{-1}$ suggest that the source is in the direct accretion regime, whereby the captured decretion disc material is not inhibited by the magnetic field of the neutron star and is instead directly accreted.

In BeXRBs, the interaction of the neutron star with the Be star decretion disc is thought to result in an accretion disc around the neutron star in order to conserve angular momentum and hence generate the luminosities observed during Type-I outbursts such as those discussed in Chapter 5. When considering the accretion process at work in the periastron environments of the sources presented in this thesis a number of different mechanisms are seen. These range from stellar wind accretion where accretion regime transitions inhibit and enhance mass transfer on to the neutron star in the case of the SFXTs to a modified form of wind accretion in the case of IGR J01217–7257 where the decretion disc acts as an enhanced stellar wind. The conservation of the decretion disc angular momentum results in the formation of an accretion disc and allows the source to reach higher luminosities than observed in the SFXTs.

While the periastron environments in all of these sources provide the neutron star with a region of high density from which to accrete, it is the configuration of this environment that is a key component in the accretion physics that generate the observed X-ray behaviour. The fundamental properties of the neutron star are also key parameters that set the accretion physics at work in the sources, however with no knowledge of the magnetic fields of these neutron stars and the failure to detect
X-ray pulsations in the \textit{XMM-Newton} observations of SAX J1818.6$-$1703 and IGR J18450$-$0435 exact determination of the mechanisms generating the SFXT phenomenon is not currently possible. Below I discuss the future direction of the study of accretion in HMXBs and outline possible avenues of investigation that could reveal these key physical parameters and help resolve outstanding questions.

### 6.1 Future direction of the field

The mass transfer and accretion mechanisms generating the observed X-ray behaviour of high mass X-ray binaries are functions of the companion star spectral type and fundamental parameters along with the binary orbit and physical properties of the neutron star. Observationally, the picture is further complicated by the requirement of accurate source luminosities in a number of accretion models which in turn requires accurate knowledge of source distances.

In the main, these sources have been studied in the X-ray band due to their initial detections in this band. Accurate X-ray positions allow for determination of the counterpart spectral type and hence the mass transfer mechanisms as discussed in Chapter 1. In the case of BeXRBs, this mass transfer is by interaction with a decretion disc of stellar material around the companion star, the origin of which is still poorly understood. In order to distinguish between the possible formation scenarios of this structure, further studies are required that test already established theoretical models. In the case of the disc being formed by magnetic torques, further optical spectroscopy campaigns are required to infer the dipole magnetic field strength of the Be companion stars and assess whether these are strong enough to steer the stellar wind into a disc structure. Future campaigns using optical photometry and spectroscopy, specifically determination of the equivalent width of the H$\alpha$ line over many epochs, will also allow further investigation of the association between the presence of non-radial pulsations, disc growth and the onset of outbursts as suggested in Chapter 5. This is made more difficult as the typical periodicities of NRPs ($\sim$1 day) is comparable to the frequency of traditional optical monitoring of sources. The equivalent width of H$\alpha$ is taken as a proxy for decretion disc size and hence repeated measurements over multiple epochs covering different flux levels of the companion star will allow changes in the size of the disc to be correlated with the X-ray activity as well as investigate the possibility of disc-loss during flux minima of the companion.

In the case of systems with supergiant companion stars, the key physical properties of the stellar winds are typically poorly constrained. In order to critically investigate the effect of the stellar winds on X-ray emission in these systems knowledge of the mass loss rates and wind speeds of these stars is vital. These are key parameters in all theories concerning the accretion of stellar wind by a compact
object, whether they be used to calculate the amount of material that is gravitationally captured by the compact object or to characterise structure formation in the winds themselves.

Observationally, measurement of these parameters may be achieved by studies in the UV band focussing on characterisation of the P Cygni profiles seen in spectral lines. Accurate determination of these parameters may also be key in understanding the differences between SgXRBs and SFXTs as small variation in stellar wind properties can have large effects on the observed X-ray behaviour of these systems. Recently, Giménez-García et al. (2016) attempted to characterise these differences by analysing archival infra-red, optical and ultraviolet observations of Vela X–1 and IGR J17544–2619 with a non-local thermodynamic equilibrium model atmosphere code designed for Wolf-Rayet stars. This study revealed significant differences in wind speed and total mass loss of the star and suggests that these differences could be major contributing factors in the apparent differences between these two classes of object.

Future multi-wavelength studies of the companion stars of SFXTs utilising the same methods as Giménez-García et al. (2016) would allow comparison of stellar wind parameters across the class and provided insights into the differences between the prototypical sources such as IGR J17544–2619 and the intermediate sources such as IGR J18450–0435. The location of the SFXTs in the Galactic Plane coupled with, in some cases, high intrinsic absorption require deep monitoring programmes in the optical and UV bands to obtain sufficient quality spectra in order to execute such studies. Consequently, these studies are not possible with the currently available observations of SFXTs though future observing campaigns aimed at studying the whole SFXT population are greatly encouraged in this area.

Numerically, stellar winds have been studied in detail for decades, however often these have been constrained to the 1- or 2D case or have neglected effects of the compact object such as photo-ionisation on the stellar wind acceleration. As discussed in Chapter 1, recent 2.5D simulations incorporating photo-ionisation have been performed by Manousakis & Walter (2015) to explain the behaviour of Vela X–1. This study does not include clumping in the stellar winds but the numerical simulations generate structures in the wind. To this end, future multidimensional hydrodynamic studies including intrinsic clumping of the wind due to line instabilities and the effects of the neutron star will facilitate an understanding of the interplay of these effects. In addition to clumping, recent studies suggest up to 10% of supergiant stars could possess magnetic field strengths of order $10^3$ Gauss (Donati & Landstreet, 2009).

Magnetohydrodynamic simulations of stellar winds including magnetic reconnection and their interaction with neutron stars would be of great value in understanding the role reconnection might play in the accretion phenomena in SFXTs as suggested
by Shakura et al. (2014). This approach, however, is computationally intensive and a first step numerically in evaluating the theory of quasi-spherical accretion would be to use the density and velocity profiles obtained from 1D radiative hydrodynamic simulations of stellar winds (such as those obtained by Oskinova et al. 2012) as inputs to this model. This would enable the impact on the accretion regimes inhabited by the neutron star to be studied and allow an investigation of the conditions under which the SFXT phenomenon are realised.

As discussed above, luminosity is a diagnostic in a number of accretion models invoked to explain the differences in behaviour between SgXRBs and SFXTs require accurate determination of the source distance. In the case of SFXTs, distances have typically been inferred from near infra-red spectroscopy using template spectra which leads to source distances either lacking uncertainty measurements or possessing large uncertainties (e.g. $9.5^{+14.1}_{-5.7}$ kpc for IGR J16465−4507) driven by the uncertainty in absolute magnitude. Unconstrained distances are the dominant contribution to the uncertainties in luminosity calculations and hence introduce difficulties when attempting to interpret results within the context of luminosity-dependent accretion models.

Constrained distance determinations of a large number of HMXBs, including a significant fraction of the SFXTs, have been achieved in the last few years by Coleiro & Chaty (2013) using broad-band SED fitting across the optical and NIR bands. This has resulted in revised distance estimates for a number of sources, including IGR J18450−0435 as discussed in Chapter 4 and also IGR J16465−4507 where the authors derive a distance of $12.7 \pm 1.3$ kpc. Expanding this work to the rest of the SFXT population would require further optical/NIR observations (across up to 8 bands; U, B, V, R, I, J, H, K$_s$) of the companion stars but would allow for critical evaluation of the models of Bozzo et al. (2008b) and Shakura et al. (2013) across the whole population.

Understanding the orbital dynamics of HXMBs is also key to investigating the accretion physics in these systems. While the majority of confirmed SFXTs have orbital period determinations (See Table 1.1), there are still a number of these systems where knowledge of this key parameter is lacking. Ongoing monitoring of these sources with INTEGRAL and *Swift*/BAT in the future will provide longer base-line light curves with which to perform searches for periodic modulation. In the case of IGR J11215−5952 the orbital period of 164.6 day has been inferred from recurrent outbursts, however no formal timing analysis of this source has been performed in order to verify that this is the true orbital period of this system and not an artefact of observing strategies. With determination of orbital periods, limits on eccentricities have been derived assuming that the supergiant companion does not fill its Roche Lobe have been obtained, however the lack of a firm calculation of this parameter drives large uncertainties in the knowledge of the
circumstellar environment experienced by the neutron star.

Determination of the orbital eccentricity can be achieved observationally by two independent methods. The first of these being studies of the radial velocity (RV) curve of the supergiant, whereby eccentricities can be calculated by characterising modulation of the centroid of spectral lines of the companion that is indicative of the neutron star orbital motion. Characterising the amplitude of RV variations in supergiant binaries is challenging due to the large mass ratios of the companions and neutron stars resulting in any variations being small as well as the presence of the large stellar wind outflows. To remove the influence of the mass outflow on any determined RV variations, spectral lines associated with the stellar photosphere must be used and as supergiants are typically bright in the NIR band, lines such as \( \text{Br}10, \text{Br}12 \) and \( \text{HeI} \) are ideal targets for study.

The combination of the small RV semi-amplitudes and the need to use near infra-red spectral lines results in only a handful of facilities currently operating being able to undertake these measurements. Coupled with the long orbital periods of the SFXTs, relative to LMXBs, determination of orbital solutions using this method would require large observation programmes over many years using facilities such as the VLT. A tentative report of this method being used to determine the binary parameters of IGR J17544−2619 was reported by Nikolaeva et al. (2013), however the derived orbital period is markedly different from that observed in X-rays and the radial velocity curve fit is unconvincing, suggesting this determination is tentative.

The second method is measurement of variations in the neutron star spin period as a result of Doppler shifting along the orbit. In the case of SFXTs this is challenging as the currently determined X-ray periodicities are of order a few hundred seconds, hence regular monitoring observations to detect the spin period at multiple epochs would have to be a few ks in duration. The known periodicities also have associated with them error bars of a few seconds and variations due to Doppler shifting will likely be much smaller than the uncertainties on each derived periodicity, hence refinement of known spin periods of SFXTs is required before this method can be used effectively to diagnose orbital parameters.

In the case of BeXRBs, once the companion is classified as a Be star, recurrent outbursts are attributed to the orbital period of the system. Determination of the orbital period, however does not constrain the other parameters of the orbit as with the supergiant systems discussed above. Instead, both radial velocity measurements and Doppler shifting of the spin period are useful in determining orbital solutions for these systems especially for those located in the SMC. Thanks to monitoring with \textit{RXTE}, \textit{Swift} and \textit{XMM-Newton}, spin periods of the neutron stars in a large number of systems have been accurately identified (see for example Chapter 5) and variations in the spin periods due to Doppler shifting have been used to infer orbital
parameters (Townsend et al., 2011; Coe et al., 2015a). Continued monitoring of the SMC for variations in spin periods of the neutron stars in binaries using current generation X-ray telescopes will allow for further characterisation of these sources.

As discussed above physical properties of the neutron stars such as spin period and magnetic field strength also play a pivotal role in the accretion physics in HMXBs. In the case of SFXTs, only a handful of pulse periods have been detected with even well studied systems such as SAX J1818.6−1703 lacking detections. The possible reasons for non-detections of spin periods in these sources are outlined in Chapters 3 & 4. Other limiting factors in detecting signatures of neutron star spin in observations include masking of the signal by the presence of large scale flaring behaviour on similar time scales as the spin period or that the observations are simply too short to acquire sufficient signal-to-noise to identify the periodicities at significant confidence. Combined with possible geometric effects, these factors make the detection of spin periods in SFXTs challenging, however the vital importance of understanding the spin periods of these systems motivates further studies using current- and next generation telescopes at differing flux states in order to comprehensively search for these signals.

Often in SFXTs, the magnetic field has been inferred from considering applicable accretion regimes based on observed luminosities and working backwards. The launch of the NuSTAR satellite, with its unbroken broad-band 3–80 keV energy coverage and unparalleled hard X-ray sensitivity, has allowed more in-depth studies of HMXB spectra in the hard X-ray band and has resulted in the first detection of a CRSF in an SFXT (IGR J17544−2619; Bhalerao et al. 2015). The inferred magnetic field of $\sim 10^{12}$ Gauss in a prototypical system challenges models that suggest the SFXT phenomenon could be generated by magnetar-like field strengths, however the picture is complicated somewhat by the lack of detection of the cyclotron feature in subsequent NuSTAR observations (Bozzo et al., 2016b). Determination of the magnetic field strengths of other neutron stars in SFXTs with future NuSTAR observations would allow for a comparison across the class and investigate the extent to which magnetic field effects are responsible for generation of the SFXT phenomenon.

In the case of SMC BeXRBs, magnetic fields have also been inferred in a model-dependant way assuming the accretion torque model of Ghosh & Lamb (1978), with a number of these sources potentially hosting magnetars (Klus et al., 2014). Verification of these magnetic field strengths is currently infeasible as cyclotron lines for magnetar-like fields are of order a few hundred to a thousand keV - outside the range of any satellite sensitive enough to detect the features. Pointed observations with NuSTAR of sources with inferred fields in the $10^{12}$ Gauss range could be used as model-independent confirmations/refutations of such a method of inference.
Periastron environments in HMXBs present the most extreme conditions in which to study the accretion of matter on to compact objects. Despite decades of study, the origin of the decretion disc in BeXRBs is still a matter of debate and further multi-wavelength campaigns are required to investigate the connection between stellar properties such as NRPs, the binary orbit and disc growth. In the case of SFXTs, the observed extreme dynamic range and underluminous nature of these sources relative to the persistent SgXRBs present challenges to models of wind accretion in HXMBs. In order to disentangle the accretion processes at work in these sources and their relationship to SgXRBS, continued monitoring and pointed observations of all sources with the full suite of current and future X-ray telescopes as well as multi-wavelength campaigns to constrain key system parameters are vital.
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