Exploring subluminous X-ray binaries

Degenaar, N.D.

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1 Introduction

Halfway the twentieth century, technological developments made it possible to carry detection instruments outside the absorbing layers of the Earth's atmosphere onboard rockets and satellites. This opened up the opportunity to detect the emission from celestial objects at X-ray wavelengths, thereby providing a window to study high energy phenomena in the Universe (Giacconi 2003). The first X-ray source to be discovered outside the Solar system was Scorpius X-1, now known to be a member of a class of objects referred to as X-ray binaries. These are stellar binary systems in which a gravitationally collapsed object, either a neutron star or a black hole, consumes matter from its companion star. X-ray binaries provide a unique probe to test the laws of physics under extreme conditions, a basic quest of science. Neutron stars are a pure marvel representing matter at supra-nuclear densities in the presence of vigourous magnetic fields: conditions that are unattainable in laboratory experiments on Earth. Equally exciting, black holes form the ultimate testbeds for Einstein's theory of General Relativity.

Although constituting the brightest X-ray point sources observed in our Galaxy, X-ray binaries can actually be observed over a wide range of luminosities. Early X-ray missions allowed only the study of the most luminous X-ray sources, but instruments have increased in sensitivity by orders of magnitude over the past decades. Owing to their high spatial resolution and sensitivity, the current generation of X-ray imaging instruments carried onboard the satellites *Chandra*, *XMM-Newton* and *Swift* provide an unprecedented deep view of the X-ray sky. This thesis is devoted to exposing the properties of X-ray binaries at low luminosities, which have long been inaccessible due to limitations of X-ray instruments. In this introductory chapter I discuss different phenomena that are observed at low luminosities, covering accretion outbursts and thermonuclear events occurring at low mass-accretion rates, as well as the crust cooling of neutron stars once the accretion has come to a halt.

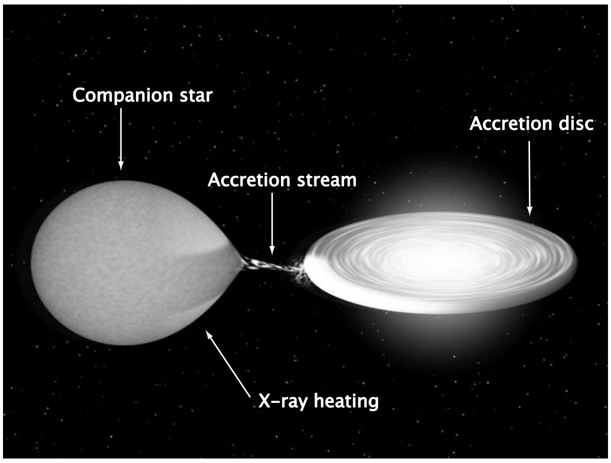

Figure 1.1: Artist impression of a low-mass X-ray binary. This image was produced using the BINSIM software distributed by R. Hynes.

1.1 X-ray binaries

Unlike our Sun, most of the stars in our Galaxy are not single, but are instead part of a binary system in which two stars orbit a common centre of mass under the influence of their mutual gravitational force. If the binary constituents are close enough, the stars can exchange matter and via this interaction they can drastically influence each others evolution. If one of the components is a neutron star or a black hole, the gravitational energy release due to the in-fall of matter towards the compact primary makes the system shine in X-rays. Conservation of angular momentum prevents that matter is transferred directly from the companion onto the compact star, and the process of accretion therefore generally involves the formation of an accretion disc (see Figure 1.1). Within the disc, half of the liberated gravitational energy is converted into kinetic energy, whereas the other half is thermalized and radiated in the form of X-rays. If the accreting body is a neutron star, the kinetic energy can also be radiated at X-ray wavelengths, once the matter hits the stellar surface. However, in case of a black hole the energy can be carried beyond the event horizon without being radiated.

Based on the nature of the donor star, two types of X-ray binaries are distinguished. High-mass X-ray binaries (HMXBs) contain a massive star with $M_{\rm donor} \gtrsim 10\ M_{\odot}$ and spectral type O or B. In such a configuration the compact primary is typically capturing matter from a circumstellar disc or the strong stellar wind of its massive companion. Low-mass X-ray binaries (LMXBs), on the other hand, harbour companion stars with $M_{\rm donor} \lesssim 1\ {\rm M}_\odot$ and a spectral type later than B. Such low-mass stars have very weak stellar winds and matter transfer usually takes place because the donor star overflows its Roche-lobe; the volume of space surrounding the star, within which co-rotating matter is gravitationally bound to it (see Figure 1.1). Ultra-compact X-ray binaries (UCXBs) form a subclass of LMXBs, in which the orbital period is $\lesssim 80$ min. This requires the donor star to be depleted of hydrogen in order to fit within such a tight orbit (Nelson et al. 1986).

The radiation emitted by X-ray binaries is proportional to the amount of fuel transferring onto the compact object, which can be expressed in terms of the mass-accretion rate $\dot{M}$, typically given in units of g s^{-1} or M$_\odot$ yr^{-1}. Matter moving into the gravitational potential well of a neutron star or black hole can, if all liberated energy is converted into radiation, give rise to an accretion luminosity of $L_{\rm acc} = GM\dot{M}/R$, where G is the gravitational constant and M and R are the mass and radius of the compact object, respectively. In some areas of research (e.g., the study of thermonuclear bursts, see Section 1.3) the accretion luminosity is often quoted as a fraction of the Eddington limit. This represents the luminosity for which the gravitational pull of the accreting body balances the radiation pressure generated in the accretion process. For a steady, spherically symmetric accretion flow consisting of pure hydrogen gas, the Eddington luminosity is given by $L_{\rm EDD} = 4\pi GMm_pc/\sigma_T \simeq 1\times10^{38}\ (M/{\rm M}_\odot)$ erg s^{-1}, with m_p being the proton mass, σ_T the Thompson cross-section for electron scattering and c the speed of light. If the Eddington limit is exceeded, the outward force of the generated radiation overcomes the gravitational attraction, thereby putting a halt to the accretion. For a canonical neutron star with $M = 1.4\ {\rm M}_\odot$ and $R = 10$ km, the mass-accretion rate associated with this threshold is $\dot{M}_{\rm EDD} \simeq 1\times10^{-8}\ {\rm M}_\odot\ {\rm yr}^{-1}$.

1.1.1 Long-term variability in X-ray binaries

When the accretion flow in an X-ray binary is continuous, the system displays a relatively steady X-ray luminosity and is denoted as *persistent*. However, in many X-ray binaries mass is being transferred primarily during outburst episodes that have a typical duration of weeks to months, whereas most of the time is spent in a quiescent state during which accretion is strongly reduced and correspondingly the X-ray luminosity is a factor $\gtrsim 100$ lower. This *transient* behaviour is illustrated by Figure 1.2, which shows long-term lightcurves of three different X-ray binaries. As demonstrated by this image, the duration and recurrence time of accretion outbursts widely varies amongst sources. Whereas the majority of X-ray transients are active for a few weeks or months, at most, there exists a subclass of systems that undergo prolonged accretion episodes that endure for years or even decades (Wijnands 2004). An example of such a *quasi-persistent* X-ray binary is shown in the bottom plot of Figure 1.2.

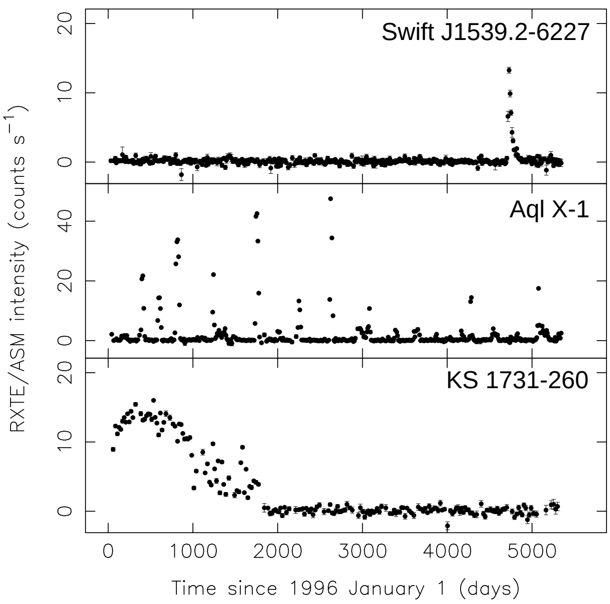

Figure 1.2: *RXTE*/ASM 10-day averaged lightcurves of different X-ray transients (1.5–12 keV).

In wind-fed HMXBs, transient behaviour can be caused by clumpy or anisotropic winds (e.g., Kaper et al. 1993; Sidoli 2009). Furthermore, members of the subclass of Be/X-ray binaries can be transient due to variability in the mass loss of the Be star, or if the compact primary is in a wide and eccentric orbit, such that accretion only takes place around periastron passage (e.g., Negueruela 2004). For LMXBs, transient cycles are explained in terms of a thermal-viscous instability that causes the disc to oscillate between a cold, neutral state (quiescence), and one in which it is hot and ionised, causing a strong increase in the mass-accretion rate and resulting in an X-ray outburst (e.g., King & Ritter 1998; Lasota 2001). During quiescence, the disc regains the mass that was lost during the outburst and the cycle repeats.

1.1.2 Very-faint X-ray binaries

X-ray binaries can be further classified based on their observed 2–10 keV peak luminosities. The temporal and spectral properties of the brightest galactic X-ray binaries, which have accretion luminosities of $L_X \sim 10^{36-39}$ erg s^{-1} in the 2–10 keV energy band, are well established through the work of numerous past and present X-ray missions. However, it has been realised that there exists a population of *very-faint X-ray binaries* that never become bright and manifest themselves with much lower accretion luminosities of $L_X \sim 10^{34-36}$ erg s^{-1} (e.g., Wijnands et al. 2006a; Campana 2009). Their identification as accreting binary systems has been established by the detection of thermonuclear X-ray bursts (in 't Zand et al. 1991; Cocchi et al. 1999; Cornelisse et al. 2002; Del Santo et al. 2007b; Degenaar et al. 2010a) or coherent X-ray pulsations (e.g., Masetti et al. 2007; Kaur et al. 2010). In addition, there are a number of unclassified subluminous X-ray sources for which the spectral properties and energies involved in their outburst phenomena are also suggestive of an X-ray binary nature (e.g., Muno et al. 2005b; Degenaar & Wijnands 2009, 2010).

Considering that the radiation emitted by X-ray binaries is proportional to the mass-accretion rate, the observed low luminosities suggest that these systems harbour slowly accreting compact objects. The rate at which matter is transferred is a driving parameter for many phenomena related to X-ray binaries and observations of very-faint objects allow us to probe a relatively unexplored regime of accretion. For instance, the mass-accretion rate averaged over a time scale of thousands of years plays an important role in the evolution of the binary. Some very-faint X-ray sources have unusually low inferred mass-accretion rates, posing challenges to explain their existence without having to invoke exotic evolutionary scenarios (e.g., King & Wijnands 2006; Degenaar & Wijnands 2009). Furthermore, several X-ray binaries accreting at low rates have displayed thermonuclear bursts with unusual properties, which are a unique probe of how matter accumulates on the surface of a neutron star and can even provide insight into the interior properties of the neutron star (e.g., Cornelisse et al. 2002; in't Zand et al. 2005b; Peng et al. 2007; Cooper & Narayan 2007; Degenaar et al. 2010a).

1.1.3 Monitoring the central part of our Galaxy

The high stellar density within several degrees around Sgr A*, the dynamical centre of our Galaxy, make this an ideal place to search for X-ray binaries. The field has been amongst the privileged targets of many X-ray missions and this has resulted in the identification of more than a dozen transient and persistent (candidate) X-ray binaries (e.g., Muno et al. 2009). Interestingly, there appears to be an overabundance of subluminous X-ray sources in the central regions of our Galaxy (e.g., Muno et al. 2005b; Wijnands et al. 2006a; Degenaar & Wijnands 2009, 2010). Repeated observations of this sky area hold good potential to refine our understanding of the nature and behaviour of transient low-luminosity X-ray sources.

In the past years, several programs have been launched aiming to study the population of X-ray binaries located in the vicinity of Sgr A*. Starting in 2006 February and continuing into 2010, the *Swift* satellite has been targeting this area with the onboard X-ray telescope. In this campaign, short ($\sim$ 1 ks) observations are carried out on a nearly-daily basis, covering a field of approximately 26×26 arcmin around

Sgr A* (Kennea & The Swift/XRT team 2006; Degenaar & Wijnands 2009, 2010).[1] Furthermore, an extensive campaign joining forces of *Chandra* and *XMM-Newton* was carried out between 2005 and 2008, during which the central 1.2 square degree of our Galaxy was targeted on 10 different epochs (Wijnands et al. 2006a, Chapter 7). Finally, a region subtending many square degrees has been regularly scanned by *RXTE* starting in 1999 (Swank & Markwardt 2001) and by *Integral* since 2005 (Kuulkers et al. 2007c). All this provides an ideal setting to spot transient events in one of the most active X-ray regions in the Milky Way.

1.2 Interior properties of neutron stars

1.2.1 Neutron star structure

The current consensus is that a neutron star is composed of three main regions: the atmosphere, the crust and the core (see Figure 1.3). The neutron star atmosphere is a thin ($\sim 0.1 - 10$ cm) layer consisting of ionised nuclei and non-degenerate electrons. The atmosphere accounts for a negligible fraction of the total stellar mass, but plays an important role in shaping the thermal photon spectrum emerging from the neutron star surface. A simple blackbody does not provide an adequate description, because the opacity of the atmosphere is strongly dependent on the photon frequency (e.g., Zavlin et al. 1996). Due to a steep temperature gradient, this causes high-energy photons to escape from much hotter atmospheric layers than low-energy photons. Fitting the spectra with a simple blackbody may therefore overestimate the effective temperature and in turn underestimate the emitting region (Rutledge et al. 1999).

The crust typically takes up about one tenth of the neutron star radius and can be subdivided into an inner and an outer part. The outer crust extends from the bottom of the atmosphere to the neutron drip density, $\rho_{\rm drip} \approx 4.3 \times 10^{11}$ g cm^{-3}. In this region, matter consists of ions and relativistic, degenerate electrons. Due to a rise in electron Fermi energy with increasing density, the nuclei are enriched by neutrons due to inverse β-decay. At the base of the outer crust, neutrons become so numerous that they start to drip out of the nuclei. The inner crust covers the region from the neutron drip density to approximately the nuclear density, $\rho_0 \approx 2.8 \times 10^{14}$ g cm^{-3}. The inner crust is composed of electrons, free neutrons and neutron rich nuclei. Atomic nuclei begin to dissolve and merge together around the crust-core interface.

The core constitutes the largest part of the neutron star, containing approximately 99% of the total mass, and may also be subdivided into an outer and an inner part. The outer core occupies the density range $\rho_0 \lesssim \rho \lesssim 2\rho_0$ and can be several kilometres

[1] Note that during the months November–February the Galactic centre is virtually unobservable due to close proximity (within 45 degrees) of the Sun.

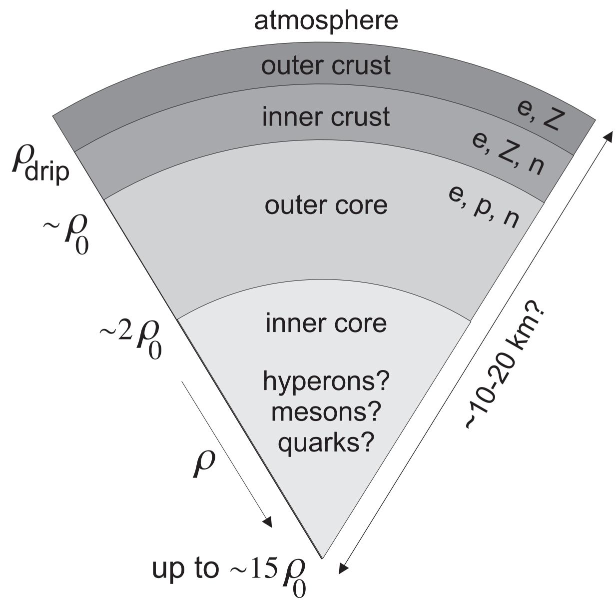

Figure 1.3: Schematic representation of the interior of a neutron star.

in depth. In this density range, matter consists mainly of degenerate neutrons and merely a few percent of protons and electrons. Due to the growing Fermi energies of the particles with increasing density, it may become energetically favourable for other particles to occur, besides the standard composition of protons, neutrons and electrons (e.g., hyperons, pions/kaons or deconfined quarks). Moving into the inner core of the neutron star, the density rises beyond $\rho \approx 2\rho_0$ and may become as high as $\rho \approx (10-15)\rho_0$. The composition of the central region of the neutron star is largely unknown and the reliability of theoretical models decreases with increasing density.

1.2.2 Thermal evolution of neutron stars

Neutron stars are born extremely hot in supernova explosions, with interior temperatures around $T \sim 10^{12}$ K. During their life, neutron stars loose energy, both by the emission of neutrinos in various particle interactions, and by thermal photon emission from the surface. Since neutron stars do not burn nuclear fuel in their interior, they cannot compensate for these energy losses, and consequently they cool in time (unless accretion takes place, see below). Neutrinos are generated in numerous reactions in the neutron star interior and can freely escape the star, thereby providing an efficient source of cooling. Already within a day, the temperature in the central

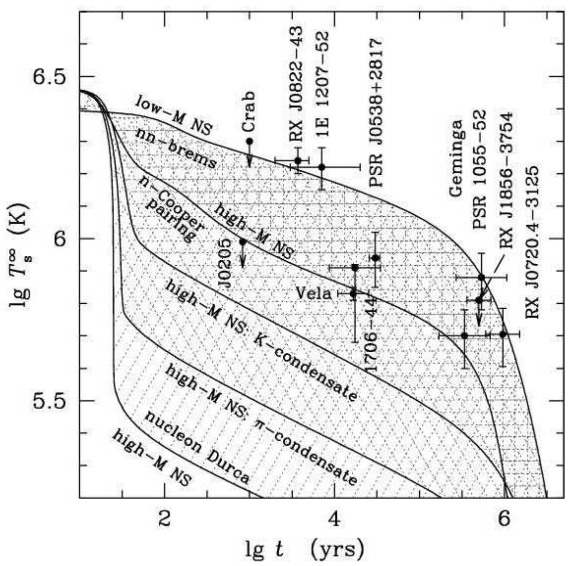

Figure 1.4: Theoretical cooling curves for different neutron star core compositions. The models are compared with observations of isolated neutron stars from which thermal surface emission is observed and for which ages can be estimated. Image from Yakovlev & Pethick (2004).

region of the neutron star will have dropped down to $\sim 10^9 - 10^{10}$ K.

The most dominant neutrino emission processes take place in the stellar core, where matter consists of free neutrons, protons, electrons and possibly different forms of exotic matter (see Section 1.2.1). The rate of neutrino emissions depends on the equation of state of cold nuclear matter and the central density of the neutron star. With increasing density the threshold for more efficient neutrino emission processes opens up and consequently the more massive a neutron star, the faster it is expected to cool (e.g., Yakovlev & Pethick 2004; Page et al. 2006). This is illustrated by Figure 1.4, which shows different possible thermal histories, or cooling curves, for isolated neutron stars. If thermal emission from the neutron star can be observed and its age can be estimated, e.g., via an associated supernova remnant, theoretical cooling curves can be compared with observations in order to explore the interior properties of the neutron stars.

The process of accretion significantly alters the thermal evolution of a neutron star. Under the weight of matter accumulating onto the neutron star surface, the crust is compressed thereby inducing a series of electron captures, neutron emissions and pycnonuclear fusion reactions (e.g., Haensel & Zdunik 2008). Most of the heat energy is released by processes occurring deep in the inner crust, close to the crust-core boundary (see Figure 1.3), and is subsequently spread over the neutron star via thermal conduction. When accretion is ongoing, the thermal emission emerging from the neutron star surface is completely overwhelmed by the X-rays generated in the accretion disc (except in the case of a type-I X-ray burst, see Section 1.3). However, during the quiescent episodes of transient X-ray binaries, thermal surface emission can potentially be observed.

1.2.3 Quiescent emission of transiently accreting neutron stars

The quiescent X-ray spectra of neutron star transients are observed to consist of one or two components: a soft, thermal component ($kT_{\rm bb} \sim 0.1 - 0.2$ keV), and/or a hard tail that dominates the spectrum above ~ 2 keV. The non-thermal component is usually well-fitted by a simple powerlaw with photon index 1–2. The fractional contribution of the hard tail to the total 0.5–10 keV X-ray flux widely varies amongst sources and possibly also with changing luminosity (Jonker 2008). The physical process that is responsible for the powerlaw spectral component remains elusive (e.g., Campana 2003), but the soft emission component is most often interpreted as thermal surface radiation from the cooling neutron star.

In approximately ten thousand years, the neutron star core reaches a thermal steady state in which the heating due to the accretion of matter is balanced by cooling via neutrino emissions from the stellar core and photon radiation from the surface. This yields an incandescent emission from the neutron star surface that is set by the time-averaged accretion rate of the system, as well as the dominant neutrino cooling mechanism (e.g., Brown et al. 1998). When combined with estimates of the outburst history, observations of quiescent neutron stars can constrain the rate of neutrino emissions, thereby providing insight into the interior properties of the neutron star, in similar fashion to what is done for isolated neutron stars (see Figure 1.5).

1.2.4 Neutron star crust cooling

Once the steady state is reached, the neutron star core temperature does not change appreciably during a single outburst. However, the temperature of the crust can be dramatically altered. In regular transients that have a typical outburst duration of weeks to months, the crustal heating processes only cause a slight increase in the crust temperature (Brown et al. 1998). However, in quasi-persistent X-ray binaries the prolonged accretion episodes can cause a significant temperature gradient between the neutron star crust and core. Once the accretion ceases, the crust is expected to thermally relax on a time scale of years, until equilibrium with the core is re-established (Rutledge et al. 2002b). During the initial stages of the quiescent phase the thermal emission is therefore dominated by the cooling crust, whereas eventually

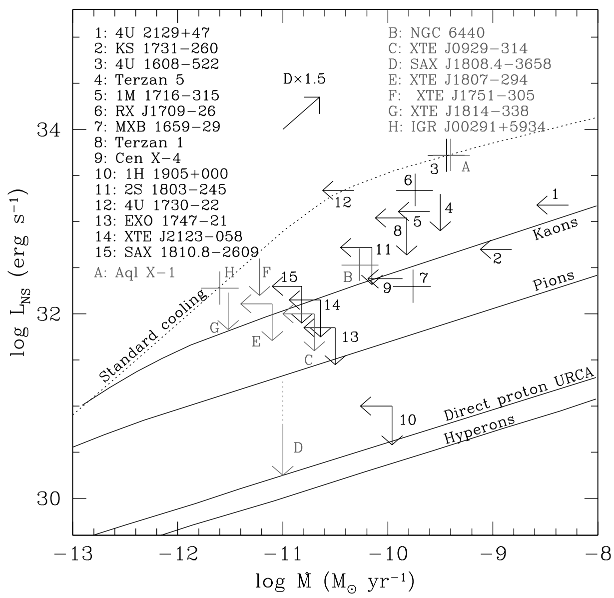

Figure 1.5: Theoretical cooling curves for different neutron star core compositions compared with measurements of (or upper limits on) the quiescent thermal emission and time-averaged mass-accretion rate of a number of neutron star X-ray transients. The data points indicated by letters concern accreting millisecond pulsars. Image from Heinke et al. (2009b).

a quiescent base level is reached that is set by the thermal state of the core (Wijnands et al. 2001; Rutledge et al. 2002b). This provides the special opportunity to separately probe the properties of the neutron star crust (e.g., Brown & Cumming 2009).

In 2001, the neutron star X-ray binaries KS 1731–260 and MXB 1659–29 both made the transition to quiescence, following accretion episodes of 12.5 and 2.5 years, respectively (Wijnands et al. 2001, 2002a, 2003, 2004; Cackett et al. 2006, 2008a, 2010a). Both systems were subsequently monitored with *Chandra* and *XMM-Newton*, which revealed that the thermal flux and neutron star temperature were gradually decreasing over the course of years. This can be interpreted as cooling of the neutron star crust that has been heated during the prolonged accretion outburst. Successful modelling of the observed quiescent X-ray lightcurves with neutron star thermal evolution models supports this hypothesis and provides important constraints on the crust properties, such as the thermal conductivity and distribution of heat sources (Shternin et al. 2007; Brown & Cumming 2009). More recently, another two neutron star X-ray binaries have been monitored in their transition from outburst to quiescence. In 2007, the $\sim$ 1.6-year long outburst of XTE J1701–462 came to a halt (Altamirano et al. 2007; Homan et al. 2007; Fridriksson et al. 2010), and in 2008 the activity of EXO 0748–676 ceased after more than 24 years (Degenaar et al. 2009, 2010d).

1.3 Thermonuclear X-ray bursts

One of the phenomena that testifies to the presence of a neutron star in an X-ray binary are type-I X-ray bursts; intense flashes of X-ray emission resulting from runaway thermonuclear burning of hydrogen (H) and/or helium (He) on the surface of accreting neutron stars. They are characterised by blackbody emission with a peak temperature of $kT_{\rm bb} \sim 2-3$ keV and typically show a fast rise followed by a slower decay phase. The observational properties (e.g., duration, radiated energy and recurrence time) of type-I X-ray bursts depend on the conditions in the ignition layer, such as the temperature, thickness and hydrogen abundance. These can drastically change as the mass-accretion rate onto the neutron star varies, such that there exist distinct accretion regimes giving rise to X-ray bursts with different characteristics (Fujimoto et al. 1981; Bildsten 1998).

1.3.1 Nuclear burning regimes

Matter that accumulates onto the surface of a neutron star undergoes thermonuclear fusion reactions. The heat that is released in these processes is transported out of the burning layer by radiative cooling. A higher temperature generally increases the energy generation due to nuclear burning, which also increases the cooling rate. A thermonuclear runaway occurs when an enhanced heating rate cannot be compensated by cooling of the layer. This gives rise to a type-I X-ray burst that briefly outshines the X-ray emission coming from the accretion disc. The stability criteria depend on the temperature dependence of the nuclear burning reactions. If the temperature dependence is strong, a small increment in temperature can lead to a huge increase in the energy generation rate, causing thermonuclear runaway.

Theoretically, accretion rates near the Eddington limit are expected to maintain the temperature in the accreted envelope at high enough values for both H and He burning to proceed in a stable manner. No type-I X-ray bursts are therefore observed. For mass-accretion rates between $\sim 3-100\%$ of Eddington, He burning is predicted to be unstable and ignite in a H-rich environment, producing a mixed H/He burst with a duration of $\sim 10-100$ s. For lower rates ($\sim 0.5-3\%$ of the Eddington rate), H will be depleted from the burning layer before He ignites. These pure He bursts are shorter, with a typical duration of $\sim 5-10$ s.[2] For the lowest accretion rate regime (below $\sim 0.5\%$ of Eddington), the temperature in the envelope becomes so low that H itself burns unstably. The resulting weak H-flashes can trigger two different types of He bursts (see Section 1.3.2).

All of the above types of X-ray bursts have been observed, although there are discrepancies between the theoretically predicted boundaries of the different regimes

[2] H-rich bursts are longer due to prolonged nuclear burning via the rapid proton (rp) process.

and those implied by observations (e.g., van Paradijs et al. 1988; Cornelisse et al. 2003). It is important to note that the local mass-accretion rate, generally expressed as $\dot{m}$ and given in units of g s^{-1} cm^{-2}, may differ from the global mass-accretion rate (i.e., averaged over the entire neutron star surface) if the accretion is not spherically symmetric. This may be the case, for example, when the accretion stream is confined to the magnetic poles.

1.3.2 Intermediately-long X-ray bursts

Although it had long been realised that H would burn unstably for low mass-accretion rates, is was not immediately clear what would happen upon H ignition. The discovery of a group of X-ray bursters that were accreting at low luminosities (Cornelisse et al. 2002), motivated recent theoretical work on this subject (Peng et al. 2007; Cooper & Narayan 2007). These studies have shown that for the lowest mass-accretion rates, the rise in temperature following a H flash is high enough to trigger He ignition giving rise to a mixed H/He burst. However, there exists a narrow range, spanning only a factor of a few in mass-accretion rate, in which the H flashes are not energetic enough to immediately trigger a He burst (Peng et al. 2007). As a result, a large layer of He develops, which upon ignition gives rise to an unusually energetic and long (tens of minutes in duration) He burst (Cooper & Narayan 2007). Despite the fact that the recurrence times of these events are thought to be long (on the order of a year) rendering them rare events, a few *intermediately-long* X-ray bursts have been observed that likely originate from the described mechanism (Chenevez et al. 2007; Falanga et al. 2009; Linares et al. 2009b; Degenaar et al. 2010a).

Type-I X-ray bursts of similar duration and comparable energy output have been observed from UCXBs, in which the mass-donating star is believed to be H-depleted, so that the neutron star accretes nearly pure He (e.g., in't Zand et al. 2005a, 2008; Falanga et al. 2008; Kuulkers et al. 2010). In the absence of H, the temperature in the accreted envelope will be low and consequently a large layer of He can accumulate before ignition is established. Regardless of the composition of the accreted material, the intermediately-long He bursts bring about some exciting opportunities to study the neutron star properties. Whereas for regular type-I X-ray bursts the temperature at the base of the ignition layer is largely set by the burning of He (and H) itself, for very low mass-accretion rates the thermal structure of the accreted envelope becomes sensitive to the heat flux emerging from the neutron star crust (Cumming et al. 2006; Peng et al. 2007). That, in turn, depends on the interior properties of the neutron star, such as the amount of heat released due to compression of the crust by the accretion of matter, as well as the rate of core neutrino cooling (see Section 1.2). The observational progress on intermediately-long type-I X-ray bursts has opened up a new window to study the behaviour of matter under extreme density and pressure conditions, complementary to studies of isolated neutron stars and accreting neutron stars in quiescence.

1.4 X-ray facilities

The work presented in this thesis focuses on the properties of (candidate) X-ray binaries at low luminosities, often located in crowded regions of sky. Out of all X-ray instruments that are currently in orbit, only those onboard *Chandra*, *XMM-Newton* and *Swift* provide the required sensitivity and spatial resolution to perform such studies. Each of these three observatories has its own strengths and weaknesses, and the instrument of choice depends on the science case. Amongst the three, *XMM-Newton* has by far the largest collective area and provides the best quality spectra for active X-ray sources. On the other hand, *Chandra* would be the primary tool for obtaining accurate positional information, given its unprecedented sub-arcsec resolution. Furthermore, it is the favoured instrument for studying transient systems in their quiescent state, owing to its low X-ray background. Finally, the niche of *Swift* is its flexibility; it is the only instrument with rapid ToO response that can accommodate a large number of short, pointed observations, making it an ideal tool for monitoring observations. Regardless of the choice of instrument, this thesis focusses on spectral analysis (i.e., decomposing the detected emission into different energy bands) to study the long-term variability of X-ray sources. The following sections briefly review the instruments that were used in this work.

1.4.1 Swift

The *Swift* satellite is a multi-wavelength observatory launched in 2004, that is dedicated to the study of gamma-ray bursts (GRBs). However, its flexibility and X-ray sensitivity also render it a very valuable tool to study X-ray binaries. For example, the onboard Burst Alert Telescope (BAT; Barthelmy et al. 2005) can serendipitously detect X-ray bursts (e.g., in't Zand et al. 2008; Linares et al. 2009b; Wijnands et al. 2009). The BAT is sensitive in the 15–150 keV energy range and detects randomly occurring energetic events in its wide field of view (2 steradians). The spacecraft automatically slews towards the location of the BAT trigger within tens of seconds so that follow-up observations with the narrow-field X-ray Telescope (XRT; Burrows et al. 2005) and UltraViolet/Optical Telescope (UVOT; Roming et al. 2005) can be performed.

The XRT has an effective area of $\sim$ 110 cm^2 at 1.5 keV and is sensitive in the 0.2–10 keV energy range. When operated in the photon counting (PC) mode, a two dimensional image is obtained of $\sim 23 \times 23$ arcmin providing an angular resolution of $\sim 3-5$ arcsec, which can be used to obtain position and spectral information for all the sources within the field of view. In the windowed timing (WT) mode, the CCD columns are collapsed and only the central 200 (out of 600) pixels are read out. This results in a one dimensional image with a frame time of 1.7 ms. To prevent heavy pile-up, count rates above ~ 1.0 counts s^{-1} cause an automated shift of the PC to the WT mode.

The UVOT has a field of view of 17×17 arcmin, slightly smaller than the XRT, and can localise sources with an angular resolution of $\sim 1 - 2$ arcsec. It can be operated using the following filters: V (5000-6000 Å), B (3800-5000 Å), U (3000-4000 Å), $UVW1$ (2200-4000 Å), $UVM2$ (2000-2800 Å), $UVW2$ (1800-2600 Å) and the broadband white filter ($\sim 1500 - 8500$ Å). Although the sources studied in this thesis are typically highly absorbed, depriving us of a view of their UV/optical counterpart, Chapter 4 discusses observations of an unusual type-I X-ray burst that was captured simultaneously by the XRT and UVOT instruments. This allowed for an unambiguous identification of the optical counterpart and a refinement of the source location that was invaluable for further follow-up observations.

1.4.2 Chandra

The *Chandra* observatory became operative in 1999 and is equipped with the High Resolution Camera (HRC; Kenter et al. 2000) and Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). The HRC provides the largest field of view ($\sim 30 \times 30$ arcmin) and highest spatial resolution of the *Chandra* instruments. It has an effective area of 225 cm^2 at 1 keV and is designed for imaging observations, whereas its energy resolution is poor. The ACIS detector is sensitive in the 0.1–10 keV passband and has an effective area of ~ 340 cm^2 at 1 keV. It covers a field of view of $\sim 16 \times 16$ arcmin and is designed for spectral studies.

1.4.3 XMM-Newton

Launched in 1999, *XMM-Newton* carries onboard the European Photon Imaging Camera (EPIC), which consists of one PN (Strüder et al. 2001) and two MOS (Turner et al. 2001) detectors that are sensitive in the 0.1–15 keV range and have spectral imaging capabilities. The relatively wide field of view ($\sim 30 \times 30$ arcmin) and large collective area (~ 1100 cm^2 at 1 keV) of the EPIC instruments make *XMM-Newton* an excellent facility for surveying sky regions down to relatively faint flux levels.

1.5 Summary: a guide to this thesis

The chapters of this thesis cover the different topics broadly outlined in Sections 1.1-1.3, using the X-ray facilities introduced in Section 1.4. The common denominator of these studies is that they focus on the properties of (candidate) X-ray binaries at low X-ray luminosities.

The first part of this thesis contains two chapters that concern the quiescent phase of neutron star transients. It describes an extensive monitoring campaign using *Chandra*, *XMM-Newton* and *Swift* to follow the transition from outburst to quiescence of the quasi-persistent neutron star X-ray binary EXO 0748–676, with the aim to study the thermal evolution of the neutron star after the cessation of its 24-year long outburst. Chapter 2 presents the first observational results obtained within 5 months after the transition towards quiescence commenced. A combined set of multiple *Chandra* and *Swift* observations showed no significant thermal evolution and several explanatory scenarios were invoked. Chapter 3 reports on continued X-ray observations of this source, using *Chandra*, *Swift* and *XMM-Newton*, now covering the first 1.6 years of the quiescent phase. The extended monitoring reveals clear evidence for a cooling neutron star crust, albeit that the shape of the decay curve is markedly different from three other quasi-persistent X-ray binaries that were monitored during their decay into quiescence. This puts constraints on the temperature of the neutron star in EXO 0748–676, which appears to be relatively hot, and on the duty cycle of the system. The latter is required to be high in order to be able to maintain the core at the high temperature inferred from observations.

Chapter 4 forms a transition in this thesis, bringing together the physics of neutron stars and actively accreting binaries. It presents the detection of an intermediately long type-I X-ray burst and multi-wavelength follow-up campaign of the previously unclassified X-ray source 1RXH J173523.7–354013. The detection of a strong $\sim$ 2-hr long type-I X-ray burst identified the system as a neutron star LMXB and the optical/infrared follow-up observations revealed that it harbours an H-rich donor. This makes it the first unambiguous example of an intermediately-long burst that is likely triggered by weak H-flashes. An interesting challenge posed by this conclusion is how the system can be large enough to harbour a H-rich donor and at the same time remain persistent at the observed low mass-accretion rate ($\sim 0.1\%$ of Eddington), apparently avoiding the thermal-viscous instability that would be expected to render the system transient.

The last part of this thesis consists of three chapters that deal with X-ray monitoring observations of a region of $\sim 0.5 - 1$ square degree around Sgr A*, aiming to study the spectral and long-term variability of transient X-ray sources located in this area. Chapters 5 and 6 discuss the results of a nearly-daily monitoring campaign of the central $\sim 26 \times 26$ arcmin of our Galaxy, carried out with *Swift*/XRT between 2006–2009. During these 4 years, a total of 8 different transients were observed in an active state, two of which were newly discovered X-ray sources. The long-term lightcurves obtained for the transients show that several systems undergo low-level accretion activity that is intermediate between quiescence and their typical outburst luminosities. Finally, Chapter 7 summarises the results from monitoring observations carried out with *Chandra* and *XMM-Newton* between 2005 and 2008, covering an area of 1.2 square degree around Sgr A^*. A total of 10 different X-ray sources were found active during this campaign. One of the serendipitous results of this study was the detection of a type-I X-ray burst pair from the known neutron star transient SAX J1747.0–2853. The time elapsed between the two bursts was merely 3.8 min, which is unusually short. Such events are rarely seen and pose an interesting challenge for theoretical burst models. The time interval between the bursts is too short to explain the second burst as being due to the ignition of a freshly accreted layer of material, and suggests that part of the initial fuel must be preserved after the first burst ignites.