1.1 X-ray binaries

As astronomical objects can attract the surrounding matter through their gravitational force, this process, known as accretion, thus plays a fundamental role at all scales encountered in the universe. X-ray binaries, as a class of binary stars emitting luminous X-rays, are excellent laboratories to study this process.

X-ray binary systems consist of a compact object, either a black hole (BH) or a neutron star (NS), and a companion star, both of which orbit a common centre of mass of the system. These systems can be subdivided into high-mass X-ray binaries (HMXBs) and low-mass X-ray binaries (LMXBs), based on the mass of the companion star. In the former systems, matter is mainly accreted via a stellar wind, whereas in the latter ones matter is accreted onto a compact object via Roche-lobe overflow in an accretion disc (see Fig. 1.1). In the following, I focus on introducing the properties of LMXBs.

In LMXBs, the companion star is usually a late-type main sequence star or a white dwarf, with a mass typically lower than 1 $M_\odot$. Such systems can be formed in two different ways: i) two stars are directly gravitationally bound from birth, both of them surviving a supernova explosion (see Tauris & van den Heuvel 2006); ii) after a massive star collapses into a compact star in an environment with a high density of stars, a second star may be captured by it (see Bhattacharya & van den Heuvel 1991; Verbunt & Lewin 2006). The latter process, however, mainly happens in globular clusters. Most of the binaries in the Milky Way have been born in a bound state.

In an LMXB system, the matter from the outer layers of the normal star is stripped off and is then accreted onto the compact object. With a large amount of angular momentum, the transferred matter cannot be radially accreted onto the compact object,
but forms a rotating disc. The X-rays stem from the conversion of the gravitational energy of the in-falling material into radiation through viscous processes or shocks occurring in the accretion disc. As the accreted matter moves inwards, the disc temperature gradually increases, which can be up to several million degrees in the region closest to the compact object. However, X-ray energy spectra of these systems can extend up to 100 keV. This indicates that the disc is not the only emitting region. The region that produces this high-energy radiation is called \textit{corona}, which is composed of hot electrons ($T > 10^9$ K) and is responsible for producing the high-energy photons by inverse Compton scattering.

\section*{1.2 Components of binary systems}

As was just mentioned in the previous section, the accretion disc plays a key role in the X-ray emission of LMXBs. The broadband energy spectrum also indicates that there is a significant contribution from the corona in X-rays. The study of the accretion disc and the corona, as well as their interaction, helps us to better understand the physics of these systems.

\subsection*{1.2.1 The accretion disc}

The accretion disc is composed of stellar plasma whose properties are determined by the ions and electrons that compose it. Depending on the temperature, the matter can be neutral, partially or fully ionized. The disc structure and geometry seem to be affected by the mass accretion rate and viscosity.
The standard accretion disc model was introduced by Pringle & Rees (1972) and Shakura & Sunyaev (1973), who described an optically thick but geometrically thin accretion disc, which is dominated by gas pressure and is close to a blackbody. This standard disc model is applied to the radiatively efficient case, whereas for some sources with a low accretion rate, this model is not capable of reproducing the corresponding spectral energy distribution (Esin et al. 1996).

The Advection Dominated Accretion Flow (ADAF) model was initially introduced by Ichimaru (1977); the model assumes that once the disc is close to the central object, its inner part becomes optically thin and is replaced by a hot flow (Narayan & Yi 1994, 1995a,b). In this scenario, only a small amount of the energy is radiated away (Narayan 1996). Meanwhile, most of the energy is advected radially with the flow onto the compact object. Therefore, the radiation efficiency of ADAF is much lower than that of the standard disc (see Narayan, Mahadevan & Quataert 1998; Kato, Fukue & Mineshige 1998). ADAF is mainly applied to black-hole systems, as part of the accretion energy is advected into the black hole. In neutron-star systems the accretion is efficient, since the energy can eventually be released by the surface of the neutron star, even in the propeller state due to the near spherical ADAF (e.g. Zhang, Yu & Zhang 1998; Menou et al. 1999).

1.2.2 The corona

The corona consists of hot electrons and is the region where the high-energy X-ray photons, up to hundreds of keV, are produced. Both the origin and the geometry of the corona are still unclear. Shakura & Sunyaev (1973) suggested that the corona may be formed by evaporation of hot material from the disc. Alternatively, Liang & Price (1977) proposed that an accretion disc may pump energy into an outer tenuous layer of its atmosphere to form a high-temperature corona analogous to the solar corona. As for its geometry, there are several main models: the ‘slab’ or ‘sandwich’, the ‘sphere’ (ADAF-like) and the ‘patchy’ or ‘pill box’ corona. Besides those, the ‘lamppost’, an on-axis isotropic point, geometry (e.g. Martocchia & Matt 1996; Miniutti & Fabian 2004) has become a popular model for accreting black holes.

1.3 X-ray spectra

As explained previously, the accretion disc and the corona play major roles in the X-ray emission of LMXBs. By modelling X-ray spectra, one can study the interactions between matter and photons, the geometry of the disc and corona, and further explore the physics of X-ray binaries.

X-ray spectra of accreting binary systems generally exhibit two main components: a soft component associated with an accretion disc, and a hard component resulting from inverse Compton scattering of soft photons by high-energy electrons in a corona.
Figure 1.2 – The three main components of the X-ray emission from an accretion black hole (top) and a plausible geometry of the accretion flow in the hard spectral state (bottom), where the black point, the blue slabs and the magenta points represent the black hole, the accretion disc and the corona, respectively. Figures from Gilfanov (2010).
1.3: X-ray spectra

(see Sunyaev & Truemper 1979; Sunyaev & Titarchuk 1980). These two components can be fitted by a multi-temperature disc blackbody (e.g. Mitsuda et al. 1984) and a power-law with a high-energy cutoff, respectively. In a neutron-star LMXB, a third soft thermal component is required by the data, which is slightly hotter than the accretion disc and originates from the neutron-star surface or the boundary layer (e.g. Gilfanov & Revnivtsev 2005). Additionally, a reflection component is often detected in such spectra and is interpreted as the result of the high-energy coronal photons irradiating an optically thick accretion disc (Fabian et al. 1989). These typical components in a black-hole LMXB system are shown in Fig. 1.2.

The reflection spectrum is the superposition of Compton scattering, fluorescence, Auger effect and recombination emission produced in the accretion disc (e.g. Fabian et al. 1989; Ross & Fabian 1993). Fig. 1.3 shows the results of a Monte-Carlo simulation modelling these processes when a power-law X-ray continuum with photon index = 2 is incident on a gaseous slab. The most notable signature of the reflection spectrum is the iron emission line at 6.4–7 keV plus a Compton hump at 10–30 keV.

Fluorescent and recombination emission lines are generated by irradiation of the cold matter nearby the compact object. X-ray photons are photoelectrically absorbed by particles and hence their K-shell electron is removed. The K-hole is then filled by an electron from outer shells and subsequently, a K-shell photon (fluorescence) or a second electron (Auger effect) is emitted (Bambynek et al. 1972). The probability of emitting a fluorescent photon over an Auger electron is determined by the fluorescent yield, which is proportional to the nuclear charge \( Z \) to the fourth power (i.e. \( \propto Z^4 \)). The combination of the high fluorescent yield and the relatively high abundance makes the iron emission line, at 6.4 keV, the most prominent one in the reflection spectrum. Highly ionized iron can be detected at 6.67–6.70 keV and 6.95–6.97 keV, associated with Fe XXV (He-like) and Fe XXVI (H-like), respectively. The He-like lines are formed partly by fluorescence and partly by recombination, whereas H-like lines are only formed by recombination (Hatchett, Buff & McCray 1976).

The above process happens mainly when the incident photons have energies lower than 15 keV. Once the energy is higher than that, photons are substantially Compton scattered until they are emitted away or are photo-absorbed. Both processes result in a Compton hump at 10–30 keV in the spectrum.

Another consequence of photoelectric absorption is the absorption edge. When the energy of an incident photon is higher than the energy of an electronic transition or to the ionization potential of an atom, the probability of the atom absorbing that photon dramatically decreases with increasing photon energy. This resulting jump in cross section is cabled an absorption edge, e.g. the iron K edge at 7.1 keV in Fig. 1.3.

The iron line in the reflection spectrum is intrinsically narrow, but may appear broadened and skewed towards lower energies. Since the iron line arises from the in-
Figure 1.3 – X-ray reflection from an illuminated slab. The dashed line shows the incident continuum and the solid line shows the reflected spectrum (integrated over all angles). The main reflected features are the iron fluorescence line at 6.4 keV, the iron absorption edge at 7.1 keV and the Compton hump peaking at 30 keV. Monte Carlo simulation from Reynolds (1996).

nermost regions of the accretion disc, its profile is modified by the combination of Doppler shifts, Doppler broadening and gravitational redshifts (Fabian et al. 2000), as illustrated in Fig. 1.4. At each radius of the disc, a symmetric double-peak line profile is produced by the emission from the matter approaching to (blue-shifted) and receding from (red-shifted) the observer. As matter proceeds closer to the central object, special relativistic beaming enhances the blue peak of the line. Moreover, gravitational redshift shifts the line to lower energy. Summing all the effects, the shape of the line appears to be broad and asymmetric.

Additionally, the line profile also depends on the inclination of the system with respect to the line of sight, the inner and outer radius of the disc, the emissivity index (Fabian et al. 1989) and the disc ionization state (e.g. Fabian et al. 2000).

Besides spectral analysis, timing analysis reveals different aspects of the accretion processes in X-ray binaries. The study of the rapid variability constitutes a powerful tool to probe the properties of the inner most regions of the accretion disc. The main
1.4: X-ray states

The existence of the X-ray states in LMXBs was first demonstrated by the work of Tananbaum et al. (1972) in which they observed that the soft X-ray flux (2–6 keV) of Cygnus X–1 decreased whereas its hard X-ray flux (10–20 keV) increased. Since then, similar X-ray transitions have been discovered in many sources which are called transients. Those LMXBs transients are bright during an outburst, in which their X-

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Figure 1.4 — Left panel: a schematic representation of the accretion disc from the top, with matter approaching (blue) and receding (red). Right panel: the first three panels showing the Doppler shift and relativistic effects on a narrow emission line profile at two different radii in the disc. The two line profiles indicate the emission from the two disc radii as shown in the left panel: the broadest profile corresponds to the ring at the smallest radius. The bottom panel shows a broad and skewed line profile after integrating all disc radii, resulting from the sum of the above effects. Figures taken from Fabian et al. (2000).

method to study the fast variability is the Fourier power density spectrum, which describes how the power of a time series is distributed with frequency.

As an energy spectrum is time averaged, one always needs to consider the influence of the source variability on its spectrum. Studying timing properties of a system also helps us to understand the source state. Combined results of spectral and timing analysis bring a more complete view of what happens in the source.

1.4 X-ray states
ray luminosity can be $L_x \sim 10^{36} - 10^{39}$ erg s$^{-1}$, and after several days to months or even years, they become quiescent.

For BH X-ray binaries, there are two main states, the soft state and the hard state, depending on the source timing and spectral properties (see Remillard & McClintock 2006, for a detailed review). During the soft state, an optically thick and geometrically thin accretion disc is observed; the disc is normally thought to extend down very close to the compact object, i.e. the inner stable circular orbit (ISCO) in BH systems or the NS surface. This component is commonly described as thermal emission with a temperature of $\sim 1$ keV and can be fitted by a blackbody or a multi-temperature blackbody. A non-thermal component is detected at energies above $\sim 10$ keV, and is fitted with a power law by a photon index $\Gamma \sim 2.1 - 3$, whose contribution is limited to $< 25\%$ of the flux in the 2–20 keV energy range (also see Remillard & McClintock 2006). During the hard state, the spectrum is dominated by a power-law component with $\Gamma \sim 1.5 - 1.9$ and a high-energy cutoff, which contributes $\geq 80\%$ of the 2–20 keV flux. A weak thermal component is detected at low energies, likely from a cool disc that appears to be truncated at relatively large distances from the compact object (Done, Gierliński & Kubota 2007).

For NS X-ray binaries the scenario is similar, except that one additional component from the NS surface or the boundary layer is required (e.g. Syunyaev & Shakura 1986; Inogamov & Sunyaev 1999). This boundary layer is formed when the rapidly rotating gas in the disc reaches the slowly/non-rotating accreting NS. During this process, part of the gravitational potential energy has been radiated by the gas in the disc and the rest of the energy is released in the boundary layer. Since this energy comes from a small region nearby the NS, the boundary layer is consequently hotter than the disc, which results in harder radiation.

1.5 X-ray facilities

The study of astronomical objects at the energy ranges of X-rays and $\gamma$-rays began in the early 1960s. Before then, the Sun was believed to be an intense source in these wavebands, but no other objects had been observed in X- or $\gamma$-rays. The Earth’s atmosphere is opaque to electromagnetic radiations at certain wavelengths, e.g. $\gamma$-rays, X-rays, most UV and Infrared light (see Fig. 1.5). This means that, in order to observe extra-terrestrial sources of such emission, these sources must be observed from above the atmosphere.

With the launch of rocket flights, the first non-solar X-ray source was successfully detected in 1962 by Riccardo Giacconi, Herb Gursky, Frank Paolini, and Bruno Rossi. Later, this bright X-ray source was designated as Scorpius X-1. Riccardo Giacconi subsequently won the Noble Prize for Physics in 2002 for his contribution to X-ray astronomy. The first earth-orbiting X-ray telescope UHURU, which was also known
1.5: X-ray facilities

Figure 1.5 – Electromagnetic radiation through the Earth’s Atmosphere, from $\gamma$-rays on the left (the most powerful, shortest wavelength) over to the Radio on the right (the longest wavelength). The wavelength and frequency of light determines how far it can penetrate into the Earth’s Atmosphere. Credits: Harris Geospatial Solutions.

as the Small Astronomical Satellite-1, based on Giacconi’s design, was launched on 12 December 1970, operated over two years and ended in March 1973. Ever since, new missions have been launched, and we entered into a new era of discovery in high energy astrophysics. In this section I briefly describe the main instruments used in this thesis.

1.5.1 NuSTAR

The Nuclear Spectroscopic Telescope Array (NuSTAR) is a National Aeronautics and Space Administration (NASA) small explorer mission that carries the first focusing hard X-ray optics into space (Harrison et al. 2013); it was successfully launched on 13th June 2012. With a mass of 350 kg for a focal length of 10.14 meters, NuSTAR was launched into a near-equatorial, low-Earth orbit, to minimize exposure to the South Atlantic Anomaly (SAA) where there is a high concentration of trapped particles. NuSTAR has a pair of co-aligned focusing telescopes (Fig. 1.6), which are designed to provide a broad-band coverage in the hard X-rays between 3–79 keV. Compared to the previous hard X-ray instruments (> 10 keV), NuSTAR results in an order of magnitude improvement in angular resolution and has two orders of magnitude improvement in sensitivity. Fig. 1.7 shows a comparison of the NuSTAR effective collecting area with some other focusing X-ray detectors currently on orbit.

1.5.2 XMM-NEWTON

XMM-NEWTON, the X-ray Multi-Mirror Mission, is an X-ray space observatory launched by the European Space Agency (ESA) on 10th December 1999. The main objective of this observatory is to investigate galactic and extragalactic X-ray sources, perform narrow- and broad-range spectroscopy, and obtain the first simultaneous imaging of objects in both X-ray and optical (visible and ultraviolet) wavelengths.

With a mass of 3,800 kg for a length of 10.8 meters, XMM-NEWTON was launched into space aboard an Ariane 504 rocket and placed into a highly elliptical orbit with
Figure 1.6 — Diagram of the NuSTAR observatory in the stowed (bottom) and deployed (top) configurations (adapted from Harrison et al. 2013).

Figure 1.7 — Effective collecting area of NuSTAR compared to selected operating focusing telescopes (Chandra, XMM-Newton, and Suzaku). NuSTAR provides good overlap with these soft X-ray observatories and extends focusing capability up to 79 keV (adapted from Harrison et al. 2013).
1.5: X-ray facilities

a perigee of 6,000 km and an apogee of 112,000 km. This mission carries three high throughput X-ray telescopes with an unprecedented effective area and an optical monitor (see Fig 1.8). The instruments on board XMM-NEWTON are:

- **The European Photon Imaging Cameras**
  The three European Photon Imaging Cameras (EPIC) are the primary instruments aboard XMM-NEWTON. The system is composed of two MOS-CCD cameras (Turner et al. 2001) and a single pn-CCD camera (Strüder et al. 2001), with a total field of view of 30arcmin and an energy sensitivity range between 0.15–12 keV, with an energy resolution of $E/\Delta E = 20 - 50$ and an angular resolution of 6arcsec.

- **The Reflection Grating Spectrometer**
  The two Reflection Grating Spectrometers (RGS) are a secondary system on the spacecraft and are composed of two Focal Plane Cameras and two Reflection grating Assemblies (den Herder et al. 2001). This system is used to collect high resolution X-ray spectral data and can determine the elements present in the target, as well as the temperature, abundance and other characteristics of those elements. The RGS system operates in the energy range of 0.33–2.5 keV, which allows the detection of carbon, nitrogen, oxygen, neon, magnesium, silicon and iron.

- **The Optical Monitor**
  The Optical Monitor (OM) is a 30 cm Ritchey-Chretien optical/UV telescope designed to provide simultaneous observations alongside the spacecraft’s X-ray instruments (Mason et al. 2001). It consists of three optical and three UV filters over the wavelength range of 180–600 nm.

1.5.3 **SWIFT**

The Neil Gehrels SWIFT Observatory*, previously called the SWIFT Gamma-Ray Burst Mission, is a NASA space telescope launched on 20th November 2004. With a mass of 1,500 kg, SWIFT was launched into a low circular Earth orbit, aboard a Delta II rocket. This telescope is a multi-wavelength space observatory dedicated to the study of $\gamma$-ray bursts (GRBs). Its three instruments work together to observe GRBs and their afterglows in the $\gamma$-ray, X-ray, UV, and optical wavebands. The three instruments are:

- **Burst Alert Telescope**
  The Burst Alert Telescope (BAT) is an alert system to detect GRB events and

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* The name ‘Swift’ is not a mission-related acronym, but rather a reference to the instrument’s rapid slew capability.
Figure 1.8 — Sketch of the XMM-Newton payload. On the lower left: the aperture doors and the mirror modules with the two Reflection Grating Arrays. The optical monitor is obscured by the lower mirror module. On the upper right: the EPIC MOS cameras (green), the EPIC pn camera (purple), and the RGS detectors (red). The direction of the incoming X-rays is indicated by the blue arrow on the left. Figure adapted from the VILSPA XMM-Newton Science Operations Centre (Dornier Satellitensysteme GmbH).

Figure 1.9 — SWIFT’s three scientific instruments work together to obtain as much information as possible about γ-ray bursts. Credit: NASA/GSFC.
compute their coordinates in the sky. It is capable of observing an event in the range of 15–150 keV and to locate the position of each event with an accuracy of 1 to 4 arcmin within 15 s.

- **X-Ray Telescope**
  The X-ray Telescope (XRT) is a focusing X-ray telescope with an effective area of 110 cm$^2$ at 1.5 keV and an 18 arcsec spatial resolution covering the range of 0.2–10 keV. It can take images and perform spectral analysis of the GRB afterglow. This provides a more precise location of the GRB, with a typical error circle of approximately 2 arcsec radius. The XRT is also used to perform long-term monitoring of GRB afterglow light-curves for days to weeks after the event, depending on the brightness of the afterglow.

- **Ultraviolet/Optical Telescope**
  After SWIFT has slewed towards a GRB, the Ultraviolet/Optical Telescope (UVOT) is used to detect an optical afterglow, in the range of 170–650 nm. The UVOT is also used to provide long-term follow-ups of GRB afterglow light-curves.

Since several X-ray sources are multi-wavelength emitters, it is extremely useful to perform simultaneous observations of a source in different energy bands, in order to better understand the physics and the connections between a compact star and the matter in its vicinity.

### 1.6 Thesis motivation and overview

The origin of the spectral components in X-ray binaries, such as the soft/hard X-ray excess and the iron Kα line complex are still unclear. Properties of the accretion flow, e.g. the accretion geometry, composition of the accreted material and the mass accretion rate, can be primarily studied through X-ray observations. How to detect and measure them accurately remains challenging.

Disc reflection, the interaction between the corona and/or other components (e.g. the NS surface/boundary layer in NS systems or the jet or the distant reflector in AGN) and the accretion disc, is a powerful tool to diagnose the physical and dynamical conditions of accreting sources. Modelling the reflection features can lead to important constraints on the disc ionization state (e.g., Ross, Fabian & Young 1999; García & Kallman 2010; García, Kallman & Mushotzky 2011; García et al. 2013), the disc inclination angle (e.g., Fabian et al. 1989; Mushotzky et al. 1995; Crummy et al. 2006), the inner radius of the disc and the spin parameter of the compact object (e.g., Fabian et al. 1989; Laor 1991; Brenneman & Reynolds 2006; Reynolds & Fabian 2008).

However, the accuracy of the measurement of some parameters derived from reflection models are debated. For instance, Pandel, Kaaret & Corbel (2008) and Sanna
et al. (2013) studied the iron emission line in the NS 4U 1636–53 with XMM-NEWTON and found a very high inclination angle of the accretion disc, consistent with $90^\circ$, even though neither eclipses or dips have ever been observed in this source. Recently, a very high value of the iron abundance in the accretion disc of several systems has been brought up. García et al. (2015b) and Parker et al. (2016) found iron abundances of, respectively, 4.0–4.3 and $4.7 \pm 0.1$ in solar units in the BHC Cyg X–1; similarly, values of $5 \pm 0.1$ and $6.6^{+0.5}_{-0.6}$ times solar for GX 339–4 have been reported by Parker et al. (2015) and Walton et al. (2016) as well.

Triggered by these findings and issues, my work is mainly focused on the study of the reflection component and the inner flow in the vicinity of a compact object in LMXBs. I conducted all my research with the instruments described in the previous section. The chapters can be summarised as follows:

- **Chapter 2 – The XMM-NEWTON spectra of 4U 1630–47 revisited**

  In this chapter, we analysed two XMM-NEWTON observations of the black-hole candidate 4U 1630–47 during the 2012 outburst, for which there had been a claim of Doppler-shifted emission lines that were interpreted as arising from baryonic matter in the jet. We applied an alternative model that, without the need of Doppler-shifted emission lines, fits the data well. The fit to all the 2012 XMM-NEWTON observations of this source require a moderately broad emission line at around 7 keV plus several absorption lines and edges.

- **Chapter 3 – The reflection spectrum of 4U 1636–53**

  To explore the anomalously high-inclination observed in the past from fits to the XMM-NEWTON spectra of the neutron star low-mass X-ray binary 4U 1636–53, we investigated three NuSTAR observations of this source in the soft, transitional and hard state. By applying different models to the data, we got a reasonable inclination angle of $\sim 56^\circ$ derived from the lamppost component RELXILLLP. We also discuss the results for these models and the possible primary source of the hard X-rays in this system.

- **Chapter 4 – The reflection component in the average and heartbeat spectra of IGR J17091–3624**

  Similar to the well known black hole candidate GRS 1915+105, IGR J17091–3624 is a black hole candidate with heartbeat variability. In this chapter, we jointly fit the NuSTAR and Swift spectra of IGR J17091–3624 during its 2016 outburst to study the evolution of the spectral parameters in this outburst and, in particular, during the QPO cycle of the heartbeat.
• **Chapter 5 – Study of the X-ray properties of the neutron-star binary 4U 1728–34 from the soft to hard state**

We fitted five XMM-NEWTON spectra of the neutron-star LMXB 4U 1728–34 with several popular reflection models and found that almost all of them yield a supersolar iron abundance, up to 10 times solar. We also explore the possible reasons why the supersolar iron abundance is required by the data and found that this high value is probably caused by the absence of the hard photons in the XMM-NEWTON data. We also found the change of the inner disc does not support the standard accretion disc model.

• **Chapter 6 – Conclusions and future work**

An overall summary of my work is provided, and future projects are discussed.
chapter 1: Thesis introduction