Exploring the outflows and evolution of accreting neutron stars

A multi-wavelength approach

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Chapter 1

Introduction

Neutron stars represent some of the most peculiar and intriguing objects in the Universe. These end products of the evolution of some massive stars ($M \gtrsim 8 M_{\odot}$) compress around $1-2.5$ times the mass of our Sun into a spherical object with a diameter comparable to a large city. Their incredible density achieves extreme states of matter in their interior, and they are also known to harbour incredibly strong magnetic fields. Observing and studying neutron stars thus allows one to study fundamental physics in extreme conditions beyond the scope of any laboratory on Earth. Moreover, when located in a binary, neutron stars can give rise to some of the most energetic and explosive phenomena seen in the Universe.

The massive star progenitors of neutron stars are predominantly born in binary or multiple star systems (see e.g. Duquennoy & Mayor 1991; Sana et al. 2012; Duchêne & Kraus 2013; El-Badry et al. 2018; Moe & Di Stefano 2017). This has implications about how they further evolve over their lifetime, as depending on their orbital separations, masses and eccentricity, the stars can interact with each other by exchanging mass for example (e.g. Frank et al. 2002; González Martínez-País et al. 2014). If one of the massive stars in an interacting binary has evolved into a neutron star, their enormous gravitational potential well causes such mass transfer to result in the liberation of large amounts of gravitational energy. This is mostly radiated away in the form of X-rays. This is where the source class name of 'X-ray binary' originates from, as they were initially discovered by X-ray telescopes due to their bright X-ray emission (e.g. Giacconi et al. 1962, 1971). Despite their namesake, X-ray binaries radiate throughout the electromagnetic spectrum, as is illustrated in Figure 1.1.

The study of X-ray binaries is highly relevant for a wide variety of scientific reasons, and hence touches on many areas of astrophysics. For instance, they are excellent laboratories for understanding accretion, which is a fundamental physical process that shapes astrophysical objects on all scales in the Universe, from young stellar objects and the formation of planets, to galaxies and the cosmic web. Similarly, X-ray binaries can provide very valuable insight into outflows of matter and energy (jets and disc winds) that are universally seen in accreting systems. They allow not only to study the physical mechanisms through which such outflows are produced, but also what their impact is on the system itself and their cosmic environment

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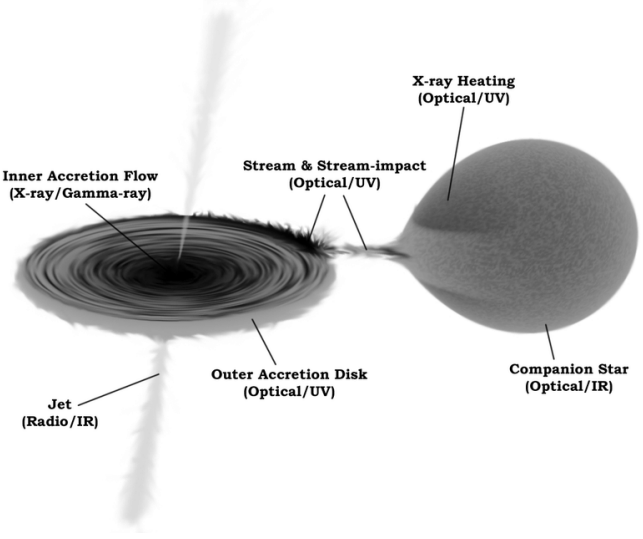

Figure 1.1: An artist impression of an low-mass X-ray binary (from Hynes 2010). It displays the anatomy, indicating the different components and the typical wavebands where these are detected in. This thesis is mostly concerned with the study of the X-ray, UV, optical and radio emission from these systems.

(e.g. Justham & Schawinski 2012; Gallegos-Garcia et al. 2024). Furthermore, low-mass X-ray binaries are pivotal to study key aspects of stellar- and binary evolution, such as common-envelope phases (e.g. Van & Ivanova 2019), and supernova kicks (e.g. Ivanova et al. 2010).

This thesis is devoted to multi-wavelength observational studies of neutron stars in low-mass X-ray binaries, in particular to characterize their outflows and to understand certain aspects of their evolution. This first chapter introduces the most relevant concepts to set the stage for the subsequent science chapters.

1.1 Accreting neutron stars in low-mass X-ray binaries

Low-mass X-ray binaries consist of a neutron star, or a black hole, accreting material from a companion star that is less massive than the accretor. For a neutron star primary, this typically concerns companion stars with a mass of $\lesssim 1 M_{\odot}$. At present, approximately 150 neutron star low-mass X-ray binaries have been identified in our Galaxy (Avakyan et al. 2023).

This thesis focusses on neutron stars, which are fundamentally different objects from black holes for having a solid surface and anchored magnetic field opposed to an event horizon. However, their formation processes and evolution are very similar. Moreover, the accretion and outflow phenomenology of neutron star and black hole low-mass X-ray binaries show many resemblances. Therefore, I occasionally discuss these black hole systems, when relevant, of which 72 (candidates) are currently known in our Galaxy (e.g. Corral-Santana et al. 2016).

1.1.1 Forming a neutron star in a binary

Core collapse supernovae

During the formation of massive stars (with masses greater than 8 solar masses, or $\gtrsim 8 M_\odot$), gravitational pressure increases the core temperature to the point where nuclear fusion begins. This starts with hydrogen fusing into helium. The energy produced by fusion counteracts the gravitational pressure, creating a stable equilibrium that lasts for millions of years. In this stage, the star is called a main-sequence star, referring to its location on the Hertzsprung-Russell diagram.

Once most hydrogen is depleted and hence the outward pressure generated by nuclear fusion drops, the core will contract due to the inward gravitational pressure. This causes the temperature and density to increase, eventually creating the conditions for helium to fuse into carbon, restoring the pressure balance. This cycle continues throughout the lifetime of a massive star, wherein it progressively fuses heavier elements until reaching iron. Since the fusion of iron does not release energy, the delicate pressure balance between fusion and gravity finally seizes, causing the core of the star to collapse under its own gravity.

The extreme density and pressure resulting from the collapse cause electrons and protons to combine into neutrons, creating a dense core composed primarily of neutrons. The collapse may be halted by neutron degeneracy pressure withstanding the gravitational pressure, thereby forming a neutron star. However, if the mass of the core is such that the gravitational pressure exceeds that of neutron degeneracy, further collapse into a black hole may occur. During the collapse, an enormous amount of energy is released, part of which is transferred to the outer layers of the star that then get violently ejected. This entire process is called a core-collapse supernova.

Accretion-induced collapse supernovae

In addition to core-collapse supernovae, neutron stars in binaries can also be formed through accretion-induced collapse of a white dwarf (e.g. Nomoto et al. 1979; Taam & van den Heuvel 1986). These are the remnants of stars with masses $\lesssim 8 M_\odot$ that are stable due to electron degeneracy pressure counteracting the inward pull of gravity. The limiting mass for which this equilibrium can be sustained is called the Chandrasekhar mass limit ($\sim 1.4 M_\odot$; Chandrasekhar 1931).

Like neutron stars and black holes, white dwarfs can also reside in binaries and accrete matter from their companion star. If its mass subsequently increases above the Chandrasekhar mass limit, the white dwarf will collapse. This creates a so-called electron-capture supernova (e.g. Nomoto 1984), which may lead to the formation of a neutron star (e.g. Dessart et al. 2006; Kitaura et al. 2006; Tauris et al. 2013), or complete destruction of the white dwarf leaving no compact remnant at all (e.g. Nomoto 1984). The expected rate of accretion-induced collapse supernovae is predicted to be relatively low (potentially with an upper limit of around 10^{-7}–10^{-5} yr^{-1} Fryer et al. 1999), and no direct evidence of such events has been detected so far.

Velocity kicks from the formation process

Asymmetries in core-collapse supernovae, e.g., in the mass ejection (Blondin et al. 2003; Buras et al. 2003; Fryer 2004) or neutrino emission (e.g. Fryer & Kusenko 2006, and references therein), can impart a high-velocity motion to the neutron star during its formation, also called a kick. The very high space velocities of some neutron stars ($v > 1000$ km s^{-1}; e.g. Chatterjee et al. 2005) suggest that such kicks can be very strong. Nevertheless, in case of an accretion-induced collapse, the expected kicks are thought to be weak (inducing a velocity of $v < 50$ km s^{-1}; e.g. Tauris et al. 2013), due to the smaller mass (Hillebrandt et al. 1984; Mayle & Wilson 1988; Woosley & Baron 1992; Fryer et al. 1999), and lower energy involved (e.g. Dessart et al. 2006; Kitaura et al. 2006) compared to core-collapse supernovae.

1.1.2 It takes two: accreting neutron stars and their donors

The neutron stars

Neutron stars in low-mass X-ray binaries have inferred magnetic field strengths of $B \approx 10^{7-12}$ G and measured spin frequencies of 0.13–599 Hz, or 7.7–0.0017 s (e.g. Patruno & Watts 2021; Di Salvo & Sanna 2022) for Roche-lobe filling low-mass X-ray binaries. The latter can be measured when there are hotspots on the surface of the neutron star. A prime example of this is when the magnetic field of the neutron star is sufficiently strong to channel accreted material along its magnetic field lines, causing the magnetic poles to heat up. This results in coherent X-ray emission from the poles as these rotate in and out of the observers view, allowing to derive the rotation period from the detected pulses (detected for so-called X-ray pulsars; e.g. Bildsten et al. 1997; Wijnands & van der Klis 1998).

Accretion spins up neutron stars through the transfer of angular momentum (e.g. Alpar et al. 1982). Moreover, accretion is also proposed to weaken the magnetic field of the neutron star (e.g. Taam & van den Heuvel 1986; Bailes 1989). Therefore, inferences can be made about the formation and age of a neutron star, based on its spin and magnetic field strength.

The donors

The low-mass donors can be brown dwarfs, main-sequence stars (i.e., hydrogen core burning) or evolved stars such as giants, white dwarfs, and stripped stars (see e.g. Bahramian & Degenaar 2022, for a recent overview). The latter are stellar remnants where much or all of the hydrogen-rich envelope has been lost, and which typically have helium burning cores.

The orbital periods measured for low-mass X-ray binaries range from approximately 10 min to several weeks (see e.g. Bahramian & Degenaar 2022, for an overview). Those low-mass the binaries that have an orbital period of less than 90 minutes (i.e., $P_{\rm orb} \leq 90$ min) form of sub-class that is referred to as ultra-compact X-ray binaries. Due to their tight orbits, only small evolved stars, stripped stars, white dwarfs, or brown dwarfs can sustain stable mass transfer in these low-mass X-ray binaries.

1.1.3 Mass transfer mechanism

For the large majority of low-mass X-ray binaries[1], mass transfer occurs because the donor star is overflowing its Roche-lobe (e.g. Paczyński 1971). Due to conservation of angular momentum, matter moving from the companion to the accretor forms an optically thick, geometrically thin accretion disc (e.g. Shakura & Sunyaev 1973) fed by the material flowing from the donor through the inner Lagrange point. Within the disc, material spirals inward as viscous processes transport angular momentum outwards and dissipate the gravitational potential energy through the disc. Half of this is released as radiation from the disc, and the other half is converted into kinetic energy and stored within the accretion flow. This will eventually be released as (X-ray) radiation when the accretion flow reaches the neutron star surface.[2]

1.1.4 Observational signatures

As shown in Figure 1.1, neutron star low-mass X-ray binaries radiate across the electromagnetic spectrum. Here, I discuss the emission components and processes that are most relevant for my thesis work.

Emission from the accretion flow

In low-mass X-ray binaries, the continuum emission at X-ray, UV, optical and infrared is dominated by the accretion flow. Broadly speaking, there are two main components that contribute to the broad-band radiation. Firstly, there is a thermal emission component produced by the accretion disc. This component can be described with local black body emission components produced at each annulus in the disc with its local temperature. Each annulus contributes and the final spectrum is a summation. This spectral energy distribution is also called a 'disc black body'. For low-mass X-ray binaries, this means that the disc produces produces emission ranging from the X-rays (in the inner regions) to infrared emission (in the outer parts; e.g. Hynes et al. 2000).

Secondly, Comptonised emission is produced by a plasma of hot electrons, referred to as the corona.[3] Low-energy photons originating from the disc or the neutron star surface (see below) are up-scattered through inverse-Compton collisions by these hot electrons. The up-scattered photons then produce a non-thermal emission component. This Comptonised emission can be detected from energies of a few keV up to a cut-off energy that can reach around a few hundred keV (e.g. García et al. 2015). Therefore, this component dominates in the X-ray band. It is often phenomenologically modeled as a simple (cut-off) powerlaw. The Comptonized emission may, in turn, be re-processed in the accretion disc resulting an additional emission component, also in the X-ray band, called the reflection spectrum (e.g.

[1] With the exception of a small subgroup, where mass transfer through the wind of an evolved companion star is important, the so-called symbiotic X-ray binaries [see Bahramian & Degenaar an references therein].
[2] In the case of a black hole accretor, the energy stored in the accretion flow can be carried beyond the event horizon.
[3] The exact geometry of this hot electron plasma is a matter of debate (see e.g. Degenaar et al. 2018, for a recent overview).

Fabian et al. 1989). Its most prominent feature, which is also most relevant to this thesis, is a broad iron Kα emission line at 6.4 keV (see Figure 1.2).

Taking stock, the broad-band X-ray spectrum of a low-mass X-ray binary thus consist of a thermal disc black body component, a Comptonised (cut-off) powerlaw component, and a reflection component manifested as a broad emission line that all result from the accretion flow. As described below, an additional component coming from the surface of the neutron star is often detected. An example of a typical X-ray spectrum of a neutron star low-mass X-ray binary containing all these components is shown in Figure 1.2. For the UV, optical, and near-infrared bands, the spectrum is typically dominated by the continuum emission from the accretion disc.

Superimposed on the continuum, emission and absorption lines are often seen. Emission lines are frequently observed in the UV, optical and infrared spectra of low-mass X-ray binaries: these are produced in the disc and can have a characteristic, double-peaked shape, as shown in Figure 1.3. This line shape is a result of the projection of Keplerian velocities of the disc onto the line-of-sight of the observer. Apart from emission lines, absorption features can also be seen in low-mass X-ray binaries. These can occur due to absorption of the continuum emission by cooler, less ionised material in the line-of-sight to the observer. This absorbing material could be the atmosphere of the accretion disc or the impact point where the accretion stream hits the disc (e.g. Wade & Hubeny 1998; Díaz Trigo & Boirin 2016).

Emission from the neutron star

In a low-mass X-ray binary, we also often detect emission from the neutron star. Its entire surface produces thermal emission and thermal emission can also be generated where the accretion flow runs into the surface. When the neutron star is channelling the material along its magnetic poles (i.e., in the case of an X-ray pulsar), this results in thermally-emitting hotspots or accretion columns (e.g. Patruno & Watts 2021). Alternatively, as the material from the disc decelerates due to friction, it spreads out and forms a 'boundary' or 'spreading' layer on the neutron star surface (e.g. Sibgatullin & Sunyaev 1998; Babkovskaia et al. 2008). All these emission components related to the surface of the neutron star can be typically be identified in X-ray spectra at energies below 10 keV (see Figure 1.2). In this introductory chapter, I will jointly refer to these spectral components as the 'neutron star surface'.

Emission from the companion

In actively accreting neutron star low-mass X-ray binaries, the companion star is typically outshone by the accretion disc. However, the companion can sometimes still be detected in the optical band. For example, due to the tidal lock of the companion in the system, the same side of the donor is always exposed to the X-ray irradiation from the accretion disc and the neutron star. This irradiated face of the companion can produce strong, narrow emission lines which are detectable in optical spectra, such as He II 4686Å, as well as the 'Bowen blend' lines (Bowen 1935), which consist of N III and C III emission lines. These lines can be used to trace the motion of the companion star in the binary (e.g. Casares et al. 1993; Steeghs & Casares 2002; Casares et al. 2006), which can be used to derive the orbital parameters of the binary.

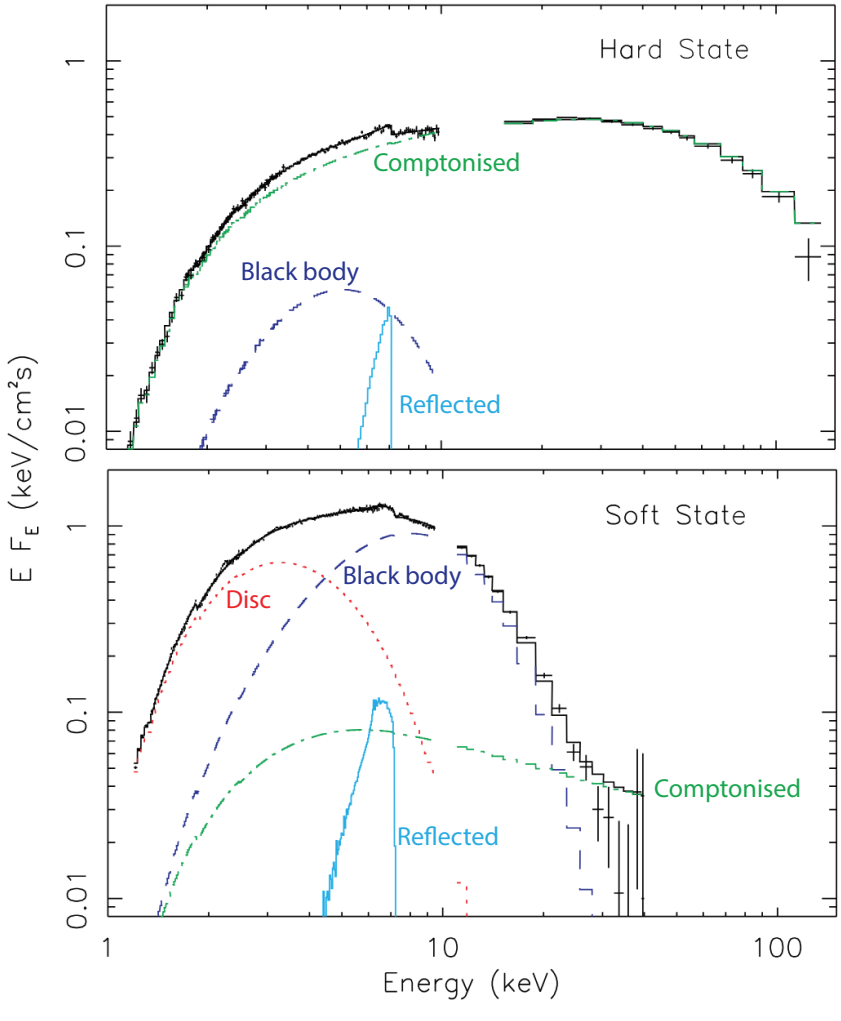

Figure 1.2: Examples of X-ray spectra from different X-ray spectral states (see Section 1.1.5) for the neutron star low-mass X-ray binary 4U 1705-44, adapted from Lin et al. (2010). The total model fit is shown as a black solid line. Several model components are shown, namely the thermal emission from the disc (red dotted line), a power-law component probing the Comptonised emission from the corona (green dot-dashed line), the reflected iron Kα line (cyan triple-dot-dashed line), and an additional black body component (blue dashed line) from the neutron star itself.

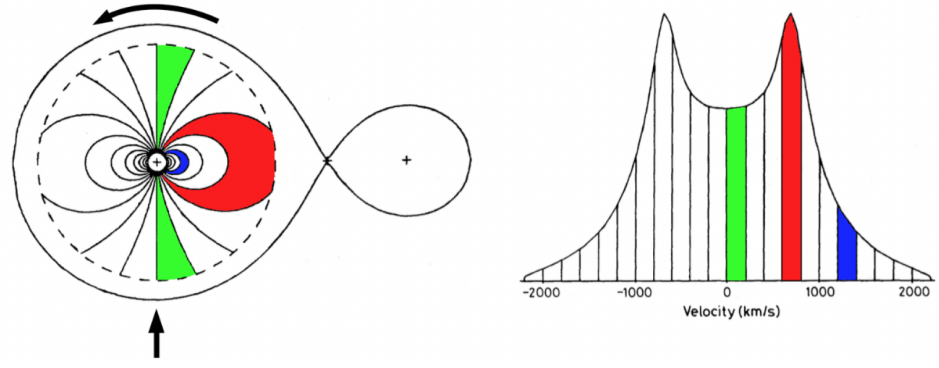

Figure 1.3: A schematic impression of a Keplerian accretion disc in a binary, and the double peaked emission line it would produce if the system was observed along the plane of the disc, also called an edge-on view (right drawing). The different coloured regions indicate the regions of the disc that produce the corresponding velocity bins in the line profile. Obtained from Castro Segura (2022), which is adapted from Horne & Marsh (1986).

Disc winds and jets

Low-mass X-ray binaries often also generate radio emission coming from outflowing jets. The phenomenology and physics of jets is discussed in Section 1.1.6, but I here briefly describe their emission mechanism. Jets generate radiation through non-thermal synchrotron emission, due to relativistic electrons spiralling upward in the collimated jet. Their emission dominates in the radio, millimeter and potentially in the infrared bands (e.g. Fender 2001; Corbel & Fender 2002). Their spectral shape is typically described using the spectral index α, defined as $\alpha = \Delta\log(S_\nu)/\Delta\log(\nu)$, where S_ν is the spectral flux density and ν the frequency.

The X-ray to infrared spectra of low-mass X-ray binaries may contain absorption lines that indicate the presence of outflowing material. Such lines arise when the (disc) continuum emission is absorbed by a disc wind. In the X-ray band, this concerns lines that are blue-shifted with respect to their rest wavelength (e.g. Neilsen & Degenaar 2023). At the longer wavelengths, disc winds are detected through blue-shifted absorption lines, but also through other spectral line features, such as P-Cygni profiles (e.g. Bandyopadhyay et al. 1999; Muñoz-Darias et al. 2016). I show an schematic example of a P-Cygni feature formed from an expanding shell of material driven by a star in Figure 1.4, which is comparable to the production of P-Cygni profiles in low-mass X-ray binaries.

In the UV, optical and infrared bands, disc winds may also produce other line profiles. For instance, asymmetric emission lines may occur if the absorption or scattering of photons in the outflow only suppresses the blue wing of an emission line (produced in the disc for example), instead of absorbing the blue wing fully and forming a classic P-Cygni profile (see also e.g. Koljonen et al. 2023, and references therein). Furthermore, flat-topped lines (e.g. Sánchez-Sierras & Muñoz-Darias 2020), broadened lines (e.g. Muñoz-Darias et al. 2016), and lines with extended emission wings (e.g. Mata Sánchez et al. 2018; Muñoz-Darias et al. 2019; Panizo-Espinar et al. 2022), have also been attributed to accretion disc wind outflows. Here, the broadened features are formed by emission components produced by the expanding

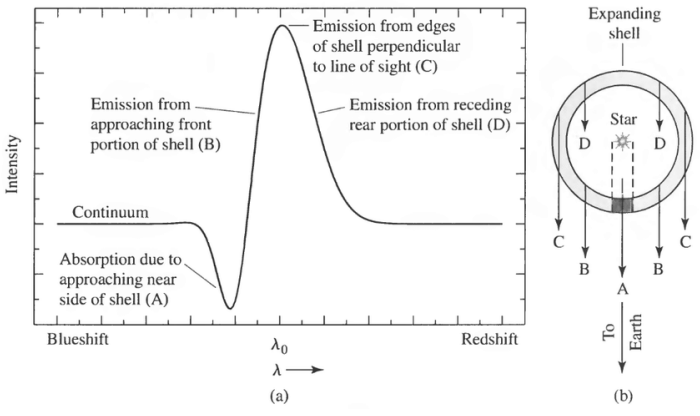

Figure 1.4: A schematic, simplified overview of the production of a P-Cygni profile from a stellar object. In panel (a), the line profile is shown, where λ_0 indicates the rest wavelength of the line. In panel (b), a schematic picture of a shell of material expanding symmetrically from a star. The star, in this case, produces the continuum emission. The letters correspond roughly indicate the region where the components of the P-Cygni line profile are produced. Obtained from Carroll & Ostlie (2017).

material in the accretion disc wind. What observational signatures we see of disc winds is in part determined by our viewing angle.

Inclination matters

If low-mass X-ray binaries are viewed at high inclination (see Figure 1.5), this will give rise to features in their observed light curves and spectra. For instance, for viewing angles of $i \gtrsim 75°$, eclipses can be observed in the light curve when the companion moves in front of the disc and the accretor, depending on the size of the donor and the disc. Moreover, in high inclination binaries ($i \approx 60-80°$; Frank et al. 1987), dips are observed in the light curve. These can be produced by structures in the disc, such as the 'hot spot' impact region, where the impact of the stream on the disc rim is rim is thought to cause a thickening or 'bulge' structure (e.g. White & Mason 1985). This bulge is typically observed around phase $\phi = 0.6-0.8$ of the binary orbit, just before the phase when the companion eclipses the accretor at phase $\phi = 1/\phi = 0$ (e.g. Frank et al. 1987), as illustrated in Figure 1.6.

For the highest inclination systems ($i > 80°$; Frank et al. 1987), all the X-ray emission produced in the inner disc and on the neutron star will be obscured by the outer disc and the companion. These are called 'accretion disc corona sources' (or ADC sources)[1], where the 'accretion disc corona' is thought to scatter only a few percent of the emission arising from the inner parts into the line-of-sight of the observer (e.g. White & Holt 1982). This implies that these low-mass X-ray binaries are observed with a far lower X-ray luminosity than would be expected based on their true accretion rate.

[1] This naming is confusing, as the 'accretion disc corona' is different than the hot electron cloud mentioned at the start of this section, which is also called the corona.

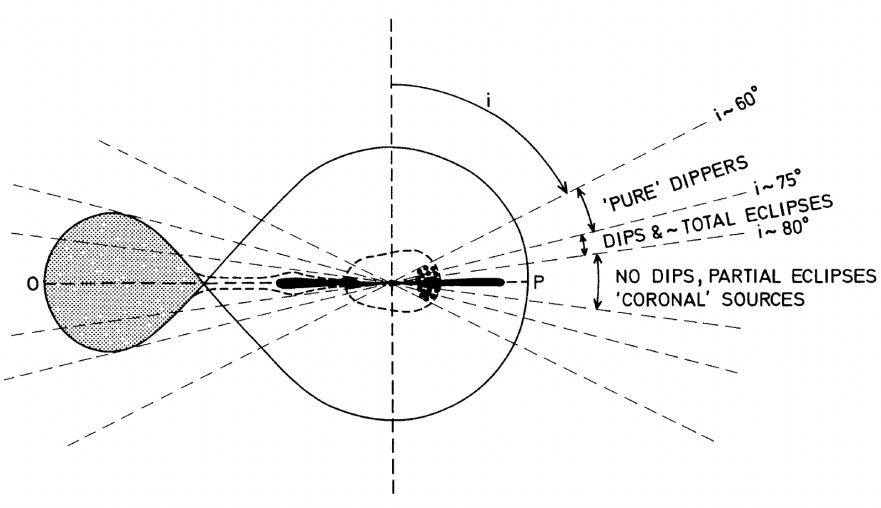

Figure 1.5: A schematic overview of an X-ray binary, obtained from Frank et al. (1987). Here, the inclination ranges are indicated where specific modulations in the light curves can be observed.

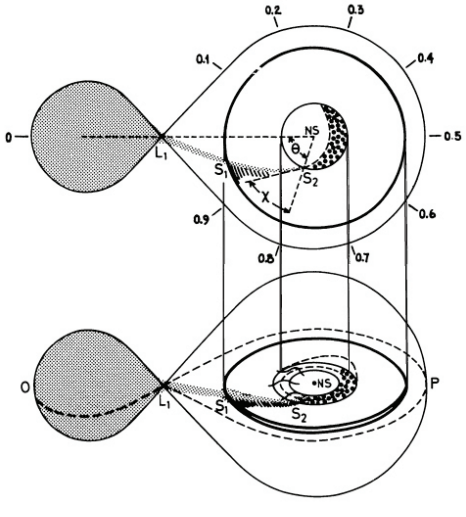

Figure 1.6: A schematic overview of a modelled X-ray binary, adapted from Frank et al. (1987). Here, the top figure shows the orbital phases of the line-of-sight-positions, with a view along the binary rotation axis, also called a face-on view. The lower figure shows a perspective view (i.e. slightly higher than a view along plane of the disc). The stream from the companion star impacts the edge of the accretion disc at 'S_1', and the ring at r_H, where the stream settles.

The detection of disc winds is also strongly dependent on the viewing inclination of low-mass X-ray binaries. Accretion disc winds are proposed to be quasi-spherical (e.g. Higginbottom et al. 2019), but the highest densities of the wind are likely near the disc plane. This is due to the matter in the wind becoming less dense as it accelerates and expands away from the disc. This results in absorption features being preferentially produced along the disc plane, and subsequently, that most disc winds have so far been confidently detected in intermediate to high inclination systems (e.g. Díaz Trigo & Boirin 2016; Neilsen & Degenaar 2023). Moreover, our viewing angle may have a strong impact on what features we see from a disc wind. In ADC sources, for instance, we may detect emission lines in the X-ray band that are produced by hot, optically-thin material from the accretion disc wind above the disc (e.g. Tomaru et al. 2023b). Moreover, the broad Fe Kα line often seen in X-ray spectra of low-mass X-ray binaries can potentially be more shallow and red-skewed as a result of scattering in a wind (e.g. Laurent & Titarchuk 2007; Titarchuk et al. 2009).

1.1.5 Accretion behaviour in X-ray binaries

A few dozen neutron star low-mass X-ray binaries accrete continuously or persistently. However, many neutron star low-mass X-ray binaries, and all black hole systems, accrete transiently (e.g. van Haaften et al. 2015; Avakyan et al. 2023). This means that they undergo periods of quiescence and active accretion. In Figure 1.7, I show an example of the X-ray lightcurve of a transient X-ray binary, where clear accretion outbursts can be seen. The most widely accepted model (called the 'disc instability model' or DIM) for causing such transient outbursts is extensively described in Lasota (2001) and Hameury (2020).

When actively accreting, low-mass X-ray binaries can exhibit different so-called 'X-ray spectral states' that are thought to reflect different accretion geometries. These states are identified based on the correlated X-ray spectral and rapid variability properties. In this thesis, I focus on the spectral properties of low-mass X-ray binaries, and therefore I will not go into detail on the associated timing behaviour (see e.g. Done et al. 2007, for a review). Much of the spectral state phenomenology was initially developed for black holes, so we start with that, but there are analogies with the behaviour seen in neutron star systems.

For black hole low-mass X-ray binaries, two main states are identified, namely the 'hard state' and the 'soft state' (see e.g. Done et al. 2007; Homan et al. 2010). In the hard state, the X-ray spectra show a power-law spectrum that has a cut-off of a few tens to a few hundred keV (e.g. García et al. 2015), indicating that the Comptonised emission component is strong (see Section 1.1.4). At the same time, the disc emission is relatively weak in the hard state, possibly because it is truncated away from the accretor (e.g. Plant et al. 2015; van den Eijnden et al. 2020). Conversely, when in a soft state, thermal emission from the accretion disc dominates the broad-band spectrum, while the Comptonised emission component is comparetively weak (e.g. Fender et al. 2005a; Done et al. 2007).

This classification of hard and soft states is now used frequently in the studies of neutron star low-mass X-ray binary outbursts as well, due to the broad similarities with black hole systems. This can be seen in Figure 1.2, where I show an example of the spectral components and the

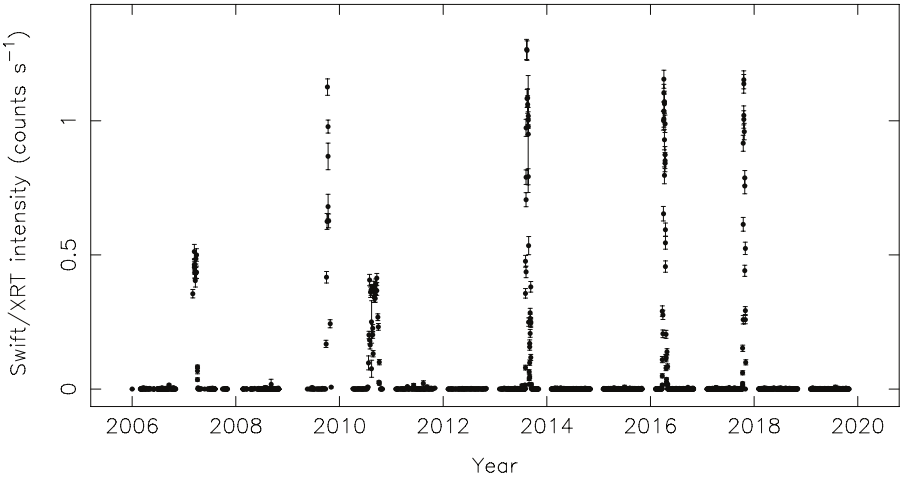

Figure 1.7: An example X-ray light curve of the transient low-mass X-ray binary GRS 1741-2853. A clear increase in the X-ray count rate can be seen when a low-mass X-ray binary goes into outburst, where the mass accretion rate increases dramatically. Figure courtesy of N. Degenaar (updated from Degenaar et al. 2015).

differences in the hard and soft state. Nevertheless, the spectral behaviour (in correlation with the rapid variability behaviour) in neutron star low-mass X-ray binaries is significantly more complex than just this broad classification in two states. As these subtleties are not relevant for my thesis work, I will not discuss them further, but I refer to Wijnands et al. (2017) for an in depth discussion on these points.

The observed X-ray luminosity of active low-mass X-ray binaries ranges all the way from the Eddington luminosity ($L_{\rm Edd}$), down to a few per cent of it. The X-ray luminosity is thought to trace the accretion rate and the Eddington limit is the maximum brightness that can be attained due to accretion. The radiation pressure arising from accretion counters the gravitational pressure of the material in the disc. Typically, the gravitational pressure far exceeds the radiation pressure. However, at certain mass accretion rates, the X-ray luminosity becomes so high that the radiation pressure is equal to the gravitational pressure, which should, in principle, halt accretion. The accretion rate where this is achieved, is when the X-ray luminosity reaches the Eddington luminosity, which is $L_{\rm Edd} = 1.3 \times 10^{38} (M/M_{\odot})$ erg s^{-1} for compact objects in low-mass X-ray binaries (e.g. Frank et al. 2002).

1.1.6 Outflows

Apart from accreting matter, neutron stars (and black holes) in low-mass X-ray binaries also generate powerful outflows, which are a central theme in my thesis. These outflows come in the form of jets (see Figure 1.1) and disc winds. Here I discuss their observational properties and underlying physics, as well as the impact of jets and disc winds on low-mass X-ray binaries and their environment.

Jets

Jets are highly collimated streams of gas and energy that can reach velocities close to the speed of light (i.e. relativistic speeds; e.g. Fender et al. 2004a; Zhang et al. 2025; Savard et al. 2025). Since black hole jets are generally more radio bright than those of neutron stars (Fender & Kuulkers 2001; Gallo et al. 2018), much of their phenomenology was initially carved out for black holes. Nevertheless, neutron star studies have steadily caught up over the past decade (van den Eijnden et al. 2021).

Two different types of jets have been observed for low-mass X-ray binaries, which can be distinguished based on their radio spectral shape. The first type of jet observed is the optically-thick, continuous (i.e., steady) outflow, often referred to as the 'compact' jet. These exhibit a flat-to-inverted spectrum, where $\alpha \geq 0$. The second type of jet are transient and made up of individual, discrete blobs of material being launched, also called 'discrete' or 'ballistic' jet ejecta (e.g. Corbel et al. 2000). From these discrete jets (also called transient jets), we detect an optically-thin spectrum with a steep $\alpha \approx -0.7$ radio spectrum (see e.g. Mirabel & Rodríguez 1999; Fender et al. 2004a, for reviews).

The observed jet properties appear to be closely linked to the accretion behaviour of low-mass X-ray binaries (e.g. Fender et al. 2004b). For instance, compact jets are solely seen during hard X-ray spectral states when their radio luminosity is strongly coupled with the X-ray luminosity (thus the accretion inflow; Gallo et al. 2003; Fender 2006). This radio/X-ray correlation can generally be described using a power-law relation, as $L_{\rm R} \propto L_{\rm X}^{\beta}$ (e.g. Gallo et al. 2003, 2018). I show an example of this radio/X-ray correlation for a sample of neutron star and black hole X-ray binaries in Figure 1.8. Whereas general trends in this correlation appear to be visible among samples of black holes and neutron stars, individual sources can have varying derived slopes and normalisations (e.g. Migliari & Fender 2006; Gallo et al. 2018). Other than evidencing a very strong correlation between the accretion inflow and jet outflow, it is not fully understood yet how the similarities and differences in this phenomenological correlation are related to the underlying jet physics.

It is well known that in black hole low-mass X-ray binaries, the radio emission from the compact jet is strongly suppressed upon a transition to a soft X-ray spectral state, which is also referred to as 'quenching' of the jet. Furthermore, during this transition, discrete jet ejecta have been detected from some black hole X-ray binaries (e.g. Mirabel & Rodríguez 1994; Corbel et al. 2002; Carotenuto et al. 2021a). The optically thin emission detected from these discrete jet ejecta could probe the re-brightening of shocks within the jet propagating away from the system, due to the collision of previously ejected, slower moving jet material with a more recently ejected, faster moving material (e.g. Fender et al. 2009). The suppression

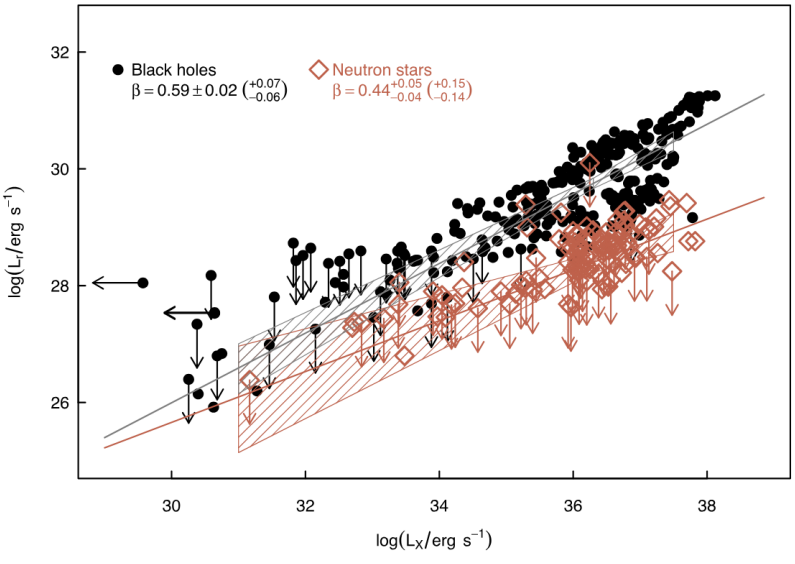

Figure 1.8: The radio/X-ray luminosity plane for a sample of black hole and neutron star X-ray binaries, as obtained from Gallo et al. (2018). The x-axis indicates the 1−10 keV X-ray luminosity, and the y-axis indicates the 5 GHz radio luminosity. The solid lines indicate fits to both the black hole (black line) and neutron star (red line) sample to constrain the correlation using the relation $L_{\rm R} \propto L_{\rm X}^{\beta}$. The hatched regions indicate the 3σ uncertainties.

or quenching of compact jets is not observed as consistently in neutron star low-mass X-ray binaries. Some neutron stars transitioning from hard to soft X-ray spectral states do show strongly reduced radio emission (see e.g. Migliari et al. 2011; Gusinskaia et al. 2017; Díaz Trigo et al. 2018). Nevertheless, there are other neutron star low-mass X-ray binaries with radio emission detected in their soft states (e.g. Migliari et al. 2003, 2004; Russell et al. 2021; Pattie et al. 2024). Whether neutron stars also eject transient jets upon a transition from hard to soft states, like black holes, is not yet established.

How the observed phenomenology of radio jets from low-mass X-ray binaries connects to the launch mechanism of jets is an open question and an active area of research. Two main jet launching mechanisms have been proposed by Blandford & Znajek (1977) and Blandford & Payne (1982). Both these models propose that rotating magnetic field lines can collimate and accelerate jets along the rotation axis in accreting systems. In Blandford & Payne (1982), these magnetic field lines are proposed to thread the inner accretion disc and are rotated by the differential rotation of the matter in the disc. This model is thus viable for both neutron star and black hole low-mass X-ray binaries. In Blandford & Znajek (1977), the magnetic field is thought to thread the ergosphere of the black hole (i.e. a region just outside the event horizon) and rotated by the black hole spin, thereby powering a jet. This model is therefore exclusively applicable for black hole low-mass X-ray binaries, as neutron stars do not have an ergosphere. On the other hand, in case of neutron stars their surface magnetic fields might partake in jet production, through coupling with the magnetic field threading the accretion

disc (e.g. Romanova et al. 2009; Parfrey et al. 2017; Das et al. 2022). Moreover, other works have proposed that the boundary layer for neutron stars could act as a dynamo, where the differential rotation and large scale heights of the boundary layer could generate magnetic fields that could contribute to launching a jet (e.g. Livio 1999; Maccarone 2008).

Winds

Accretion disc winds are dense, quasi-spherical flows that are thought to carry away substantial amounts of matter and angular momentum from the accretion flow (e.g. Neilsen & Lee 2009; Ponti et al. 2012; Neilsen 2013; Miller et al. 2015; Higginbottom et al. 2017; Gallegos-Garcia et al. 2024). The generation of disc winds had been predicted by accretion disc theory (e.g. Begelman et al. 1983), and the detection of blue-shifted absorption features from high velocity, expanding material moving toward the observer provided smoking-gun evidence of the presence of these winds. Such lines were initially detected using X-ray spectroscopy, where they probe hot, highly ionised gas flowing out from the disc (e.g. Ueda et al. 1998, 2004; Miller et al. 2006; Neilsen & Lee 2009; Ponti et al. 2012). Signatures of accretion disc winds have also been detected in UV (e.g. Boroson et al. 2001; Ioannou et al. 2003; Bayless et al. 2010; Castro Segura et al. 2022), optical (e.g. Rahoui et al. 2014; Muñoz-Darias et al. 2016; Cúneo et al. 2020; Mata Sánchez et al. 2022), and (near-)infrared spectra (e.g. Bandyopadhyay et al. 1999; Sánchez-Sierras & Muñoz-Darias 2020; Ambrifi et al. 2025), showing the presence of relatively cold, lower-ionization outflowing gas.

Disc outflow signatures have shown to be transient in low-mass X-ray binaries. This could be due observational effects, such as changes in ionisation (e.g. Muñoz-Darias et al. 2019), the density or clumping of the material (e.g. Mata Sánchez et al. 2018; Muñoz-Darias et al. 2019; Ambrifi et al. 2025), or other line-of-sight effects (e.g. Charles et al. 2019; Jiménez-Ibarra et al. 2019). It is not yet established if disc winds physically turn on and off, as is the case for the jets discussed above. Similar to these jets, accretion disc winds do show changes related the X-ray spectral states. For instance, blue-shifted absorption lines from accretion disc winds detected at X-ray wavelengths are typically only observed in the soft state (see e.g. Rogantini et al. 2025, and references therein). Conversely, disc winds signatures in the optical band have mainly been detected in the hard state (e.g. Muñoz-Darias et al. 2016, 2019), while near-infrared disc winds features have been detected in both soft and hard states (e.g. Sánchez-Sierras & Muñoz-Darias 2020). At present, the connection between the disc winds detected at different wavelength is poorly understood. For instance, it is currently unclear if these sample different, individual outflows, or if these trace different parts of the same outflowing wind. This is an important to establish for understanding the launch mechanism of disc winds (see below), as it is unclear within current models how these outflows can sustain a sufficiently low ionisation to produce optical and UV signatures, potentially requiring self-shielding by the wind to prevent over-ionisation (e.g. Castro Segura et al. 2022; Muñoz-Darias & Ponti 2022). Very recent multi-wavelength observing campaigns yielded wind detections simultaneously in multiple wavebands (e.g. Castro Segura et al. 2022), supporting the scenario of the outflow features tracing the same outflow (e.g. Muñoz-

Darias & Ponti 2022). This demonstrates the vital role of multi-wavelength observations in studying and understanding accretion disc winds.

Disc winds have been detected with velocities between a few hundred to a few thousand kilometres per second (e.g. Neilsen & Degenaar 2023). This is based on the observed Doppler shifts of the blue-shifted absorption line in X-rays for example, as well as the blue-edge of the absorption feature in a P-Cygni profile. Furthermore, for broadened lines, the projected velocities of the expanding material can be derived using the width of the lines. The observed line spectra also allow for an estimate of the mass-loss rate through disc winds (e.g. Castro Segura et al. 2022), some of which appear to indicate that this can be very high (some predictions range from $2-15 \times \dot{M}_{acc}$; e.g. Neilsen & Lee 2009; Ponti et al. 2012). Constraining the amount of mass (and angular) momentum lost through disc winds is an important endeavour as it may significantly alter the evolution of an X-ray binary.

As with the study of jets, understanding how the observed disc winds are launched is an important open question. A few mechanisms have been proposed, for instance thermal driving (e.g. Begelman & McKee 1983; Woods et al. 1996; Proga & Kallman 2002). Here, the upper layers of the accretion disc are heated by X-ray emission from the inner disc and corona, causing these layers to expand. At a critical radius the expanded upper layers can then be accelerated and lifted off the disc (e.g. Begelman & McKee 1983). This proposed critical radius is based on the Compton radius (R_{IC}), which is the radius where the thermal velocity exceeds the local escape velocity in the accretion disc. Typically, a thermal wind is expected to be launched at around $0.1R_{IC}$ (e.g. Higginbottom et al. 2017). However, this radius is found to be smaller if effects of radiation pressure are taken into account (e.g. Díaz Trigo & Boirin 2016). Indeed, recent simulations show that for low-mass X-ray binaries with an accretion luminosity of $L_X \gtrsim 0.2 L_{Edd}$, radiation driving enhances a thermal wind (e.g. Tomaru et al. 2019; Higginbottom et al. 2020). For accretion rates around the Eddington luminosity, radiation pressure of electron scattering may even drive a fully radiative disc wind (Icke 1980; Shlosman et al. 1985; Shlosman & Vitello 1993; Proga & Kallman 2002).

Finally, magnetic driving is proposed to launch winds, as magnetic field lines thread the accretion disc and are expected to accelerate gas via magneto-centrifugal forces (e.g. Blandford & Payne 1982; Emmering et al. 1992; Miller et al. 2006; Chakravorty et al. 2016; Fukumura et al. 2017). This mechanism is proposed to launch fast and massive winds (e.g. Miller et al. 2008), but is complicated to unambiguously identify in observational studies (e.g. Tomaru et al. 2023a). So far, observational evidence has mostly pointed to thermal driving being the main contributing mechanism in launching winds in low-mass X-ray binaries, mostly based on their inferred launch radius. Indeed, disc winds have typically been detected only in low-mass X-ray binaries with large accretion discs, far exceeding the required radius of $0.1R_{IC}$: accretion disc winds have primarily been detected in systems with large orbital periods exceeding $P_{orb} \geq 20$ hr (e.g. Panizo-Espinar et al. 2022; Neilsen & Degenaar 2023). Furthermore, simulations of thermally-driven accretion disc winds for black hole X-ray binaries show that these can be launched during both hard and soft states (e.g. Higginbottom et al. 2020). Ultimately, it is very likely that a combination of thermal, radiative and magnetic driving mechanisms allows disc wind launching in low-mass X-ray binaries.

The impact of outflows on the evolution and environment of low-mass X-ray binaries

The aforementioned outflows can have a great impact on the low-mass X-ray binary and its surroundings. In particular, consensus has been growing that mass transfer in X-ray binaries is highly non-conservative, as both jets and disc winds may carry away a substantial amount of mass and angular momentum. This can affect the accretion process, e.g. by triggering state changes and regulating the duration of an accretion outburst (e.g. Begelman et al. 1983; Shields et al. 1986; Muñoz-Darias et al. 2016; Tetarenko et al. 2018; Higginbottom et al. 2019). The angular momentum loss can also impact the orbital evolution of the binary (e.g. Degenaar et al. 2014a; Marino et al. 2019). Motivated by observational studies, recent theoretical work has shown that disc winds are vital to consider for binary population studies and occurrence rates of cataclysmic transient phenomena, as the presence of disc winds can greatly impact the predicted orbital separations of low-mass X-ray binaries (e.g. Gallegos-Garcia et al. 2024). Moreover, the outflows of X-ray binaries may significantly impact their local environment. Observationally, this is evident by the detection of cavities and bow shocks around black hole X-ray binaries with strong jets (e.g. Gallo et al. 2005; Motta et al. 2025). This interaction may stir up and heat the local interstellar medium to the extent that it might impact star formation and hence the evolution of galaxies, potentially even rivalling the feedback from supernova explosions (e.g. Fender et al. 2005a; Justham & Schawinski 2012).

1.2 Observatories used in this work

The research questions addressed in this thesis require a multi-wavelength approach and hence a multitude (no less than 12) of ground-based and space-based observatories were used. Here I describe the various observatories and instruments, divided over the approximate wavebands they cover, from X-ray to UV, optical, near-infrared, and radio. A visual representation of all telescopes used in this thesis is shown in Figure 1.9.

X-rays

A major X-ray satellite used in my thesis is the *X-ray Multi-Mirror Mission* (XMM-Newton; Jansen et al. 2001) telescope. This ESA satellite was launched on December 10, 1999. It contains European Photon Imaging Cameras (EPIC), Reflection Grating Spectrometers (RGS), and an optical/UV monitor (OM)[1]. The EPIC has a pn-CCD, and two Metal Oxide Semiconductor (MOS) CCD arrays. The EPIC-pn instrument covers a calibrated energy range of 0.15−10 keV with a spectral resolution of $E/\Delta E \approx 20-50$ (e.g. Strüder et al. 2001). Due to the large effective area of EPIC, and relatively high resolution over a broad wavelength range when compared to other X-ray instruments, it is particularly well suited for studying the X-ray spectrum of relatively faint low-mass X-ray binary sources. The RGS provides an even higher energy resolution ($E/\Delta E \approx 150-800$) over a smaller spectral range (between 5−35Å, or 0.33−2.5 keV, for the first spectral order; e.g. den Herder et al. 2001). In this thesis, the RGS was leveraged to study spectral lines in the soft X-ray regime, which can trace the composition of the accreted material, as well as disc winds in low-mass X-ray binaries.

[1] The OM telescope is not used in this thesis, and will therefore not be discussed further here.

In addition to *XMM-Newton*, I use the *Rossi X-ray Timing Explorer* (RXTE; Bradt et al. 1993) telescope. This satellite was launched on December 30, 1995, and has been out of commission since January 5, 2012. The instruments used in this thesis are the Proportional Counter Array (PCA) and the All-Sky Monitor (ASM). PCA contains five proportional counters that can record X-ray emission between the range of 2−60 keV. The PCA allows for spectroscopic measurements with an energy resolution of $E/\Delta E \approx 6$ (at 6 keV; e.g. Jahoda et al. 1996). The PCA was designed as a timing instrument, but it is its broad X-ray spectral range and scheduling flexibility that was leveraged in this thesis, in particular to measure the evolving hard X-ray Comptonised emission of a neutron star low-mass X-ray binary.

This thesis further investigated the capabilities of the *Neutron Star Interior Composition Explorer* (NICER; Gendreau et al. 2016), which is an X-ray telescope mounted on the International Space Station (ISS). The telescope was commissioned on June 3, 2017. The X-ray Timing Instrument (XTI) is the only instrument mounted on NICER, consisting of 56 individual X-ray detectors. It covers the 0.2−12 keV range with a similar energy resolution as *XMM-Newton* ($E/\Delta E \approx 12-44$). *NICER* truly distinguishes itself in its timing capabilities when compared to other, currently operational X-ray telescopes, with an absolute time-tagging resolution of $<$300 ns. However, in this thesis its X-ray spectral capabilities were considered, to show *NICER*'s capabilities to constrain the thermal emission component in X-ray spectra of neutron star low-mass X-ray binaries.

The observatory most often used in this thesis is the *Neil Gehrels Swift Observatory* (*Swift*; Gehrels et al. 2004). *Swift* was launched on November 20, 2004, and named for the small, agile bird because of its rapid-response performance. *Swift* includes gamma-ray, X-ray and optical/UV telescopes, which correspond to the Burst Alert Telescope (BAT), the X-ray Telescope (XRT), and the UV/Optical Telescope (UVOT), respectively. The BAT is a large FOV instrument, allowing the collection of photons in a range of 15−150 keV over a FOV of 1.4 steradian (e.g. Barthelmy et al. 2005). The XRT is a pointed telescope with an X-ray CCD imager, covering the range of 0.3−10 keV (e.g. Burrows et al. 2000). It can collect spectral data in two modes, namely the Photon Counting (PC) mode, which provides a time-resolution of 2.5 s, or Window Timing (WT) mode, which can achieve a high time-resolution of 2.2 ms. *Swift* is exceedingly useful for X-ray binary research, due to its broad wavelength coverage and unprecedented scheduling flexibility, both of which were leveraged. The BAT instrument records and can monitor the outbursts of transient X-ray binaries. Moreover, the XRT collects data simultaneously with the UVOT (see below).

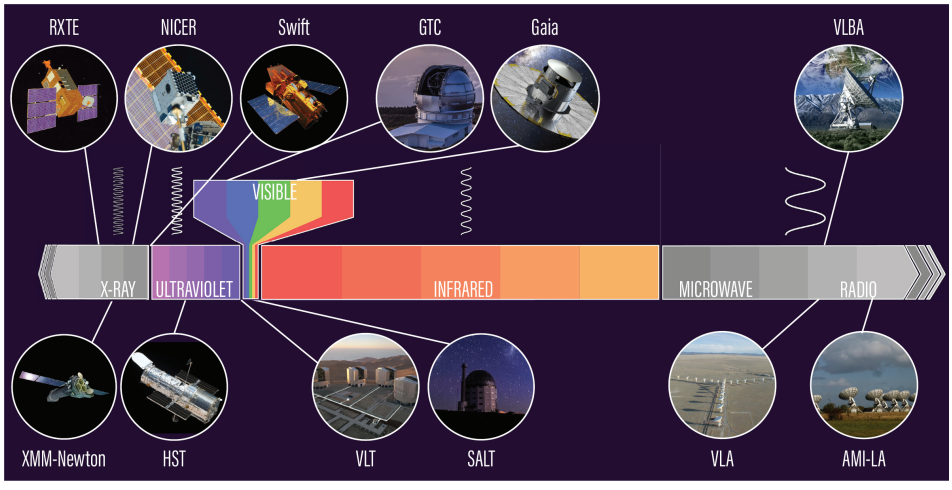

Figure 1.9: A visual representation of all the telescopes used in this thesis. The exact wavelength range of each instrument used in this thesis is noted in the text. As these telescopes can cover a wide wavelength ranges due to the many instruments available, I do not match these exactly in this visual, and only show this as an approximation. Credits: NASA/ESA/CSA, Joseph Olmsted (STScI), ESA/XMM-Newton, NASA E/PO, Sonoma State University/Aurore Simonnet, NASA/STS-125, Space Shuttle Atlantis, Ruffnax (Crew of STS-125), Daniel López/IAC, ESO/G. Hüdepohl, Jeff Miller/UW-Madison, J. Hellerman, NRAO/AUI/NSF, Cmglee.

UV and optical

Swift's UVOT contains a modified Ritchey-Chrétien telescope with an aperture of 30 cm (e.g. Roming et al. 2005). The instrument has seven different filters, including white, v, b, u, $uvw1$, $uvm2$ and $uvw2$. The white filter spans the full UVOT wavelength range of 1600−8000Å. The v, b, u, $uvw1$, $uvm2$ and $uvw2$ filters have central wavelengths of 5468Å, 4392Å, 3465Å, 2600Å, 2246Å, and 1928Å respectively (see e.g. Poole et al. 2008; Breeveld et al. 2011). The simultaneous coverage of both XRT and UVOT allows the study of correlated behaviour in the X-ray flux and optical/UV flux in X-ray binaries. In this thesis, I use the UVOT to study near-UV to optical flux densities, in order to obtain the (approximate) spectral energy distribution for a neutron star low-mass X-ray binary at different observing epochs.

In addition, I employed UV data from the The Hubble Space Telescope (HST), which was launched 35 years ago on April 24, 1990. In this thesis, I use the COS instrument, which provides medium- to low-resolution UV spectroscopy ($R \approx 1500-20000$) using various grisms between 815−3200Å (e.g. Green et al. 2012). HST/COS is currently unrivalled in its capabilities for (far-)UV spectrography for faint UV sources. This is vital for low-mass X-ray binary research, as the far-UV band contains strong transitions of key elements in tracing the composition and outflows in low-mass X-ray binary accretion discs.

Optical and near-infrared

The final satellite used in this thesis is *Gaia* (Gaia Collaboration et al. 2016). It was launched on December 19, 2013, and only recently ended its operations on March 27, 2025. It continuously scanned while the field-of-view sweeped across the sky, allowing it to make precise astrometric measurements. It is highly valuable for X-ray binary research, as it allows to constrain their distances based on the measured parallax. Moreover, recorded proper motions of X-ray binaries can help in constraining their transverse velocity. This allows determining their space velocities and potential kicks in their formation, as I do in this thesis.

I also used several ground-based optical telescopes, such as the Very Large Telescope (VLT), located on Cerro Paranal in the Atacama Desert in Chile. The VLT contains four 8.2-metre diameter Unit Telescopes (UTs). These can be used individually, and can be combined to perform interferometry. The UTs are mounted with various instruments, but I will only focus on the two relevant to this thesis. This include the FOcal Reducer and low dispersion Spectrograph (FORS2; Appenzeller et al. 1998) instrument, as well as the X-Shooter instrument (Vernet et al. 2011). FORS2 is a spectrograph covering the range 330−1100 nm, i.e. covering optical and near-UV wavelengths. It is a multi mode instrument, meaning it can achieve imaging, polarimetry, long slit and multi-object spectroscopy. The long slit spectroscopic measurements can achieve a resolution between $R = 260 - 2600$. X-Shooter is an intermediate resolution ($R = 4000-17000$) spectrograph, covering a wide wavelength range from near-UV to near-IR (300−2500 nm) with three spectroscopic arms. These are the UVB, VIS and NIR arms, where each arm consists of an individual spectrograph. X-shooter is unparalleled in obtaining simultaneous spectra over the near-UV to near-IR bands, which is optimal for studying many important emission and absorption lines in X-ray binary spectra.

In addition, I use data from the Gran Telescopio Canarias (GTC), located at the Roque de los Muchachos Observatory on La Palma, one of the Canary Islands. GTC contains a 10.4 m diameter telescope. The telescope contains various different instruments, but I will focus on the instrument used in this thesis, namely the Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy (OSIRIS) instrument. OSIRIS is an optical imager and spectrograph, covering the wavelength range of 365−1050 nm. Its longslit spectroscopy mode has various grisms, covering low to intermediate resolutions ($R = 300-2500$). Due to its large mirror, GTC is very well suited to study the faint optical emission from X-ray binaries.

Another large telescope that I leveraged to study the faint optical emission from low-mass X-ray binaries is the Southern African Large Telescope (SALT), located at the South African Astronomical Observatory (SAAO) in Sutherland, South-Africa. SALT contains a 9.2 m diameter telescope and has multiple instruments. The one used in this thesis is the Robert Stobie Spectrograph (RSS). With RSS longslit spectroscopy, different gratings are available covering the 320−900 nm range with a resolving power of $R \approx 400-5500$. Similarly to GTC, due to its large mirror, SALT is well suited to study the faint optical emission from X-ray binaries. Due to its location, SALT is particularly useful to study X-ray binaries located in the southern hemisphere.

Radio

The Karl G. Jansky Very Large Array (VLA) is an observatory consisting of an array of 27 active radio telescopes. The dish of each of these radio telescopes is 25 m in diameter. The VLA is located in Socorro County, New-Mexico in the United States, as part of the National Radio Astronomy Observatory (NRAO). The radio telescopes are organized in a "Y"-shaped set-up, and can be placed in different configurations, from A to D. The radio telescopes are placed over a diameter of 35 km in the A-configuration, and subsequently closer together for the others, with the smallest diameter of 1 km in the D-configuration. The configurations are changed over different observing cycles, and which one is best depends on the specific science goal. Due to the high sensitivity of the VLA, as well as the point source nature of low-mass X-ray binaries, generally any configuration is suitable. The VLA can cover a frequency range from 0.074−50 GHz, depending on the receivers used. It was used in this thesis for its high radio sensitivity, which is needed to study the radio emission of neutron star jets.

The Very Long Baseline Array (VLBA) is the second radio observatory used in this thesis, containing ten radio telescopes in different locations in the United States, which are remotely operated from Socorro, New-Mexico. The dishes of each radio telescope have a diameter of 25 m, and the VLBA can cover a frequency range of 0.3−96 GHz depending on the used receiver. Due to the wide separation of the radio telescopes, with the furthest telescopes being more than 8000 km apart, this telescope can perform very long baseline interferometry. The wide separation of the radio telescopes thus allows for a high angular resolution of around $0.12 - 22$ milliarcseconds (depending on the receiver) in radio images, which allows one to resolve radio emission from compact and/or ballistic jets in (neutron star) low-mass X-ray binaries.

Finally, the Arcminute Microkelvin Imager (AMI) was used in this thesis, which is located near Cambridge in the United Kingdom as part of the Mullard Radio Astronomy Observatory. It consists of two arrays, a Large Array (LA) and Small Array (SA). The AMI-LA is used in this thesis, and consists of 8 radio telescopes, each of which has a 12.8 m diameter. The AMI-LA telescopes are spaced out in such a way that the minimum distance between two telescopes is 18 meters, and the largest distance between two telescopes is 110 meters. Moreover, the AMI-LA covers a frequency range between 12−18GHz. The AMI telescope is particularly efficient in studying transient sources due to its scheduling flexibility, allowing for high-cadence monitoring of low-mass X-ray binaries. In this thesis, it was used for a two week monitoring campaign in order to probe transient radio emission of a neutron star low-mass X-ray binary on day time scales simultaneously with X-ray and UV instruments.

1.3 Thesis outline

The title of this thesis is ”Exploring the outflows and evolution of accreting neutron stars”. This reflects the objectives of this thesis, which is to study the outflows of accreting neutron stars in X-ray binaries, to study the evolutionary histories of low-mass X-ray binaries, as well as the impact of their outflows on their further evolution. To achieve this goal, I present in this thesis four different studies of accreting neutron star low-mass X-ray binaries that align with these different objectives.

In Chapter 2, I present a study of the accretion/jet coupling of the neutron star low-mass X-ray binary Aquila X-1 (Aql X-1), using *Swift*/XRT, *RXTE*/PCA, VLA, and VLBA data recorded during its 2009 accretion outburst. Phenomenological differences between the accretion/jet coupling of black hole and neutron star low-mass X-ray binaries have been observed, yet the underlying reasons for these differences remain unclear. In this chapter, I present for the first time a study wherein I disentangle the individual X-ray spectral components and evaluated their coupling with the radio jet emission. Based on this analysis, I show that there is no evidence of a significant thermal contribution in the *Swift*/XRT spectra that could cause scatter in the radio/X-ray coupling. i.e., that emission from the neutron star surface cannot account for this. Furthermore, I evaluate the scenario of neutron stars displaying powerful ballistic jet ejections similar to black holes, based on the detection of a strong thermal X-ray emission component coinciding with the brightest radio detection. Motivated by my work presented in this Chapter, I successfully proposed for and carried out a high-cadence multi-wavelength observing campaign of Aql X-1 during an outburst that occurred in 2024, which involved X-ray, optical and sub-mm radio observatories. This campaign indeed detected these discrete jet ejections, as I hypothesized, which will be published in a future work.

In Chapter 3, I present the surprising discovery of an UV outflow in the short-period neutron star low-mass X-ray binary UW Coronae Borealis (UW CrB) using archival UV spectral data recorded with HST/COS. By performing time-resolved analysis, I detected a transient P-Cygni outflow feature for the Si IV 1400Å line, and tentatively for the N V 1240Å line, tracing an outflow with a terminal velocity of $\approx$1500 km s^{-1}. The orbital period is very short compared to previous wind detections ($P_{\rm orb} \approx 111$ min), and below the limit expected theoretically for thermally-driven disc winds. Indeed, through simulating the acceleration of gas in an accretion disc of the size expected for UW CrB, I show that heating from the disc is insufficient for launching a strong thermally driven wind, but I show that the hot black body emission from the neutron star surface does create the conditions to launch an accretion disc wind in UW CrB. Therefore, I show that thermally-driven disc winds can be launched in much shorter period (and hence smaller) neutron star X-ray binaries than previously realised.

In Chapter 4, I present the results of an intensive follow-up observing campaign, which I successfully proposed for and coordinated, to confirm the presence of a disc wind in UW CrB and constrain its properties. The quasi-simultaneous observations covered radio to X-ray wavelengths and were recorded using *XMM-Newton*, *Swift*, HST, VLT, GTC, and the AMI-LA telescopes in 2023 and 2024. Through extended analysis of this rich multi-wavelength data set I find evidence for the presence of a persistent outflow in this system,

where optical features trace the outflow with a terminal velocity of ≈1800 km s^{-1}, typical of an accretion disc wind. This result suggests that mass transfer in low-mass X-ray binaries can be highly non-conservative down to very short orbital periods, which has direct impact on our understanding of the orbital evolution of low-mass X-ray binaries.

Finally, in Chapter 5, I study the formation of the peculiar ultra-compact X-ray binary 4U 1626-67, which is thought to be a rare example of the result of an accretion-induced collapse supernova. While those events are proposed to induce little to no kicks to the binary, I show in this Chapter that its location relative to the Galactic plane points to the system being formed with a large kick velocity. In particular, I present the analysis of astrometric data recorded with *Gaia* and optical spectroscopic data from VLT/FORS2 and SALT/RSS to derive that 4U 1626-67 has a high space velocity. Subsequently, I use these measurements are to estimate probability distributions of the potential kick velocity imparted to the binary in its formation. From these probability distributions, I conclude that the binary likely obtained a strong kick in its formation. This result suggests that accretion-induced collapse can induce strong natal kicks in some binaries, which has important implications for understanding the physics of such supernovae, as well as for binary evolution models.

“Sisyphus put his shoulder to the boulder
and began to push it up the slope!”
Stephen Fry, Mythos