Observations and dynamical studies of X–ray binaries in a low-accretion state

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geboren te Milaan, Italië
Promotor: Prof. Dr. Wim Hermsen
Co-promotor: Dr. Peter Jonker
To Gionata,  
Monica  
and  
to my parents

Considerate la vostra semenza:  
fatti non foste a viver come bruti  
ma per seguir virtute e canoscenza

[Consider the seed from which you sprang:  
you were not made to live like brutes  
but to pursue virtue and knowledge]

(Ulisse ne La Divina Commedia, Inferno, canto XXVI)  
[(Ulysses in the Divine Comedy, Inferno, canto XXVI)]

Dolce e chiara e' la notte  
e senza vento

[soft and clear is the night  
and no wind blows]

(da ‘La sera del di’ di festa’, G. Leopardi)  
[(from ‘The evening after the holy day’, G. Leopardi)]
Contents

1 Introduction .............................................................. 1
  1.1 XRBs: the astrophysical context ................................... 1
  1.2 Accretion discs and Roche geometry ............................ 4
  1.3 Outburst and quiescence ......................................... 5
  1.4 Observing the companion star: optical counterparts .......... 6
    1.4.1 Optical spectra of LMXBs and CVs ....................... 10
  1.5 Dynamical mass measurements .................................. 10
  1.6 Synopsis of this thesis ......................................... 13

2 Chandra localisation and optical/NIR follow-up of Galactic X-ray sources 15
  2.1 Introduction ......................................................... 16
  2.2 X-ray data: reduction and analysis ............................ 19
  2.3 Optical and NIR data: reduction and analysis ................ 20
  2.4 Individual sources ............................................... 23
    2.4.1 IGR J16194-2810: a SyXB ................................. 23
    2.4.2 IGR J16293-4603: a new LMXB (possibly SyXB) ....... 25
    2.4.3 IGR J16479-4514: an eclipsing SFXT .................. 27
    2.4.4 IGR J16500-3307: an Intermediate Polar ............... 30
    2.4.5 XTE 1710-281: an eclipsing LMXB ...................... 31
    2.4.6 XTE J1716-389: an obscured HMXB system ............ 33
    2.4.7 IGR J17254-3257: a candidate UCXB ................... 34
    2.4.8 XTE J1743-363: a candidate SFXT .................... 36
    2.4.9 IGR J17597-220: a dipping LMXB ....................... 37
    2.4.10 IGR J18490-0000: a Pulsar Wind Nebula ............... 38
    2.4.11 IGR J19308+0530: an L/IMXB with an F8 companion .. 40
  2.5 Conclusion ........................................................ 41

3 Optical spectroscopy of the quiescent counterpart to EXO 0748−676: a Black Widow scenario? 45
  3.1 Introduction ........................................................ 46
3.2 Observations and data reduction ......................................... 48
3.3 Analysis and results .......................................................... 50
  3.3.1 Individual and trailed spectra ........................................ 50
  3.3.2 Radial velocity of the Balmer lines ................................ 50
  3.3.3 Averaged spectrum ....................................................... 51
  3.3.4 Measuring the intrinsic broadening of the emission lines ... 55
  3.3.5 Evidence for Mg\textsubscript{i} in emission ......................... 56
  3.3.6 Doppler tomography .................................................... 56
3.4 Summary of the results ..................................................... 58
3.5 Discussion ........................................................................... 60
3.6 conclusions ......................................................................... 63

4 CXOGBS J174444.7$-$260330: a new long orbital period cata-
clysmic variable in a low state .............................................. 65
  4.1 introduction ....................................................................... 66
  4.2 Observations and data reduction ........................................ 68
    4.2.1 Phase-resolved imaging .............................................. 68
    4.2.2 Optical spectroscopy .................................................. 68
  4.3 Analysis and results .......................................................... 72
    4.3.1 Spectral features ........................................................ 72
    4.3.2 Binary period .............................................................. 73
    4.3.3 Radial velocity curve .................................................... 74
    4.3.4 Rotational broadening and mass ratio ......................... 77
    4.3.5 Companion star spectral type ....................................... 78
    4.3.6 Ellipsoidal modulations and system inclination ............. 79
    4.3.7 Mass of the stellar components ................................... 80
    4.3.8 UV counterpart .......................................................... 80
  4.4 Discussion ........................................................................... 80
    4.4.1 Distance and X–ray luminosity ................................... 81
    4.4.2 The difficult classification of quiescent XRBs .............. 82
  4.5 Conclusion ......................................................................... 83

5 Roche lobe overflow onto a compact object from a donor 1.8
times as massive ..................................................................... 85
  5.1 introduction ....................................................................... 86
  5.2 Observations and data reduction ........................................ 87
  5.3 Analysis and results .......................................................... 88
    5.3.1 Spectroscopy ............................................................... 88
    5.3.2 Ellipsoidal modulation and system inclination ............. 91
    5.3.3 Upper limits in the radio waveband ......................... 92
  5.4 Discussion and conclusion ................................................ 92
6 The black hole candidate XTE J1752−226 towards and in quiescence: optical and simultaneous X–ray – radio observations 95
6.1 Introduction ............................................. 96
6.2 Observations, data reduction and results ............................. 99
  6.2.1 Chandra X–ray observations .................................. 99
  6.2.2 Quiescent X–ray emission from XTE J1752−226 ..... 102
  6.2.3 New Chandra sources in the vicinity of XTE J1752−226 102
  6.2.4 Optical observations .......................................... 104
  6.2.5 Optical outburst amplitude of more than 8 magnitudes 106
  6.2.6 Optical counterparts to unidentified Chandra sources . 107
  6.2.7 Radio observations: EVLA ................................. 107
  6.2.8 Radio observations: VLBA ................................. 108
  6.2.9 Upper limits to the radio quiescent flux .................... 110
  6.2.10 The X–ray – radio correlation ............................. 111
6.3 Discussion ..................................................... 112
  6.3.1 Distance .................................................... 114
  6.3.2 Companion star ............................................. 115
  6.3.3 Orbital period ............................................. 115
  6.3.4 The X–ray – radio correlation ............................. 116
  6.3.5 X–ray detection in quiescence? ............................. 117
  6.3.6 X–ray detection of a jet? ................................. 117
6.4 Conclusion ..................................................... 120

Summary
(Samenvatting) ........................................... 123

References ......................................................... 135

Publications ....................................................... 147

Acknowledgments
(Ringraziamenti) ........................................ 149
Chapter 1

Introduction

X-ray binaries (XRBs) are binary systems where a compact object - a black hole (BH) or a neutron star (NS) - accretes material from a companion star. The compact object is commonly referred to as the accretor or the primary star in the binary, while the mass donor is the companion or secondary star. Similar systems hosting a white dwarf (WD) accretor are called cataclysmic variables (CVs). In the mass accretion process a large amount of energy is radiated, mainly in the X–rays wavelength for XRBs and in the soft X–rays and UV for CVs. When matter falls into the strong gravitational field of the compact object, in fact, gravitational potential energy is converted into kinetic energy and partly radiated by means of the interactions in the accreting flow. A sketch of an XRB, schematising the multi-wavelength emission from these systems, is shown in Figure 1.1.

1.1 XRBs: the astrophysical context

The accretion mechanism itself is an important reason to study XRBs. It is ubiquitous in the universe (from young T-Tauri stars to AGN) and it reaches its most extreme form when involving compact objects. As the efficiency depends on the compactness of the accretor, mass accretion onto a NS or BH is the most efficient mechanism currently known in terms of energy released for a given amount of mass (with the sole exception of particle annihilation). Moreover, the accretion flow radiates from close to the compact object, where the gravitational field strength is extreme and the predictions of general relativity can be tested. This is also true for AGN, but the changes in the accretion process are harder to follow around supermassive BHs, as they happen on $10^5 - 10^8$ much longer time-scales than for stellar-mass accretors. Stellar mass objects make it possible to study variable accretion phenomena on timescales of years or shorter, compatible with the duration of the human life.
An interesting phenomenon associated with the accretion process is also the production of jets, which are collimated outflows of accelerated particles typically detected at radio wavelengths due to synchrotron radiation (see, e.g., Gallo 2010). Accreting BHs can accelerate particles up to a large fraction of the speed of light, and several BH XRBs are known whose jets appear superluminal (e.g., GX 1915+105, Mirabel & Rodríguez 1994 in Figure 1.2 and GRO J1655-40, Hjellming & Rupen 1995). Jets and outflows powered by AGN in external galaxies are thought to have an important effect in regulating the evolution of cosmic structures, because of the large amount of energy they pump into their surrounding. XRBs with both BHs and NSs and the subclass of CVs called Dwarf Novae (DNe) are known sources of powerful jets on a smaller scale, once again providing favoured laboratories to increase our knowledge about the jet production mechanism because of the shorter time-scales. At the same time, a systematic comparison between outflows produced by NS, BH and WD systems can potentially reveal a connection between the jet features and characterising properties of the different classes of compact objects, such as the presence (or lack) of an event horizon.

Another reason of interest in XRBs is that they offer the possibility to measure the mass of NSs and BHs based on dynamical arguments, with minimal dependence on modelling. Accurate measurements of compact object masses serve multiple scientific goals: the equation of state of NSs, e.g., is still not known, and the maximum mass of a NS is a key parameter to distinguish among different models. NSs in XRBs are particularly favourable targets for this measurement, as accretion increases their mass. The minimum mass of a BH is also a matter of debate as it has implications for the modelling of supernova explosions. The dynamical measurement of compact object masses
Figure 1.2: Radio jets from the BH XRB IGR J1915+105, from Mirabel & Rodriguez (1994). The cross indicates the core of the XRB, the radio contours are the moving superluminal jets, the first ones discovered from an XRB.

(in particular of NSs) is the main topic of this work.

Finally, the formation and evolution of XRBs and CVs is complex and not fully understood. In order to explain the orbital separation in close binaries, e.g., models require a phase of common envelope evolution when the accretor spirals in the mantle of its giant companion star. However, the details of the process are not well constrained (see Tauris & van den Heuvel 2006 for a review). Reliable and model independent measurements of parameters such as component masses, but also the orbital period, companion star type, age and system velocity on individual XRBs are important for testing our understanding of their evolution, because any viable evolutionary scheme must be able to reproduce the specific properties of each observed source. Moreover, each measurement on a single source contributes to the distribution of parameters such as components masses and orbital period for the XRBs and CVs
populations.

1.2 Accretion discs and Roche geometry

Without aiming for completeness, in this section I want to summarise some of the basic information on the geometry of an accreting system that underlie this study. A binary with a compact object becomes an active XRB when, at a certain point in its evolution, mass is transferred from the companion onto the primary star. This can happen in two main ways: some of the mass lost from the secondary via strong stellar winds can be captured by the compact object (wind accretion), or the envelope of the mass donor star reaches the inner Lagrangian point (L1) of the system, a saddle in the binary gravitational potential through which material can flow into the potential well of the accretor. This manner of accretion is called Roche lobe overflow, and the two lobes defined by the equipotential surface passing through L1, one around each object in the system, are called Roche lobes (Figure 1.3). In this work we will focus on Roche-lobe accreting XRBs, as their geometry allows one to determine the mass and the orbital velocity of both the accretor and the donor from the observation of the secondary star only. In these systems, tidal forces induce the secondary star to co-rotate with the orbital motion (the companion is tidally locked). On a similar timescale the orbits circularise, simplifying the equations of motion of the two stars around the centre of mass. Moreover, the radius of the companion star becomes the radius of the Roche lobe (defined as the radius of a sphere whose volume is equal to that of the Roche lobe), which depends on the ratio $q$ between the mass of the accretor and that of the donor. Thanks to this dependence (and because the companion is tidally locked), in Roche lobe filling systems $q$ can be inferred as a function of directly measurable quantities, such as the rotational and orbital velocity of the companion (see Section 1.5).

Because of angular momentum conservation, the flow of material spiralling towards the compact object takes the shape of a geometrically thin accretion disc, which is in differential rotation around the accretor (Figure 1.1). The accretion disc can extend to the vicinity of the compact object (i.e., reaching the last stable orbit for a BH) and radiates across a large fraction of the electromagnetic spectrum, from the X–rays in the innermost region to the optical and near infra-red (NIR) wavelengths in the outskirts. A hot-spot due to shocks can form in the region where the stream of accreting material from L1 impacts the edge of the accretion disc. Depending on system parameters such as the orbital separation, the mass ratio between the binary components, the presence of a magnetic field from the accretor, the composition of the accreting material and the rate of mass transfer, the geometry and internal properties
1.3 Outburst and quiescence

A fundamental parameter that drives accretion is the accretion rate $\dot{m}$, i.e. the rate of matter captured by the primary star per unit of time. Depending on $\dot{m}$, the luminosity of an XRB can vary in the typical range $10^{31-39}\text{erg s}^{-1}$ and that of a CV in the range $10^{30-34}\text{erg s}^{-1}$. Many XRBs (the majority of BH systems, many NS XRBs and DNe) show transient behaviour within this range, with changes of several orders of magnitude in luminosity occurring on timescales of days to months. Transient sources (X-ray transients, XRTs) alternate periods of outburst, when accretion happens at a high rate and reach the highest X-ray luminosity (up to the Eddington luminosity), to periods of quiescence, when of the disc vary. Differences can be observed among different classes of XRBs but also as a consequence of various accretion regimes in the same system. The disc can be more or less extended, it can be optically thin or thick and its shape can deviate from the standard geometrically thin scenario due to tidal interactions, reprocessing of radiation or general relativity effects (see Hynes 2012 for a review). In the presence of highly magnetic NSs or WDs, accretion can also proceed mainly along the magnetic field lines, instead of forming a disc. However, in most XRBs evidence is found for the presence of an accretion disc. Because of its broad-band emission, the potential presence of a disc has always to be considered when observing XRBs, even when accreting at a low rate.

Figure 1.3: Equipotential lines in the gravitational potential of a binary system. The black curve passing through the inner Lagrangian point $L_1$ defines the Roche lobes of the two binary component masses. Units are arbitrary.
they are thought to be roughly stable around $10^{30} - 10^{32}$ erg s$^{-1}$, often falling below the detection threshold of the X-ray all-sky monitors. The typical duration of the outburst phase is several months, but there are sources which have been in outburst for over 10 years (e.g., the BH XRB GX 1915+105 or the NS system EXO 0748−676). The month-to-year-long outbursts are usually explained by the so-called disc-instability model (Smak 1971, Dubus et al. 2001). According to this model, the outburst is triggered by an instability causing a sudden rise of viscosity in the accretion disc, whose internal regions subsequently rapidly fall towards the accretor. During quiescence, the disc is replenished until another instability is triggered. The trigger of tens of years long outburst, instead, is possibly related to the evolution of the companion star (Remillard & McClintock, 2006a).

Because of its brightness, the phase of outburst is the best studied part of the XRBs behaviour. In the last two decades tens of XRTs have been monitored, mostly with X-rays satellites such as Swift and RXTE but also at longer wavelengths, allowing the development of a detailed phenomenological picture of the outburst evolution. XRTs have been found to evolve through a series of accretion states, originally defined on the basis of the observed X-ray properties, such as the X-ray spectrum and by the presence of specific modulations in the arrival times of the X-ray photons. Later on, the radio emission from XRBs was found to vary as well in combination with the X-ray states (Figure 1.4 and Belloni 2010 for a review). The radio and X-ray emission are known to correlate over a large span of luminosities for many XRBs. This connection seems to be crucial in order for us to start understanding the energetics of the accretion process (Fender 2010 for a review).

While many outbursts have been observed, quiescence is an ill studied piece in the current picture of the XRBs behaviour, due to the observational challenge presented by its faintness at all wavelengths. However, exploring the low luminosity states can provide new guidelines to theoretical models. For example, recent results on the evolution of the X-ray-radio correlation towards quiescence might shed light on open questions raised by observations at higher luminosity. A more detailed description of this aspect is reported in Chapter 6, dedicated to the BH XRT XTE J1752−226 during its luminosity decay towards quiescence.

### 1.4 Observing the companion star: optical counterparts

The observation of the secondary star is often crucial in order to perform dynamical studies and mass measurements on XRBs, as those studies rely on the detection of spectral absorption lines from the stellar atmosphere of
Figure 1.4: Hardness intensity diagrams (HID) for a black hole, a neutron star and the dwarf nova SS Cyg (Körding et al., 2008). The hardness is the ratio between the flux in two energy bands, and serves as an indicator of the shape of the spectrum. Arrows indicate the temporal evolution of an outburst. The dotted line indicates the jet line observed in black hole and neutron star XRBs: on its right side XRBs are generally radio loud, while on its left they are radio quiet. The crossing of this line from right to left usually coincides with a radio flare. For SS Cyg the optical flux is plotted against the ‘power-law fraction’, measuring the prominence of the power law component in the hard X-ray emission in relation to the boundary layer/accretion disk luminosity. This power-law fraction has similar properties to the X-ray hardness used for XRBs.
the mass donor (see section 1.5). However, there are other reasons why it is important to observe the secondary star in an XRB.

Although X-rays are the most direct source of information on the accretion process and most of the sources are discovered in this band, the study of XRBs is multi-wavelength in nature. Optical or NIR observations constraining the luminosity class and spectral type of the secondary star are important for understanding the XRBs population, as the type of mass donor is connected to the mode of accretion. The donor mass, e.g., provides the primary division between low-mass XRBs (LMXBs), mainly accreting via Roche lobe overflow, and high-mass XRBs (HMXBs), mostly wind-fed, but which can also accrete via Roche lobe overflow or from interaction with a circumstellar disc (e.g., Tauris & van den Heuvel 2006 or Hynes et al. 2011 for a review).

LMXBs have companions of $\lesssim 1 M_\odot$ and spectral type G, K or M, close to the main sequence (secondary stars in LMXBs are typically slightly undermassive for their spectral type) for most of the sources. Since the bright XRB phase requires the late companion to fill its Roche lobe, LMXBs are typically compact systems with orbital periods of $\lesssim 1$ day, where tidal forces soon produce synchronous rotation and circularised orbits. HMXBs have instead O or B type companions above $\sim 10 M_\odot$. The strong winds from the mass donor allow accretion with long orbital periods -up to hundreds of days- where the eccentricity of the orbit can be maintained much longer (see, e.g., Kaper 2001 for a review on HMXBs). The eccentricity and the presence of a circumstellar disc around the Be secondary star cause, for instance, the periodic outbursts of the Be-HMXBs. In close HMXBs (orbital period of a few days) Roche lobe accretion combines with the presence of wind: the density and properties of the latter are invoked to explain the short outbursts and the high local hydrogen density observed in the HMXBs subclasses of supergiant fast X-ray transients and absorbed HMXBs (Negueruela et al. 2006, Walter et al. 2006). Another example of the connection between the nature of the donor and the type of accretion are ultra-compact X-ray binaries, a subclass of LMXBs with a hydrogen poor WD donor. The composition of the donor star produces characteristic features in the X-ray spectra and enables these sources to be persistent at a low luminosity compared to other LMXBs (for an overview of the XRBs classes, see also the introduction to Chapter 2 and references therein).

Intermediate-mass XRBs, with donor star masses intermediate between HMXBs and LMXBs, are rarely observed especially among CVs and NS systems. The mass ratio between the donor and the accretor, in fact, can cause the accretion phase to be short-lived (see introduction to Chapter 5) biasing observations towards LMXBs and HMXBs.

Observations of the companion star can also provide constraints on the distance to an XRB, which may be used to estimate the X-ray luminosity,
1.4 Observing the companion star: optical counterparts

Figure 1.5: Finding charts for one of the sources in Chapter 2, which was detected by \textit{INTEGRAL}, XMM-\textit{Newton} and \textit{Chandra}, exemplifying the different levels of positional accuracy of the three satellites (the 90\% confidence radius is 2', 4'' and 0.6'' for the three satellites respectively). \textit{Chandra} is clearly favoured in order to select the right optical counterpart to the X–ray source.

determine the activity state of the source and obtain indications about the orbital period and the type of accretor (e.g., Chapter 2 and 6).

Although important, the observation of the companion star is often not easy. First of all, the counterpart to the XRB has to be identified in the optical or NIR, by matching an image of the source field at those wavelengths with the X–ray position. As previously mentioned, since the discovery of the first XRB (Sco X–1 in 1962) a few hundred additional sources have been found thanks to X–ray satellites, in particular with recent missions such as \textit{BeppoSAX}, \textit{RXTE}, \textit{Swift}, \textit{INTEGRAL}, XMM-\textit{Newton} and more recently \textit{MAXI}. CVs are often discovered as optical transients or as H\textalpha emitters, in surveys like the Catalina real-time transient survey (CRTS), the INT/WFC photometric H\textalpha survey of the northern Galactic Plane or the Sloan Digital Sky Survey (SDSS). However, many of them are also discovered as faint X–ray sources. Unfortunately the positional accuracy of the X–ray satellites is usually worse than a few arc seconds, which is in general not good enough to unambiguously identify an optical counterpart (Figure 1.5). Since LMXBs are often located in high stellar density regions of the Galaxy, multiple stars can fall in an error circle of few arcseconds radius. Observations with the \textit{Chandra} satellite,
providing the best positional accuracy among the X-ray observatories (0.6 arcseconds, 90% confidence) are often required to select the actual counterpart to an XRB, combined with careful astrometry (referring the frames to the same astrometric standard frame) on the optical images. The process of finding the optical/NIR counterpart to an X-ray source is exemplified in Chapter 2, for a sample of 11 targets.

Once the optical counterpart is determined, observations can be performed in order to study the secondary star and the system dynamics. However, the accretion disc during the outburst phase can easily outshine the companion star all the way up to the NIR, unless the latter is a giant or supergiant star. Only towards quiescence, when the accretion flow is reduced, can late type secondaries become observable. Still, for many LMXBs the companion can be too faint to study even during quiescence. At a typical XRB distance of $\sim 8$ kpc, the apparent magnitude of a late K or M star can easily be more than 22 magnitudes, requiring long observations with large telescopes in order to be detected and to collect enough S/N for spectroscopic observations. For many of the known XRBs, an optical or NIR counterpart in quiescence was never detected.

1.4.1 Optical spectra of LMXBs and CVs

The optical and NIR spectra of XRBs in outburst are dominated by the accretion disc, whose characteristic features are emission lines in the Balmer series and from Helium. Emission lines from the disc often display a double-peaked profile, due to opposite Doppler shift of the emission from the two sides of the disc, one rotating away and one towards the observer. In quiescence, absorption lines from the companion star stellar atmosphere can become detectable above the disc continuum. Residual emission from hydrogen and helium I is often detected in quiescence as well. This can originate from different sources, e.g. coronal activity on the companion itself, a faint accretion disc, a disc hot-spot or the inner face of the companion star, heated by X-ray or UV irradiation from residual accretion or from a hot compact object. Direct emission from the accreting WD is sometimes visible in CVs. Systems with a highly magnetised accretor also display typical lines such as prominent HeII (Williams 1989, Schwarz et al. 2004). Several examples of spectra from XRBs at low luminosities are shown in the Chapters 3, 4 and 5 of this thesis.

1.5 Dynamical mass measurements

As previously mentioned, accurate and model independent measurements of masses of BHs and NSs are difficult to obtain, but fundamental to solve outstanding scientific questions related to their formation and nature. Several
authors attempted to infer constraints on the masses from the modelling of XRBs X–ray spectra or variability features such as quasi periodic oscillations, but these methods are strongly model dependent and often based on uncertain assumptions.

Reliable methods for mass estimates are, instead, those based on the Keplerian binary dynamics. The basic idea is to track the orbital motion of at least one of the objects in the binary, measuring the orbital period $P$, the projected radial velocity semi-amplitude $K_2$ of the observed star and thereby its mass function

$$f(M_2) : \frac{M_1^3 \sin^3 i}{(M_2+M_1)^2} = M_1 \frac{\sin^3 i}{(1+q)^2} = \frac{PK_2^3}{2\pi G}$$

where $G$ is the universal constant of gravity, $M_1$ and $M_2$ are the masses of the binary components, $q \equiv M_2/M_1$ and $i$ is the inclination of the orbital plane with respect to the line of sight (e.g. Charles & Coe 2006a). With a few exceptions (double pulsars and a few HMXBs) $f(M)$ is measurable only for one of the stars in the binary (typically either a pulsar or the companion star) and needs to be combined with further relations containing $q$ and $i$ (or direct measurements of the latter, see below) in order to solve for all the unknowns.

The best NS mass measurements can be achieved in systems hosting a pulsar in an eccentric orbit. Accurate pulse-timing in the radio allows one to measure relativistic effects providing the extra equations necessary to solve for the masses of the binary components. However, this method has some disadvantages in the context of finding the distribution and the maximum mass of NSs. The largest mass for a NS is expected to be found in a system which experienced significant accretion, namely among millisecond pulsars - that are thought to be spun up by accretion- and NSs in LMXBs. Unfortunately, the orbits are typically circularised in those systems, while the relativistic effects that permit precise mass measurement are not measurable when the eccentricity of the orbit is low. Moreover, a selection effect against NSs whose mass was increased to extreme values by accretion is introduced when observing millisecond pulsars, because prolonged accretion seems to reduce the magnetic field and prevent pulsations to appear (see, e.g., Phinney & Kulkarni 1994 and van Kerkwijk 2004 for a review).

Still, the groundbreaking discovery of a NS with a mass of $\sim 2M_{\odot}$ was recently achieved for the millisecond pulsar J1614-2230, with radio pulse-timing observations of the Shapiro delay (Demorest et al., 2010). This effect depends on inclination and mass and can be observed in high inclination binaries (nearly edge on) when the pulsar passes behind the companion star. In this configuration, the increase in the light travel time of the pulse photons passing through the curved space-time around the companion star on its way towards the observer can be measured, as a delay in the arrival time of the pulse signal (that is the Shapiro delay). It is possible that the mass of this NS was already high...
at formation, and not increased to this extreme value by accretion only.

In non-pulsating XRBs the potentially observable mass function is that of the companion star. The mass ratio $q$ can be obtained if the secondary star is Roche-lobe filling. As mentioned in Section 1.2, under this condition $q$ can be expressed as a function of the two observable quantities $K$ and $v \sin i$, where the latter is the projected rotational velocity of the companion star (see the introduction to Chapter 3 for a more detailed description of the method). Both $K$ and $v \sin i$ can be measured through phase-resolved spectroscopic observation of the secondary star in the optical or NIR, provided that absorption lines from its stellar atmosphere are detected. In eclipsing systems, where the inclination can be inferred based on geometrical arguments only, this provides virtually model independent mass measurements for both NSs and BHs, with no mass biases. Because they are Roche lobe accreting and because estimates of $i$ from the eclipses duration are more accurate when the radius of the secondary is small compared to the orbital separation, the best candidates for dynamical studies are in general LMXBs. However, as mentioned in the previous section, the faintness of the companion star presents an observational challenge. On top of the fact that they host faint, late-type mass donors, LMXBs often have short orbital periods of a few hours, so that the exposure time for phase-resolved observations is limited by the smearing of the spectral features during to orbital motion. An example of this observational difficulty is provided in Chapter 3, where we had to work with very low S/N spectra despite the use of the Very Large Telescope (VLT).

When eclipses are not detected, the inclination becomes the first source of uncertainty on the masses. A method that, in principle, can provide good constraints on the inclination is the modelling of the orbital variation of the brightness of the companion star, due to the fact that the latter is Roche lobe filling. This causes a deformation of the shape of the mass donor with respect to a sphere, with the consequence that the area of the star that is towards the observer varies with the orbital phase. The modulation of the light from the secondary star due to this effect is called ellipsoidal modulation, and the observed amplitude of this modulation depends on the system inclination. Measuring this effect requires accurate phase-resolved photometry as the variation in luminosity can be as low as a tenth of a magnitude. We applied this technique in Chapters 4 and 5, to bright nearby systems in quiescence. However, as also shown by our results, the modelling of ellipsoidal variation becomes uncertain if the optical light is contaminated by the presence of a residual accretion disc. For this reason, eclipsing systems remain the best targets for dynamical mass measurements in non pulsating XRBs.
In conclusion of this section, it is worth to mention another recent development in the field of dynamical measurement of compact object masses regarding BH binaries. Doppler shifted absorption lines have been found in the X–ray spectra of the BH XRB GRO J1655−40 (Zhang et al., 2012), showing sinusoidal variations consistent with the orbital motion of the accretor. The lines are thought to originate in a disc outflow which absorbs the X–rays in its denser region around the BH. If the applicability of this method will be confirmed by observing different sources, this technique combined with observations of the companion star could provide a way to solve the binary dynamics without knowing the inclination, since the mass function for both the companion and the compact object would be known.

1.6 Synopsis of this thesis

The goal that drove this work is to constrain the NS equation of state via the detection of massive NSs. Chapter 2 is dedicated to the first step needed to achieve this goal, which is finding XRB candidates with a detectable optical counterpart. The Chapter also shows how the properties of the optical counterpart combined with basic X–ray information can be used to classify X–ray sources and determine the nature of the compact object.

Chapters 3, 4 and 5 present dynamical studies of XRBs whose optical counterparts were identified in quiescence. The LMXB analysed in Chapter 3, EXO 0748−676, is in principle the ideal source for the purpose of measuring the mass of potentially massive NSs. It is showing surface phenomena (thermonuclear bursts) that unambiguously identify the accretor as a NS, it is an eclipsing system and it turned into quiescence one year before our observations, after a 24-years-long outburst. On the other hand, the sources studied in Chapter 4 and 5, CXOGBS J174444.7−260330 and IGR J19308+0530 (which is one of the sources identified in Chapter 2) respectively, are both low-accretion rate systems that never showed an outburst. They were both targeted as potential NS XRBs, CXOGBS J174444.7−260330 based on the equivalent width of the Balmer emission lines detected in a single preliminary optical spectrum, and IGR J19308+0530 based on the X–ray spectrum and the common wisdom that the mass ratio in Roche lobe overflow systems should be less that ~1. Both systems are not eclipsing, but have bright optical counterparts suitable for ellipsoidal modulation modelling. Both were found to host (most likely) a WD accretor.

The dynamical study of the above three systems, apparently very favourable for dynamical mass measurements, opened a window on three different low-accretion rate configurations, providing insights in the behaviour and activity of XRBs at low luminosities. Those studies showed that the quiescent state is
more complex than expected. Nevertheless, constraints on the orbital parameters and masses in all three systems were derived.

The last Chapter of this thesis is about the candidate BH XRB XTE J1752−226. Our multi-wavelength (optical, X–ray and radio) campaign focussed on the last stage of an outburst, following the source in its return back to quiescence.
Chapter 2

*Chandra* localisation and optical/NIR follow-up of Galactic X-ray sources

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Abstract

We investigate a sample of eleven Galactic X-ray sources recently discovered with *INTEGRAL* or *RXTE* with the goal of identifying their optical and/or near-infrared (NIR) counterpart. For this purpose new *Chandra* positions of nine objects are presented together with follow-up observations of all the targets in the optical and NIR. For the four sources IGR J16194−2810, IGR J16479−4514, IGR J16500−3307 and IGR J19308+0530, the *Chandra* position confirms an existing association with an optical/NIR object, while for two sources (XTE J1716−389 and IGR J18490−0000) it rules out previously
proposed counterparts indicating new ones. In the case of IGR J17597–220, a counterpart is selected out of the several possibilities proposed in the literature and we present the first association with an optical/NIR source for IGR J16293–4603 and XTE J1743–363. Moreover, optical/NIR observations are reported for XTE J1710–281 and IGR J17254–3257: we investigate the counterpart to the X-ray sources based on their XMM-\textit{Newton} positions. We discuss the nature of each system considering its optical/NIR and X-ray properties.

2.1 Introduction

X-ray binaries (XRBs) are binary systems where a compact object, either a black hole (BH), a neutron star (NS) or a white dwarf (WD) accretes matter from a stellar companion (the donor or secondary star). In case the compact object is a WD, the XRB is called a cataclysmic variable (CV). In these systems, gravitational potential energy is extracted from the matter falling onto the compact object via the accretion process, producing the observed X-ray luminosity. XRBs represent a large fraction of X-ray sources in our Galaxy (see Psaltis 2006 for a review). The majority of XRBs accreting onto a NS or BH can be grouped in two classes, defined by the mass of the secondary star: high mass X-ray binaries (HMXBs) and low mass X-ray binaries (LMXBs). In HMXBs the mass of the donor is \( M_D \gtrsim 10 \, M_\odot \); in LMXBs \( M_D \lesssim 1 \, M_\odot \). A few intermediate mass XRBs (IMXBs) are also known (see Charles & Coe (2006b) for a review).

HMXBs are further divided into Be-XRBs and supergiant X-ray binaries (SXRBs). Be-XRBs are characterized by a Be-star companion and typically have eccentric orbits: the compact object accretes in major outbursts near the periastron, when it passes through the circumstellar disk of the Be-star. On the other hand, SXRBs host an early type O/B supergiant companion and are 'traditionally' found to be persistent X-ray sources. However, recent observations by the International Gamma-ray Astrophysics Laboratory (\textit{INTEGRAL}) have revealed a class of fast X-ray transient sources spending most of their time at a quiescent level, that have sporadic outbursts lasting a few minutes to hours. The class was named "supergiant fast X-ray transients" after follow-up optical and near-infrared (NIR) spectroscopic observations of a number of systems revealed supergiant secondary stars (Negueruela et al., 2006). The physical origin of the fast X-ray outbursts is not yet understood (for different models see in’t Zand 2005, Sidoli et al. 2007, Bozzo et al. 2008, Ducci et al. 2010). The \textit{INTEGRAL} satellite also discovered a population of XRBs characterized by a large amount of absorption local to the source (Lutovinov et al., 2005) as the accreting compact object is immersed in the dense...
Table 2.1: *Chandra* observations. Source counts and positions are given in the table. The positional uncertainty is 0.6 arcsec on all the positions (see Section 2.2).

<table>
<thead>
<tr>
<th>Source</th>
<th>Date</th>
<th>Instrument</th>
<th>Exposure time (s)</th>
<th>Counts</th>
<th>RA(J2000)</th>
<th>Dec.(J2000)</th>
<th>WAVDETECT error on RA, Dec.(arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGR J16194−2810</td>
<td>2008 Jan. 18</td>
<td><em>HRC-I</em></td>
<td>1129</td>
<td>1075</td>
<td>16$^h$ 19$^m$ 33$^{s}$30</td>
<td>−28$^\circ$ 07′ 40″30</td>
<td>0.018, 0.014</td>
</tr>
<tr>
<td>IGR J16293−4603</td>
<td>2008 Jan. 24</td>
<td><em>ACIS-I</em></td>
<td>1135</td>
<td>237</td>
<td>16$^h$ 29$^m$ 12$^{s}$86</td>
<td>−46$^\circ$ 02′ 50″94</td>
<td>0.072, 0.068</td>
</tr>
<tr>
<td>IGR J16479−4514</td>
<td>2007 Oct. 24</td>
<td><em>HRC-I</em></td>
<td>1174</td>
<td>44</td>
<td>16$^h$ 48$^m$ 06$^{s}$58</td>
<td>−45$^\circ$ 12′ 06″74</td>
<td>0.061, 0.061</td>
</tr>
<tr>
<td>IGR J16500−3307</td>
<td>2007 Sep. 29</td>
<td><em>HRC-I</em></td>
<td>1150</td>
<td>198</td>
<td>16$^h$ 49$^m$ 55$^{s}$65</td>
<td>−33$^\circ$ 07′ 02″28</td>
<td>0.032, 0.029</td>
</tr>
<tr>
<td>XTE J1716−389</td>
<td>2008 Sep. 23</td>
<td><em>ACIS-I</em></td>
<td>1141</td>
<td>12</td>
<td>17$^h$ 15$^m$ 56$^{s}$42</td>
<td>−38$^\circ$ 51′ 54″13</td>
<td>0.227, 0.256</td>
</tr>
<tr>
<td>XTE J1743−363</td>
<td>2009 Feb. 08</td>
<td><em>HRC-I</em></td>
<td>1172</td>
<td>11</td>
<td>17$^h$ 43$^m$ 01$^{s}$31</td>
<td>−36$^\circ$ 22′ 22″00</td>
<td>0.14, 0.043</td>
</tr>
<tr>
<td>IGR J17597−220</td>
<td>2007 Oct. 23</td>
<td><em>HRC-I</em></td>
<td>1180</td>
<td>227</td>
<td>17$^h$ 59$^m$ 45$^{s}$52</td>
<td>−22$^\circ$ 01′ 39″17</td>
<td>0.022, 0.022</td>
</tr>
<tr>
<td>IGR J18490−0000</td>
<td>2008 Feb. 16</td>
<td><em>HRC-I</em></td>
<td>1174</td>
<td>22</td>
<td>18$^h$ 49$^m$ 01$^{s}$59</td>
<td>−00$^\circ$ 01′ 17″73</td>
<td>0.0432, 0.061</td>
</tr>
<tr>
<td>IGR J19308+0530</td>
<td>2007 Jul. 30</td>
<td><em>HRC-I</em></td>
<td>1129</td>
<td>26</td>
<td>19$^h$ 30$^m$ 50$^{s}$77</td>
<td>+05° 30′ 58″09</td>
<td>0.061, 0.072</td>
</tr>
</tbody>
</table>
stellar wind of a massive companion star. The NIR counterparts identified for a number of sources are all consistent with supergiant stars. It has been suggested that all the obscured HMXBs are hosting supergiant companions (Walter et al., 2006).

LMXBs are traditionally divided into NS and BH binaries. Surface phenomena occurring on the accreting object, like thermonuclear X-ray bursts or the detection of a pulsating signal are evidence for the presence of a NS. Nevertheless, in the absence of such phenomena no definitive conclusion can be drawn about the nature of the compact object from X-ray observations alone (see Psaltis 2006 for a review). Dynamical constraints on the mass of the compact object are required in order to confidently distinguish a NS from a BH. These can be obtained via orbital phase-resolved spectroscopy of the optical or NIR counterpart to the X-ray source (van Paradijs & McClintock, 1995a).

Two sub-classes of LMXBs also exist that are characterised by peculiar companion stars: ultra compact X-ray binaries (UCXBs) and symbiotic X-ray binaries (SyXBs). The signature of UCXBs is an orbital period of $\sim 1$ hour or less. This implies that the orbital separation is very small and the donor must be hydrogen poor to fit in its Roche lobe (in’t Zand et al., 2007). SyXBs are defined by the presence of an M-type giant companion. Those systems are rare, as the giant phase does not last long, and are characterised by a lack of accretion signatures in the optical spectra, since the accretion disk is out-shined by the companion star unless the X-ray luminosity is particularly high (Masetti et al. 2007 and references therein).

Since the classification is based on the mass of the companion and/or of the compact object, the identification of counterparts of XRBs in optical or NIR is important. In this article we present a search for the optical/NIR counterpart of a sample of 11 Galactic sources, recently discovered with INTEGRAL or with the Rossi X-ray Timing Explorer (RXTE). A classification has been proposed in the literature for all but one of the sources (IGR J16293-4603) on the basis of the X-ray behaviour alone or the spectrum of an optical/NIR candidate counterpart. Nevertheless, none of the proposed counterpart identi-

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Table 2.2: Known X-ray positions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>XTE J1710–281</td>
<td>$17^h10^m13^s$</td>
<td>$-28^\circ07'51''$</td>
<td>$1''$</td>
<td>XMM-Newton $^a$</td>
</tr>
<tr>
<td>IGR J17254–3257</td>
<td>$17^h25^m25^s$</td>
<td>$-32^\circ57'15''$</td>
<td>$2''$</td>
<td>XMM-Newton $^b$</td>
</tr>
</tbody>
</table>

fications are conclusive due to the lack of an accurate X-ray position. For the 9 sources listed in Table 2.1 we obtained Chandra observations, with the main goal of determining an accurate X-ray position. Thanks to the high spatial resolution of Chandra we could verify previously proposed candidate counterparts and investigate sources for which no counterpart was known. For the two sources listed in Table 2.2 we do not have Chandra data. We have searched for their optical/NIR counterparts referring to previous XMM-Newton observations.

This paper is structured as follows: sections 2 and 3 present the observations and the data reduction procedures. In section 4 we provide a short introduction for each source followed by the results from our analysis. All the coordinates reported in the text and tables are referred to epoch J2000.

2.2 X-ray data: reduction and analysis

We observed the sources in Table 2.1 with Chandra, using the High Resolution Camera (HRC-I) and the Advanced CCD Imaging Spectrometer (ACIS-I). We have reprocessed and analysed the data using the CIAO 4.0.1 software developed by the Chandra X-ray Centre. All data have been used in our analysis, as background flaring is very weak or absent.

We localized X-ray sources on each observation with the tool WAVDETECT from the total energy range of HRC-I and ACIS-I. The uncertainty on the localization on the image as given by WAVDETECT (Table 2.1) is negligible with respect to the Chandra boresight uncertainty of 0.6 arcsec (90 per cent confidence, slightly dependent on the instrument\textsuperscript{1}) for all the sources but the weakest, XTE J1716–389 and XTE J1743–363. Although the centroiding uncertainty for those targets is of the same order of magnitude as the boresight uncertainty, the latter still dominates the overall X-ray positional accuracy. Therefore we adopt a 90 per cent confidence uncertainty of 0.6 arcsec on the X-ray position of all the sources. We extracted the source counts in a 40-pixel radius around the position from WAVDETECT using the tool DMEXTRACT. We estimated the background in an annulus centered on the WAVDETECT position, with an inner and outer radius of 70 and 200 pixels. We considered all the counts from HRC, while we select the counts in the 0.3 – 7 keV energy band for ACIS observations. The net, background subtracted counts for each source are given in Table 2.1.
Table 2.3: Properties of the instruments employed for optical/NIR observations.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Pixel scale (arcsec)</th>
<th>Binning</th>
<th>Field of view (arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMMI</td>
<td>0.166</td>
<td>2×2</td>
<td>9.1×9.9</td>
</tr>
<tr>
<td>IMACS</td>
<td>0.111</td>
<td>2×2</td>
<td>15.4×15.4</td>
</tr>
<tr>
<td>LDSS3</td>
<td>0.189</td>
<td>1×1</td>
<td>Diameter=8.3</td>
</tr>
<tr>
<td>MOSAIC</td>
<td>0.27</td>
<td>1×1</td>
<td>36×36</td>
</tr>
<tr>
<td>PANIC</td>
<td>0.127</td>
<td>1×1</td>
<td>2×2</td>
</tr>
</tbody>
</table>

2.3 Optical and NIR data: reduction and analysis

We performed optical and/or NIR imaging of the field of each X-ray source in our sample from various Chilean sites, with the following instruments:

- the ESO Multi Mode Instrument (*EMMI*) at the 3.5 m New Technology Telescope on La Silla

- the Low Dispersion Survey Spectrograph (*LDSS3*), the Persson’s Auxiliary Nasmyth Infrared Camera (*PANIC*) and the Inamori Magellan Areal Camera and Spectrograph (*IMACS*) at the 6.5 m Magellan telescopes Clay and Baade on Las Campanas

- the *MOSAIC II* imager at the 4 m Blanco telescope on Cerro Tololo.

Table 2.3 reports the pixel scale and the field of view (FOV) of each instrument, together with the binning we employed. A journal of the observations is presented in Table 6.1. All optical observations include a short (10-15 s) exposure image for the astrometry, where bright stars do not saturate, and several deeper exposures to observe faint objects. We observed four of the sources in the $K_s$ band using the PANIC camera. The observations consisted of five point dither patterns with a 5s or 15s exposure repeated three times at each offset position. Table 6.1 gives the total time expended on source.

Optical images have been reduced for photometry with standard routines running within *midas* or *IRAF*, corrected for the bias and flat-fielded. The *PANIC* NIR data were reduced through the *PANIC* software: the raw frames were first dark subtracted and flat-fielded. Normalized flat-fields were made by combining twilight flat field frames scaled by their mode. Next, a sky image was built by masking out stars from each set of dithered frames and was subtracted.

\footnote{http://cxc.harvard.edu/cal/ASPECT/celmon/}
Table 2.4: Journal of the optical/NIR observations.

<table>
<thead>
<tr>
<th>Source</th>
<th>Date</th>
<th>Instrument(s)</th>
<th>Filter(s)</th>
<th>Exposures (s)</th>
<th>Seeing (arcsec)</th>
<th>Photometric calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGR J16194−2810</td>
<td>2006 Jun. 24</td>
<td>MOSAIC II</td>
<td>r′</td>
<td>1×10+5×300</td>
<td>1.6</td>
<td>PG1323-086</td>
</tr>
<tr>
<td></td>
<td>2006 Aug. 03</td>
<td>PANIC</td>
<td>Ks</td>
<td>1×75</td>
<td>0.5</td>
<td>2MASS</td>
</tr>
<tr>
<td>IGR J16293−4603</td>
<td>2008 Jun. 24</td>
<td>LDSS3</td>
<td>g′, r′, i′</td>
<td>3×180 (r′)+1×180 (g′,i′)</td>
<td>1.1</td>
<td>SDSS(1)s82</td>
</tr>
<tr>
<td>IGR J16479−4514</td>
<td>2006 Jun. 24</td>
<td>MOSAIC II</td>
<td>i′</td>
<td>1×10+5×300</td>
<td>1.6</td>
<td>PG1323-086</td>
</tr>
<tr>
<td>IGR J16500−3307</td>
<td>2006 Jun. 24</td>
<td>MOSAIC II</td>
<td>r′</td>
<td>1×10+5×300</td>
<td>1.6</td>
<td>PG1323-086</td>
</tr>
<tr>
<td></td>
<td>2006 Aug. 03</td>
<td>PANIC</td>
<td>Ks</td>
<td>1×75</td>
<td>0.7</td>
<td>2MASS</td>
</tr>
<tr>
<td>XTE J1710−281</td>
<td>2005 May 07</td>
<td>IMACS I</td>
<td>I</td>
<td>2×10+2×300</td>
<td>0.9</td>
<td>Landolt109-954</td>
</tr>
<tr>
<td>XTE J1716−389</td>
<td>2009 May 07</td>
<td>LDSS3</td>
<td>i′</td>
<td>2×10+4×300</td>
<td>0.75</td>
<td>non-phot.(2)</td>
</tr>
<tr>
<td>IGR J17254−3257</td>
<td>2006 Aug. 03</td>
<td>PANIC</td>
<td>Ks</td>
<td>1×75</td>
<td>0.8</td>
<td>2MASS</td>
</tr>
<tr>
<td>XTE J1743−363</td>
<td>2007 Jun. 22</td>
<td>EMMI I</td>
<td>I</td>
<td>1×30+1×600</td>
<td>1.7</td>
<td>non-phot.</td>
</tr>
<tr>
<td>IGR J17597−220</td>
<td>2009 May. 07</td>
<td>LDSS3</td>
<td>i′</td>
<td>2×10+4×300</td>
<td>0.75</td>
<td>non-phot.(2)</td>
</tr>
<tr>
<td></td>
<td>2007 Jun. 22</td>
<td>EMMI I</td>
<td>I</td>
<td>1×20+2×600</td>
<td>1.7</td>
<td>non-phot.</td>
</tr>
<tr>
<td>IGR J18490−0000</td>
<td>2006 Jun. 25</td>
<td>MOSAIC II</td>
<td>i′</td>
<td>1×10+5×300</td>
<td>1.1</td>
<td>PG1323-086</td>
</tr>
<tr>
<td></td>
<td>2009 Jul. 16</td>
<td>PANIC</td>
<td>Ks</td>
<td>1×450</td>
<td>0.8</td>
<td>2MASS</td>
</tr>
<tr>
<td>IGR J19308+0530</td>
<td>2006 Jun. 22</td>
<td>MOSAIC II</td>
<td>r′</td>
<td>1×10+5×300</td>
<td>1.1</td>
<td>PG1323-086</td>
</tr>
</tbody>
</table>

(1) SDSS=Sloan Digital Sky Survey (2) see text (Section 2.3)
from the set of target frames. Finally, a mosaic image was built by combining and averaging the sky-subtracted images. The DAOPHOT II package (Stetson, 1987a), running inside MIDAS, was used to determine instrumental magnitudes through a Point Spread Function (PSF) fitting technique. The aperture correction was measured from aperture photometry on bright and isolated stars. Unless we detect the counterpart to an X-ray source only on deep images, we preferably perform photometry on the short-exposure astrometric images, which have the advantage of being less crowded than deeper ones.

The last column in Table 6.1 lists the fields employed for photometric calibration. The PANIC $K_s$-band images have been calibrated with respect to $K$ band magnitudes of 2MASS stars in the field. An accurate calibration for the LDSS3 observations of XTE J1716−389 and IGR J17597−220 is not possible since the observing night was not photometric. Nevertheless we provide indicative magnitudes by calibrating the images with the zero point from a previous LDSS3 observing run in November 2007, correcting for the different air mass.

For the astrometry, we compared the position of the stars against entries from the second USNO CCD Astrograph Catalogue (UCAC2, Zacharias et al. 2004) or from the Two Micron All Sky Survey (2MASS). The positional accuracy of UCAC2 varies between 0.02 arcsec (for stars with magnitude $R < 14$) and 0.07 arcsec ($14 < R < 16$); that of 2MASS is $\sim$0.1 arcsec (for stars with magnitude $K < 14$). UCAC2 positions were preferably adopted, unless less than 5 stars from that catalogue overlap with stars in the field. In this case we compared with the more rich but less precise 2MASS catalogue. An astrometric solution was computed by fitting for the reference point position, the scale and the position angle, considering all the stars that are not saturated and appear stellar and unblended. We obtain solutions with root-mean-square (rms) residuals ranging from 0.05 to 0.1 arcsec when 2MASS is used, and from 0.05 to 0.07 arcsec in case UCAC2 is used. The uncertainty on the position of a star due to centroiding is negligible with respect to that of the astrometry. Once astrometrically calibrated, short-exposure images have been adopted as secondary catalogues for the calibration of the longer-exposure images (see Table 6.1), obtaining rms residuals negligible with respect to those of the 'primary' solution against the standard catalogues. We adopted as the accuracy on our stellar positions the quadratic sum of the residuals of the 'primary' astrometry and the accuracy of the catalogue employed (although the latter could be a systematic error): the resulting positional accuracy is ranging from 0.07 to 0.13 arcsec ($1\sigma$) on both right ascension (RA) and declination (Dec.).

In order to identify the optical/NIR counterpart of the X-ray sources in our sample, we plotted the 90 per cent confidence error circle around Chandra or XMM-Newton positions on optical/NIR charts, taking into account the posi-
2.4 Individual sources

2.4.1 IGR J16194-2810: a SyXB

IGR J16194–2810 was discovered by INTEGRAL/IBIS (Bird et al. 2006a; Bassani et al. 2006) and soon identified as the ROSAT object 1RXS J161933.0-280736 (Stephen et al., 2006). Based on its Swift/XRT and ROSAT position, Masetti et al. (2007) associated the source with the bright object USNO-A2.0 U0600_20227091. The optical spectrum presented by the authors indicates an M2 III star, thus IGR J16194–2810 was classified as a SyXB (Masetti et al., 2007).

We observed the field with Chandra/HRC-I for ∼ 1.1 ks on 2008 Jan. 18,
detecting a single, bright source (1075 counts) inside the ROSAT and Swift error circles at RA = 16h 19m 33s 42, Dec. = −28° 07′ 40″.3. NIR and optical images, collected with Magellan/PANIC in Ks band on 2006 Aug. 3 and with Blanco/MOSAIC II in r′ band on 2006 Jun. 24, reveal a bright source overlapping with the Chandra error circle. The source is not saturated only in the 10s-long exposure with MOSAIC II shown in Figure 2.1. It falls on the border of the 90 per cent Chandra error circle, at RA = 16h 19m 33s 346, Dec. = −28° 07′ 39″.92 (±0.08 arcsec on both coordinates). Comparing our finding charts with those in Masetti et al. (2007) we identify this object with the candidate counterpart proposed by the authors. The position reported in the USNO-A2.0 catalogue from observations performed in 1979 is in agreement with our measurements if the strong proper motion of the source is taken into account (1.3 ± 4.7 mas yr−1 in RA and −20.2 ± 4.7 mas yr−1 in Dec., from UCAC2). The magnitudes of the object from USNO-A2.0 in the R and B bands is R = 11 and B = 13.2. We found the source also in UCAC2 and in 2MASS, where the following magnitude are reported: J = 8.268 ± 0.029, H = 7.333 ± 0.044 and K = 6.984 ± 0.016. We measure an apparent magnitude r′ = 10.98 ± 0.04 in r′ band. The probability that such a bright star falls by chance in the Chandra error-circle is ∼ 2 × 10−7. Based on its position and proper motion we confirm the red giant USNO-A2.0 U0600_20227091/2MASS 16193334-2807397 (first proposed by Masetti et al. 2007) as the optical and NIR counterpart to IGR J16194 −2810 and the classification of the source as a SyXB.

We investigated the high proper motion of the source by calculating its peculiar velocity, i.e. the velocity with respect to the local standard of rest. The distance d can be estimated by comparing the apparent magnitude we measure in the r′ band with the typical R-band absolute magnitude of an M2 III star (M_R ∼ −2, Cox 2000), accounting for extinction. We obtain the extinction coefficient in the R band from that in the V band following the optical extinction laws in Cardelli et al. (1989a). The standard value of the extinction-law parameter R_V for the diffuse interstellar medium is assumed (R_V = 3.1). We derived A_V from the hydrogen column density N_H in accordance with Güver & Özel (2009a). With N_H = (0.16±0.08) × 10^{22} cm^{-2} from Masetti et al. (2007), the distance is d = 3.0 ± 0.2 kpc, in agreement with the upper limit estimated by those authors. While the systemic radial velocity, γ, is unknown, we can use the measured proper motion and source distance to derive the three-dimensional space velocity components as a function of γ. Using the transformations of Johnson & Soderblom (1987a) and the standard solar motion of Dehnen & Binney (1998) we derive the space velocity components and compare with those predicted by the Galactic rotation parameters of Reid et al. (2009a) (but note McMillan & Binney 2009), obtaining the peculiar velocity as a function of γ (Figure 2.2) under the assumption that the object
2.4 Individual sources

Figure 2.2: From top to bottom, modelled Galactocentric radial velocity and circular velocity and peculiar velocity of IGR J16194−2810 against systemic radial velocity: the solid line in each case shows the best fitting values while the dotted lines show the uncertainty. The dashed lines show the expected values for Galactocentric radial and circular velocities for an object participating in the Galactic rotation. The minimum peculiar velocity is 280±66 km s$^{-1}$, corresponding to a systemic radial velocity of −35 km s$^{-1}$.

participates in the Galactic rotation. We find a minimum peculiar velocity of 280 ± 66 km s$^{-1}$, at $\gamma = -35$ km s$^{-1}$. This limit on the peculiar velocity is high, indicating that either the binary is a halo object or that it has received a kick. The latter possibility is more natural in the case of a NS/BH accretor.

2.4.2 IGR J16293-4603: a new LMXB (possibly SyXB)

The source IGR J16293−4603 was discovered in 2008 combining INTEGRAL IBIS/ISGRI data collected over the period from 2003 Mar. 2 to 2006 Feb. 24. The discovery is reported in Kuiper et al. (2008), together with a Chandra localisation and preliminary results regarding the optical counterpart of the source: in this paper we report the conclusive results of that analysis.

We observed the field of IGR J16293−4603 with Chandra/ACIS-I for ~1.1 ks on 2008 Jan. 24, detecting a single source (237 counts) inside the IBIS/ISGRI error circle, at RA= 16$^h$ 29$^m$ 12$^s$86, Dec.= −46° 02′ 50′′94.

Optical images have been acquired with Magellan/LDSS3 on 2008 Jun. 24 in the $g′$, $r′$ and $i′$ bands. An object is visible in all the observed bands inside the 90 per cent Chandra error circle (see Figure 2.3) at RA= 16$^h$ 29$^m$ 12$^s$885, Dec.= −46° 02′ 50′′55 (± 0.1 arcsec on both coordinates). After absolute photometric calibration, we measure the following magnitudes: $g′ = 23.35 \pm 0.07$, $r′ = 20.67 \pm 0.04$ and $i′ = 19.12 \pm 0.07$. In order to constrain the intrinsic
Figure 2.3: IGR J16293−4603: LDSS3, 180 s in the $i'$ band. The error circle indicates the Chandra position.

colour index $(r' - i')_0$ for the counterpart to IGR J16293−4603, we derived the extinction coefficients in the $g'$, $r'$ and $i'$ bands as we did for IGR J16194−2810, obtaining the extinction coefficient in the $V$ band, $A_V$ from the hydrogen column density $N_H$. With $N_H = (0.7 \pm 0.5) \times 10^{22}$ cm$^{-2}$, as measured in Kuiper et al. (2008) from the fitting of Chandra-ACIS spectra in the 0.3-7 keV range, we obtain $A_V = 3 \pm 2$ and $(r' - i')_0 = 0.9 \pm 0.4$. If the counterpart we observe has no flux contribution from an accretion disk, this colour index indicates a main sequence star of K or early M spectral type or a giant (Cox, 2000). If we are observing a combination of the optical light emitted by the disc and by the companion star, the latter is even redder than $(r' - i')_0 = 0.9 \pm 0.4$, since the disk is bluer than a K-type star (van Paradijs & McClintock, 1995b). Therefore, IGR J16293−4603 is most likely not a HMXB. Single stars have been observed in hard X-rays only during flares (Osten et al., 2007): the fact that IGR J16293−4603 was discovered by combining multiple INTEGRAL observations suggests that the X-rays are not due to a single active star. Thus, IGR J16293−4603 is most likely an LMXB or a CV. Moreover, Figure 2.4 shows the colour-magnitude diagram of the source field, where the apparent magnitude of the stars in $g'$ band is plotted versus the $(r' - i')$ colour index: the counterpart to IGR J16293−4603 lies on the Giant Branch of the diagram, suggesting the system has a giant companion. For $N_H \sim 0.7 \times 10^{22}$, the source has the $(r' - i')_0$ of a K5-M0 giant. This value of $N_H$ is in the middle of the range allowed by Chandra measurements and corresponds to the Galactic value from Dickey & Lockman (1990a). For extreme values of the $N_H$ within the error of INTEGRAL measurements, the companion could also be a G5-M2 giant ($N_H$ respectively lower or higher than the Galactic value). The typical absolute magnitude in $R$ band of an M2 giant is $M_R \sim -1.94$; that of a G5
Figure 2.4: Colour-magnitude diagram of the field of IGR J16293−4603, observed with LDSS3. The apparent magnitude of the stars in $g'$ band is plotted versus the $(r' - i')$ colour index. The counterpart to IGR J16293−4603 is indicated by the black star.

is $M_R \sim 0.2$ (Cox, 2000). Comparing these values with the magnitude we observe in the $r'$-band and assuming the appropriate column density in the two cases, we can estimate the distance $d$ to the source: $d \sim 28$ kpc if the donor is an M2-III type and $d \sim 45$ kpc if the donor is a G5-III type. The X-ray flux from our Chandra observations is $4 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ in the band 0.3-7 keV, assuming a simple power-law spectrum with photon index $\gamma = 1.0$ (Kuiper et al., 2008). This results in a luminosity of $\sim 4 \times 10^{35}$ erg s$^{-1}$ at 28 kpc and $\sim 2 \times 10^{36}$ erg s$^{-1}$ at 45 kpc. Intermediate luminosities and distances are obtained for a K-type companion. All the possibilities lead to an X-ray source that is too bright for a CV, but consistent with an LMXB (although in the case of a G secondary star the source would be located very far in the halo). We conclude that IGR J16293−4603 is an LMXB, probably with a giant companion of spectral type K, M or, less likely, a G. Since the donor can also be an M-type giant, we also indicate IGR J16293−4603 as a candidate SyXB.

### 2.4.3 IGR J16479-4514: an eclipsing SFXT

IGR J16479−4514 was discovered with the IBIS/ISGRI detector on board the INTEGRAL observatory on 2003 Aug. 8-9 (Molkov et al., 2003) and observed several times by the same satellite during the following years (Sguera et al. 2005; Markwardt & Krinn 2006). It has been regularly monitored with Swift from October 2007 to October 2008 (Sguera et al. 2008; Romano et al. 2008
and Romano et al. 2009) and observed with XMM-\textit{Newton} in 2008 (Bozzo et al., 2008). The X-ray behaviour of the source is typical of SFXTs, characterized by short outbursts that have been observed with both \textit{INTEGRAL} and \textit{Swift} (Kennea et al. 2005; Sguera et al. 2006; Walter & Zurita Heras 2007; Sidoli et al. 2009). Evidence of possible X-ray eclipses is presented in Bozzo et al. (2008) on the basis of XMM-\textit{Newton} observations and has been recently confirmed by Romano et al. (2009) from the analysis of \textit{Swift}/BAT data. The orbital period obtained from the eclipses is $\sim 3.3$ days, short compared to other SFXTs. Moreover, the luminosity of IGR J16479$-4514$ is $\sim 10^{34}$ erg s$^{-1}$ in quiescence. This is the typical luminosity of the fainter persistent SXRBs and two orders of magnitude higher than typical for SFXTs. This suggests that IGR J16479$-4514$ is persistently accreting at a low level, in agreement with its short orbital period. Due to its quiescent luminosity level, compatible with ‘canonical’ SXRBs, combined with the short outbursts typical of SFXTs, IGR J16479$-4514$ has been proposed as the missing link between the two classes (i.e. Jain et al. 2009).

The 2MASS star J16480656-4512068 has been proposed as a possible counterpart to IGR J16479$-4514$ by Kennea et al. (2005) and Walter et al. (2006). NIR spectra of that object are presented in Chaty et al. (2008) and Nespoli et al. (2008), indicating an O/B supergiant. This is supported by the SED in Rahoui et al. (2008). In particular, Nespoli et al. (2008) classify the source as a spectral type O9.5 Iab. A second, fainter candidate counterpart is also indicated in Chaty et al. (2008) in $K$ band, inside the 4 arcsec XMM-\textit{Newton} error circle.

In order to select the actual counterpart to IGR J16479$-4514$, we observed the field with \textit{Chandra}/HRC-I for $\sim 1.2$ ks on 2007 Oct. 24. A single source (44 counts) is detected in the XMM-\textit{Newton} error circle, at coordinates RA= $16^h 48^m 06^s 6$, Dec. = $-45^\circ 12^\prime 06^\prime\prime 7$.

Follow-up observations, performed with \textit{Blanco}/MOSAIC II in the $i'$ band on 2006 June 24, revealed no candidate counterpart inside the \textit{Chandra} 90 per cent confidence error circle, down to a limiting magnitude of $i' \sim 23$. We detect the object labelled 2 in Chaty et al. (2008) at RA= $16^h 48^m 06^s 56$, Dec. = $-45^\circ 12^\prime 08^\prime\prime 1$ (± 0.1 arcsec on both coordinates) inside the XMM-\textit{Newton} error circle but outside the \textit{Chandra} one (see Figure 2.5). We can exclude that source as a counterpart to IGR J16479-4514. We do not detect the candidate counterpart labeled 1 in Chaty et al. (2008) in $i'$ band, but this is not surprising on the basis of its NIR spectrum. In order to verify its association with IGR J16479$-4514$ we compared its coordinates from 2MASS with our \textit{Chandra} position, finding a separation of 0.2 arcsec (< 1$\sigma$). Based on its position, we confirm the object 2MASS J16480656-4512068 (indicated in Kennea et al. 2005) as the counterpart of the hard X-ray source IGR J16479$-4514$. The magnitudes from 2MASS are $J = 12.95 \pm 0.03$, $H = 10.825 \pm 0.02$. 
2.4 Individual sources

Figure 2.5: IGR J16479−4514, MOSAIC II, 300 s in the i’ band. Solid error circle: Chandra position. Dashed error circle: XMM-Newton. The arrows indicate the position of the candidate counterparts 1 and 2 in Chaty et al. (2008).

Figure 2.6: Possible \((J - H)_0\), \((H - K)_0\) combinations allowed by the 2MASS \(J\), \(H\) and \(K\) magnitudes of the sources IGR J16479−4514 (top hatched area), XTE J1716−389 (lower limit to \((J - H)_0\) indicated by the solid line and arrow) and XTE J1743−363 (bottom hatched area), for different values of the absorption \((A_V\) increasing from right to left). For comparison, the symbols indicate the couples \((J - H)_0\), \((H - K)_0\) for stars of different spectral type (O9 to M7) and luminosity class (I,III and V) (from Tokunaga 2000): dots represent main sequence stars, empty circles are red giants and stars are supergiants.
Figure 2.6 shows a comparison between the intrinsic NIR colours \((J - H)_0\) and \((H - K)_0\) of the counterpart to IGR J16479–4514 and the same colours for typical stars of luminosity class I, III and V and spectral type from O9 to M7 (from Tokunaga 2000). The intrinsic NIR colours for the counterpart are obtained from the 2MASS magnitudes for different values of \(A_V\). The comparison is constructed as follows: we assume \((H - K)_0\) as for the tabulated spectral types and calculate the \(A_V\) that is required to obtain such an intrinsic colour from the observed \((H - K)\) (\(A_V\) related to \(A_J\), \(A_H\) and \(A_K\) as for IGR J16194–2810, with the typical central wavelength of 2MASS filters from Skrutskie et al. 2006). With this \(A_V\), \((J - H)_0\) is derived from the observed \((J - H)\). We accounted for the difference in the photometric system employed by Tokunaga (2000) and the 2MASS \(J,H,K\) \(^2\). Interestingly, the possible combinations of \((J - H)_0\) and \((H - K)_0\) obtained for IGR J16479–4514 seem not to agree with the spectral classification as a O9.5 Iab. The NIR colours point instead toward a late type red giant, or a spectral type not included in the comparison such as a supergiant earlier than O9. The comparison method has been tested by obtaining the NIR colours for objects with a known spectral type: we tested all the sources classified in Nespoli et al. (2008) (IGR J16465-4507, AX J1841.0-0536, 4U 1907+09, IGR J19140+0951), with IGRJ 17544-2619 and XTEJ17391-3021 (Negueruela et al., 2006), IGRJ16207-5129 (Negueruela & Schurch, 2007), HD 306414 (Negueruela et al., 2005) and with the sources IGR J16194–2810 and IGR J19308+0530 included in this paper (see section 2.4.1 and 2.4.11). The agreement is good for all the systems but the O8 Ia type XTEJ17391-3021, which is offset by \(\sim 0.1\) mag from to the closest spectral type in our reference table, an O9 I object. The test source 4U 1907+09 has the same spectral type (O9.5 Iab) as IGR J16479–4514 and indeed its NIR colours are fully consistent with the spectral classification, while those of IGR J16479–4514 are not. This discrepancy is difficult to explain. There is no indication that the 2MASS photometry is subject to additional uncertainties and it seems unlikely that the spectra are compatible with that of a late-type giant. We conclude that the counterpart to IGR J16479–4514 is peculiar in the NIR region of the spectrum.

2.4.4 IGR J16500–3307: an Intermediate Polar

IGR J16500–3307 was discovered by INTEGRAL (Bird et al., 2006a) and has been associated with the ROSAT bright object 1 RXS J164955-330713 (Voges et al., 1999). It has been also observed by Swift (Masetti et al., 2008).

The USNO A2-0 object U0525-24170526 has been proposed as a possible optical counterpart to IGR J16500–3307 based on the X-ray position from

\(K = 9.80 \pm 0.02\).

\(^2\)following the transformations at http://www.astro.caltech.edu/jmc/2mass/v3/transformations/
2.4 Individual sources

Figure 2.7: IGR J16500−3307, PANIC, 75 s in the $K_s$ band. Solid error circle: Chandra position. Dashed error circle: Swift.

*INTEGRAL* and *Swift/XRT*. An optical spectrum of this source is presented in Masetti et al. (2008) and is compatible with IGR J16500−3307 being an intermediate polar (IP) CV. The source is included in the study of hard X-ray detected magnetic CVs by Scaringi et al. (2010).

We observed the source with Chandra for $\sim 1.2$ ks on 2007 Sept. 29, detecting a single source (198 counts) compatible with the INTEGRAL, Swift and ROSAT positions, at RA= $16^h$ 49$^m$ 55$^s$7, Dec.= $-33^\circ$ 07$'$ 02$''$3.

Follow-up observations, performed with Blanco/MOSAIC II in the $r'$ band on 2006 Jun. 24 and with Magellan/PANIC in the $K_s$ band on 2006 Aug. 3, show a bright source inside the Chandra error circle (see Figure 2.7), at RA= $16^h$ 49$^m$ 55$^s$633, Dec.= $-33^\circ$ 07$'$ 02$''$13 ($\pm$ 0.09 arcsec on both coordinates). This position corresponds to the previously proposed counterpart from Masetti et al. (2008). The star is also reported in 2MASS as 16495564-3307020, with magnitude $J = 14.409 \pm 0.039$, $H = 13.969 \pm 0.044$ and $K = 13.712 \pm 0.049$. After absolute photometric calibration, we measure a magnitude $K_s = 13.64 \pm 0.04$ with PANIC and $r' = 15.94 \pm 0.04$ with MOSAIC II. The probability that a star with that brightness falls by chance in the Chandra error circle is very low ($\sim 3 \times 10^{-7}$ in PANIC observations). Based on its position, we confirm the object USNO A2-0 U0525-24170526/2MASS 16495564-3307020 (first proposed by Masetti et al. 2008) as the counterpart of the X-ray source IGR J16500-3307.

2.4.5 XTE 1710-281: an eclipsing LMXB

XTE J1710−281 was serendipitously discovered in 1998 by RXTE/PCA and associated with the ROSAT source 1RXS J171012.3-280754 (Markwardt et al.,
The source was detected by INTEGRAL/IBIS (Revnivtsev et al., 2004) and recently by XMM-Newton (Watson et al. 2008; Younes et al. 2009). Complete X-ray eclipses and dips have been detected in the RXTE/PCA light curves, indicating an orbital period of $\sim 3.28$ hours. Thermonuclear type I X-ray bursts indicate the object is a NS and strongly suggest that the system is an LMXB (Lewin et al., 1995). The distance $d$ has been constrained from type I X-ray bursts: Markwardt et al. (2001) indicate $d = 15 - 20$ kpc, while Galloway et al. (2008) obtain $d = 12 - 16$ kpc.

XTE J1710−281 is reported in the second XMM-Newton serendipitous source catalog (Watson et al., 2008) at RA=17$^{h}$10$^{m}$12$^{s}$532, Dec.=$-28^\circ$07’50’’95, with an accuracy of 1 arcsec at 1$\sigma$ on both coordinates. Taking advantage of this recent position we performed a search for the counterpart in $I$ band, observing on 2006 Aug. 3 with Magellan/IMACS. We detect one object inside the 90 per cent confidence radius around the XMM-Newton position (see Figure 2.8) at RA= 17$^{h}$ 10$^{m}$ 12$^{s}$6, Dec. = $-28^\circ$ 07’ 51”0 (± 0.1 arcsec on both coordinates). Its magnitude in $I$ band is $I = 19.7 \pm 0.1$. The probability that this source falls by chance inside the XMM-Newton error circle is $2.3 \times 10^{-4}$. Since the distance of the source has been constrained, we can infer an upper and lower limit to the absolute magnitude $M_I$ of that candidate counterpart in $I$ band. We derive the absolute extinction coefficient in the $I$ band similarly to what we did for IGR J16293−4603 (see Section 2.4.2), assuming the $N_H$ obtained by Younes et al. (2009) from XMM-Newton spectra. Considering a distance 12 kpc < $d$ < 20 kpc (see above), the $I$ band absolute magnitude of the counterpart to XTE J1710−281 is in between $M_I \sim 3.43$ and $M_I \sim 2.32$. This is in agreement with what is expected if we are observing the disk of an high inclination LMXB (van Paradijs & McClintock, 1995a) and supports the
2.4 Individual sources

2.4.6 XTE J1716-389: an obscured HMXB system

XTE J1716–389 was discovered by RXTE between 1996 and 1997 (Remillard, 1999) and corresponds to the source KS1716-389 (Cornelisse et al., 2006) detected two years before the launch of RXTE itself by the TMM/COMIS telescope on board the Mir-Kvant module (Aleksandrovich et al., 1995). It is also reported in the EXOSAT Slew survey catalogue (Reynolds et al., 1999) as EXO J1715557.7-385 and is associated with the ROSAT source 1RXH J171556.7-385150. It has been observed with ASCA and detected in hard X-rays by INTEGRAL (Bird et al., 2006a).

Extensively monitored by RXTE, the system has shown a highly-variable persistent emission (Wen et al. 1999; Cornelisse et al. 2006). It presents dips with a duration of \( \sim 30 \) days and a recurrence period of \( \sim 100 \) days, associated with sudden increases in the absorption column density \( N_H \). Even outside the dipping phase the \( N_H \) is high \( (\sim 10^{23} \text{ cm}^{-2}) \) compared to the Galactic value towards the source \( (\sim 2 \times 10^{22} \text{ cm}^{-2}) \), indicating that the system is absorbed locally. The source presents remarkable similarities with the class of obscured HMXBs (Wen et al. 1999; Walter et al. 2006). The \( \sim 100 \)-day recurrence of the dips is likely not associated with the system orbital period, but with a super-orbital periodicity (Wen et al., 1999) as has been observed in many HMXBs with a supergiant companion.

Stephen et al. (2005) present a search for an optical/NIR counterpart to XTE J1716–389 based on its ROSAT position. They indicate a candidate counterpart in optical, also reported in 2MASS and a few NIR sources inside the ROSAT/HRI error circle.

We observed XTE J1716–389 with Chandra/ACIS for \( \sim 1.1 \) ks on 2008 Sep. 23 detecting one faint source (12 counts in a 0.3 – 7 keV energy band) compatible with the ROSAT pointing from Stephen et al. (2005), at coordinates RA= 17\(^{h}\) 15\(^{m}\) 56\(^{s}\)42, Dec. = –38\(^{\circ}\) 51‘ 54″127. This position excludes the optical counterpart proposed in Stephen et al. (2005), being \( \sim 4.5 \) arcsec (more than \( 10\sigma \)) far away from it.

Follow-up optical observations in \( i' \) band were performed on 2009 May 7 with Magellan/LDSS3, showing a very faint source inside the 90 per cent confidence Chandra error circle, at RA= 17\(^{h}\) 15\(^{m}\) 56\(^{s}\)457, Dec. = –38\(^{\circ}\) 51‘ 53″9 \( \pm 0.1 \) arcsec on both coordinates (see Figure 2.9). The probability that the source falls by chance in the Chandra error-circle is \( \sim 3 \times 10^{-4} \). The object is reported in the 2MASS catalogue, with magnitude \( H = 13.569 \pm 0.09, \) \( K = 12.579 \pm 0.059 \). A limit to the magnitude in \( J \) band is also reported, the object being fainter than \( J = 15.058 \). We observed the source in a non photometric night: we obtain an estimate of the \( I \)-band magnitude \( I \sim 22.7 \)
by calibrating our \textit{LDSS3} observation with the zero-point from a previous observing run (see Section 2.3). As for IGR J16479$-$4514 (see last paragraph in Section 2.4.3), the possible combinations of $(J-H)_0$ and $(H-K)_0$ allowed by the 2MASS observed colours $(J-H)$ (lower limit) and $(H-K)$ are shown in Figure 2.6. The colours are compatible with a star of any class, but only for an $A_V$ ranging between $\sim 8$ and $\sim 17$. Those are acceptable values for a HMXB, where the companion star can be highly obscured in the optical due to its own wind ($A_V \sim 9 - 15$, i.e., for the five systems investigated in Torrejón et al. 2010). On the other hand, a main sequence star or a red giant are unlikely since the high $A_V$ requires a dense stellar wind to be justified. An even higher $A_V$ ($\sim 45$) corresponds to the $N_H$ obtained from the X-rays observations (see above). This indicates that there is absorption in the surroundings of the compact object, not affecting the companion star. We conclude that the source 2MASS 17155645-3851537 is most likely a massive self-absorbed star: this supports its positional association with XTE J1716$-$389 and the classification of the latter as an obscured HMXB.

2.4.7 IGR J17254-3257: a candidate UCXB

IGR J17254–3257 was discovered by \textit{INTEGRAL} in 2003 (Walter et al., 2004) and reported in various catalogues of \textit{INTEGRAL/IBIS} sources (i.e. Bird et al. 2004). It is also a \textit{ROSAT} source (1RXS J172525.5-325717), it has been continuously detected by \textit{RXTE/PCA} at very low count-rate since 1999.
2.4 Individual sources

Figure 2.10: IGR J17254−3257: PANIC, 15 s in the $K_s$ band. Error circle: XMM-Newton position. The arrows indicate the position of the two candidate counterparts in Zolotukhin (2009) (first and second from bottom to top).

(Stephen et al., 2005) and was also observed with XMM-Newton (Chenevez et al., 2007) and Swift (Cusumano, 2009).

A type I X-ray burst detected on 2004 Feb. 17 (Brandt et al., 2006) indicated that the system is an LMXB hosting a NS. Moreover, a long thermonuclear burst lasting about 15 minutes was observed on 2006 October 1, placing IGR J17254−3257 in the small group of XRBs showing bursts very different in duration (Chenevez et al. 2007 and references therein). Based on the persistent behaviour of the source at a low accretion rate, in’t Zand et al. (2007) proposed IGR J17254−3257 as a candidate UCXB. An upper limit to the distance of 14.5 kpc has been estimated from the bursts (Chenevez et al., 2007). Zolotukhin (2009) reported two possible optical counterparts to IGR J17254−3257 that are compatible with the XMM-Newton position.

We observed the field of IGRJ17254-3257 with Magellan/PANIC on 2006 Aug. 03 in $K_s$ band: in addiction to the two sources indicated by Zolotukhin (2009) (see Figure 2.10), 11 further object are resolved by our PSF photometry within the XMM-Newton error circle.

Considering a maximum distance to the source of 14.5 kpc and with the $N_H$ from Chenevez et al. (2007), we can set a limit to the absolute magnitude $M_K$ of the candidates, similarly to what we did for XTE J1710−281 (see Section 2.4.5). In order to reduce the number of possible counterparts we compared those magnitudes with that of the UCXB 4U 0614+09, for which the case for an ultracompact nature is strong (Nelemans et al. 2004; Shahbaz et al. 2008). For 4U 0614+09, $d = 3.2$ kpc (Kuulkers et al., 2010), $K = 17.1$ and $A_V = 1.41$ (Russell et al., 2007), thus $M_K = 4.46$. This is consistent with what expected
for an UCXB (van Paradijs & McClintock, 1995a). The first candidate from Zolotukhin (2009) should be very close by \( d = 0.6 \) kpc in order to have a similar \( M_K \approx 4 \): this is unlikely because IGR J17254−3257 would then be the nearest XRB known and its X-ray luminosity during X-ray bursts would be anomalously low. Beside that, unfortunately the comparison does not provide any constraint to further reduce the number of candidates in the XMM-\textit{Newton} error circle. A localization of the X-ray source with \textit{Chandra} is necessary to identify the actual counterpart.

### 2.4.8 XTE J1743-363: a candidate SFXT

XTE J1743−363 was discovered with \textit{RXTE} in 1999 (Markwardt et al., 1999). The system has been detected by \textit{INTEGRAL}/\textit{IBIS} several times in 2004 at diverse flux levels (Revnivtsev et al. 2004; Grebenev & Sunyaev 2004). It also showed a few-hour long outburst, because of which XTE J1743−363 is considered a candidate SFXT (Sguera et al., 2006). No search for an optical or NIR counterpart is reported in the literature.

We observed XTE J1743−363 with \textit{Chandra}/HRC on 2008 Feb. 8 for \( \sim 1.2 \) ks detecting one faint source (11 counts) compatible with the \textit{INTEGRAL} position (from Bird et al. 2006a) at coordinates \( \text{RA} = 17^h \ 43^m \ 01^s 324 \), \( \text{Dec.} = -36^\circ \ 22' \ 22'' 0 \).

Optical images in the \textit{I} band, collected with \textit{EMMI} on 2007 June 22, show a bright star lying inside the \textit{Chandra} error circle (see Figure 2.11) at \( \text{RA} = 17^h \ 43^m \ 01^s 324 \), \( \text{Dec.} = -36^\circ \ 22' \ 22'' 2 \) (\( \pm 0.1 \) arcsec on both coordinates). The position of the source is coincident within the error with the object

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.11.png}
\caption{XTE J1743−363: \textit{EMMI}, \( 600 \) s in the \textit{I} band. Error circle: \textit{Chandra} position.}
\end{figure}
2.4 Individual sources

2MASS 17430133-3622221, for which the following magnitudes are reported in the catalogue: $J = 9.616 \pm 0.024$, $H = 8.305 \pm 0.034$, $K = 7.624 \pm 0.026$. We cannot report a magnitude in $I$ band since the field was observed in a non-photometric night.

Given the classification as a SFXT, the companion star in XTE J1743–363 is expected to be a supergiant, locally absorbed in the NIR due to its own wind (see Section 2.1 and 2.4.6). As for IGR J16479–4514 and XTE J1716–389, figure 2.6 shows the combination of $(J - H)_0$ and $(H - K)_0$ allowed by the observed 2MASS colours, for different values of the absorption. The colours are compatible with a type G0-6 III ($A_V$ between 8 and 9) or G/K I ($A_V$ between 6 and 9) and do not exclude a supergiant of spectral type earlier than O9 (see last paragraph in section 2.4.3) if $A_V > 12$. As in the case of XTE J1716–389, a main sequence or giant star are allowed by the colours, but unlikely due to the high $A_V$.

Based on its position we conclude that the object 2MASS 17155645-3851537 is most likely the NIR counterpart to XTE J1716–389. The NIR colours of the counterpart are consistent with a late type supergiant and do not exclude an early O I type. This is consistent with the classification of the X-ray source as a SFXT and supports the counterpart association.

2.4.9 IGR J17597-220: a dipping LMXB

IGR J17597–220 was first detected in 2001 by RXTE/PCA (Markwardt & Swank, 2003) but it was reported for the first time in 2003 (Lutovinov et al., 2003) as a new INTEGRAL source. For that reason it is usually indicated as either IGR J17597–220 or XTE J1759-220. Type I X-ray bursts from the source have been observed by INTEGRAL/JEM-X, identifying the compact object as a NS (Brandt et al., 2007) and the system as a probable LMXB. IGR J17597–220 has also shown dips of $\sim 30$ per cent with a duration of $\sim 5$ minutes, from which Markwardt & Swank (2003) suggested an orbital period of 1-3 hours.

XMM-Newton observations localised the source with a 4 arcsec accuracy (Walter et al., 2006). Chaty et al. (2008) identified 6 candidate counterparts consistent with the XMM-Newton position on NIR observations in $J$, $H$ and $K_s$ bands. We detect a single Chandra/HRC source (227 counts) inside the XMM-Newton error circle, at RA = 17$^h$ 59$^m$ 45$^s$52, Dec. = $-22^\circ$ 01$'$ 39$''$17, during a $\sim 1.2$ ks-long observation performed on 2007 Oct. 23.

Follow-up observations in $I$ band were performed with NTT/EMMI on 2006 June 22 and with Magellan/LDSS3 in $i'$ band on 2009 May 7. A single, faint source lies inside the Chandra error circle in both bands, at RA = 17$^h$ 59$^m$ 45$^s$525, Dec. = $-22^\circ$ 01$'$ 39$''$25 (±0.1 arcsec on both coordinates). The detection is evident in the 300 s-long LDSS3 images (see Figure
2.12), while it is less significant in the 600 s-long EMMI one. We consider the detection with EMMI as real due to its positional coincidence with that of the source in LDSS3. The observing nights with both instruments were not photometric: we obtain an estimate of the $I$-band magnitude $I \sim 22.4$ by calibrating our LDSS3 observation with the zero-point from a previous observing run (see Section 2.3). The probability that our candidate counterpart falls by chance inside the Chandra error circle is $\sim 1 \times 10^{-4}$ and $\sim 8 \times 10^{-4}$ for LDSS3 and EMMI respectively (photometry on a smaller field for EMMI). Its position matches that of the Candidate 1 in Chaty et al. (2008) that we establish as the very likely optical/NIR counterpart of IGR J17597−220.

2.4.10 IGR J18490-0000: a Pulsar Wind Nebula

A Pulsar Wind Nebula (PWN) is a nebula powered by the interaction of the highly relativistic particle wind formed in the magnetosphere of a pulsar with the surrounding material. IGR J18490−0000 was discovered by INTEGRAL in the spring of 2003, during a survey of the Sagittarius arm tangent region of the Galaxy (Molkov et al., 2004). In the soft X-rays the source is composed of a point-like source surrounded by an extended nebula (Terrier et al., 2008). Its morphology and spectral properties at X-rays are reminiscent of a PWN, although pulsations have not been detected so far (Mattana et al., 2009). The association of IGR J18490−0000 with a PWN was further strengthened by the discovery of a TeV counterpart with the High Energy Stereoscopic System HESS (Terrier et al., 2008).

Swift/XRT observations are presented in Rodriguez et al. (2008a): based
on the Swift position, the object 2MASS 18490182-0001190 has been proposed as a possible NIR counterpart (Rodriguez et al., 2008a).

A \(\sim\)1.2 ks-long Chandra/HRC observation of the field, obtained on 2008 Feb. 16, shows a single source (22 counts) inside the Swift error circle, at RA= 18\(^{h}\) 49\(^{m}\) 01\(^{s}\)59, Dec.= -00\(^{\circ}\) 01\(^{\prime}\) 17\(^{\prime\prime}\)73, whose morphology is compatible with an extended nebula. Those coordinates exclude the association of IGR J18490−0000 with the candidate counterpart proposed by Rodriguez et al. (2008a), which is located at \(\sim\)3.8 arcsec (over 9\(\sigma\)) from the Chandra position.

We observed the field of IGR J18490−0000 with Blanco/MOSAIC II on 2006 June 25 in \(i^{\prime}\) band and did not detect any optical counterpart. Nevertheless, giving the low number of sources that we observe in the field and comparing the \(i^{\prime}\) band images with 2MASS infrared ones, we consider it likely that a dark cloud is located between us and the source, obscuring the counterpart. Further observations in the \(K_s\) band, performed on 2009 Jul. 16 with Magellan/PANIC, revealed a faint candidate counterpart on the edge of the 90 per cent Chandra error circle (Figure 2.13 ) at RA= 18\(^{h}\) 49\(^{m}\) 01\(^{s}\)563, Dec.= -00\(^{\circ}\) 01\(^{\prime}\) 17\(^{\prime\prime}\)35 (\(\pm\) 0.1 arcsec on both coordinates). After absolute photometric calibration, we measure a magnitude of \(K_s = 16.4 \pm 0.1\).

The object does not look extended as one would expect for a PWN: our PSF fitting indicates a point-like source, which looks partially blended with a nearby star (Figure 2.13). The two sources are resolved by the PSF fitting. This suggests that the object is a foreground star, although its positional coincidence with IGR J18490−0000 within the accuracy of Chandra has a low
Figure 2.14: IGR J19308+0530: MOSAIC II, 10 s in the I band. Solid error circle: Chandra position. Dashed error circle: Swift probability of being due to chance ($\sim 1.6 \times 10^{-5}$). We encourage spectroscopic observations of the source in order to investigate its association with IGR J18490-0000.

2.4.11 IGR J19308+0530: an L/IMXB with an F8 companion

IGR J19308+0530 was discovered by INTEGRAL (Bird et al., 2006a) and observed by Swift in X-rays and in the UV band 170-650 nm (Rodriguez et al., 2008a).

Based on the Swift position, Rodriguez et al. (2008a) identify the star TYC 486-295-1/2MASS J19305075+0530582 as a possible counterpart. This object is classified as an F8 star in the survey by McCuskey (1949a). Based on the typical parameters of an F8 star, Rodriguez et al. (2008a) suggest IGR J19308+0530 is a L/IMXB in quiescence or a CV at a distance of $\sim 1$ kpc or lower. Fitting the Swift spectrum with a black body of temperature $kT = 0.2$ keV the authors obtained a 2-10 keV luminosity of $\sim 4 \times 10^{31}$ erg s$^{-1}$ at 1 kpc. The corresponding luminosity in the 0.5-10 keV range is $\sim 4 \times 10^{33}$ erg s$^{-1}$.

The spectrum is very soft, suggesting IGR J19308+0530 is most likely not a CV (Pooley & Hut, 2006) but an L/IMXB hosting a NS or a BH in quiescence. This suggestion is strengthened by the fact that the spectra of NS/BH LMXBs in quiescence at a 0.5-10 keV luminosity level of $\sim 10^{33}$ erg s$^{-1}$ are expected to be dominated by the soft black-body component, as found by Jonker et al. (2004b) and updated in Jonker (2008).

In a $\sim 1.1$ ks-long Chandra/HRC observation on 2007 Jul. 30, we detected a single source (26 counts) inside the Swift error circle, at RA= 19$^\text{h}$ 30$^\text{m}$ 50$^\text{s}$77,
2.5 Conclusion

We searched for an optical counterpart with *Blanco/MOSAIC II* in *r* band, on 2006 Jun. 22: the *Chandra* error circle includes a very bright star that is saturated even in the 10 s-long image (Figure 2.14). Its position is compatible with the position of the previously proposed F8-type counterpart as reported in the Tycho catalogue, in 2MASS, in the LF Survey catalogue and also in UCAC 2 and 3, if the motion of the source since the epoch of each catalogue to that of our observations in 2006 is taken into account. The object has a proper motion of \( -2.9 \pm 0.6 \text{ mas yr}^{-1} \) in RA and \(-10.5\pm0.5 \text{ mas yr}^{-1} \) in Dec. (from UCAC3). The magnitudes reported in 2MASS are \( J = 9.617 \pm 0.032 \) (poor photometry) \( H = 9.245 \pm 0.023 \) and \( K = 9.130 \pm 0.023 \). The intrinsic NIR colours (obtained with the method used for IGR J16479−4514, XTE J1716−389 and XTE J1743−363) are consistent with the spectral classification. Moreover, the Supplement-1 to the Tycho-2 catalogue reports \( B_T = 11.706 \) and \( V_T = 10.915 \).

We confirm the association of IGR J19308+0530 with the F8 star TYC 486-295-1/2MASS J19305075+0530582 (first proposed by Rodriguez et al. 2008a) and we suggest the source is most likely an L/IMXB in quiescence.

2.5 Conclusion

We have investigated a sample of 11 Galactic X-ray sources recently discovered by *INTEGRAL* or *RXTE*. For 9 of those, we presented a refined position from *Chandra* observations (Table 2.1), localising the targets with a positional accuracy of 0.6 arcsec at a 90 per cent confidence level. Thanks to the accurate X-ray position, we have detected a counterpart for all the sources we observed with *Chandra*: the previously proposed counterparts to IGR J16194−2810, IGR J16500−3307, IGR J19308+0530 and IGR J16479−4514 are confirmed by our observations, supporting their classification as, respectively, a SyXB, a CV, an L/IMXB and a SFXT (although we evidenced some peculiarity in the NIR colours of the latter). The counterpart to the obscured source XTE J1716−389 is consistent with it being a HMXB. The NIR colours of the counterpart to the SFXT candidate XTE J1743−363 indicate indeed a supergiant companion. A point-like NIR source is located at the position of the PWN IGR J18490−0000, although its morphology suggests a foreground star despite its positional coincidence with the nebula. The photometry of the counterpart to the unclassified source IGR J16293−4603 indicates it is an LMXB with a giant companion star, possibly a SyXB.

We also presented optical/NIR observations of the two LMXBs XTE J1710−281 and IGR J17254−3257, searching for a counterpart based on their XMM-*Newton* position. We detected only one source compatible with the position of XTE J1710−281, whose magnitude is consistent with
what is expected for an LMXB. This supports its association with the X-ray source. Twelve NIR candidates are consistent with IGR J17254−3257: a Chandra position of the source is necessary to select the counterpart. Table 2.5 summarizes the results of our counterpart search in comparison with previous results.
Table 2.5: Results of our optical/NIR counterpart search. The upper part of the table lists sources that we observed with *Chandra*. For the last two sources we obtained *XMM-Newton* positions from the literature. Candidate counterparts previously proposed are discarded or confirmed based on the *Chandra* position (see text). The coordinates of the counterparts in the table are from 2MASS when available, from our astrometry elsewhere.

<table>
<thead>
<tr>
<th>Source</th>
<th>Classification</th>
<th>Counterparts in literature</th>
<th>New counterpart</th>
<th>(RA, Dec.) (J2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chandra</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGR J16194−2810</td>
<td>SyXB</td>
<td>M2 III$^{(a)}$</td>
<td>confirmed</td>
<td>(16h 19m 33s 348, −28° 07' 39.74&quot;)$^{2}$MASS</td>
</tr>
<tr>
<td>IGR J16293−4603</td>
<td>LMXB$^1$</td>
<td>none</td>
<td>yes: K, M or G (unlikely) III</td>
<td>(16h 29m 12' 9, −46° 02' 50.58&quot;)±0'.1</td>
</tr>
<tr>
<td>IGR J16479−4514</td>
<td>SFXT (eclipsing)</td>
<td>O/B I star$^{(b)}$</td>
<td>confirmed</td>
<td>(16h 48m 06'56, −45° 12' 06''8$^{2}$MASS</td>
</tr>
<tr>
<td>IGR J16500−3307</td>
<td>CV</td>
<td>dwarf nova$^{(c)}$</td>
<td>confirmed</td>
<td>(16h 49m 55'64, −33° 07' 02'.1$^{2}$MASS</td>
</tr>
<tr>
<td>XTE J1716−389</td>
<td>obscured HMXB</td>
<td>in (d): excluded</td>
<td>2MASS J17155645-3851537</td>
<td>(17h 15m 56'46, −38° 51' 53''7$^{2}$MASS</td>
</tr>
<tr>
<td>XTE J1743−363</td>
<td>SFXT</td>
<td>none</td>
<td>2MASS J17430133-3622221</td>
<td>(17h 43' 01's, −36° 22' 22'.2$^{2}$MASS</td>
</tr>
<tr>
<td>IGR J17597−220</td>
<td>NS LMXB (dipper)</td>
<td>6 NIR candidates$^{(e)}$</td>
<td>Select candidate 1 (see text)</td>
<td>(17h 59m 45'5, 22° 01' 39'.6 ±0'.1</td>
</tr>
<tr>
<td>IGR J18490−0000</td>
<td>PWN</td>
<td>in (f): excluded</td>
<td>yes/tentative</td>
<td>(18h 49m 01's,35, −00° 01' 17'.20)±0'.1</td>
</tr>
<tr>
<td>IGR J19308+0530</td>
<td>L/IMXB$^1$</td>
<td>F8 star$^{(g)}$</td>
<td>confirmed</td>
<td>(19h 30m 50'76, +05° 30' 58'.3$^{2}$MASS</td>
</tr>
<tr>
<td><strong>XMM-Newton</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XTE J1710−281</td>
<td>NS LMXB (eclipsing)</td>
<td>none</td>
<td>yes</td>
<td>(17h 10' 12'6, −28° 07' 51'.0)±0'.1</td>
</tr>
<tr>
<td>IGR J17254−3257</td>
<td>UCXB</td>
<td>none</td>
<td>12 candidates (see text)</td>
<td>-</td>
</tr>
</tbody>
</table>

$^1$: New classification

$^1$: Optical/NIR spectrum reported in the literature.

$^{(a)}$: USNO-A2.0 U0600.00227091: Masetti et al. (2007).

$^{(b)}$: 2MASS J16480656-4512068; Kennea et al. (2005); Walter et al. 2006; Chaty et al. (2008).

$^{(c)}$: 2MASS J16480656-4512068; Kennea et al. (2005); Walter et al. 2006; Chaty et al. (2008).

$^{(d)}$: Stephen et al. (2005), also indicates the presence of several further NIR objects.

$^{(e)}$: USNO A2-0 U0525-24170526:Masetti et al. (2008).

$^{(f)}$: 2MASS J18490182-0001190: Rodriguez et al. (2008a)
Chapter 3

Optical spectroscopy of the quiescent counterpart to EXO 0748–676: a Black Widow scenario?

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Abstract

We present phase-resolved optical spectroscopy of the counterpart to the neutron star low mass X-ray binary EXO 0748–676, almost one year after it turned into quiescence. The spectra display prominent H$\beta$ and H$\gamma$ and weak Fe II lines in emission. An average of all the spectra (corrected for the orbital
motion) also exhibits a very weak line from Mg I. Tomographic reconstructions show that the accretion disc is not contributing to the optical line emission, which is instead dominated by the irradiated hemisphere of the companion star facing the neutron star. We could not detect absorption features from the mass donor star in the spectra. The emission lines appear broad, with an intrinsic FWHM of $255 \pm 22$ km s$^{-1}$. Under the assumption that the width of the Fe II emission lines is dominated by rotational broadening, we obtain a lower limit on the compact object mass which is inconsistent with a NS accretor. We discuss this incongruity and conclude that either the lines are blends of unresolved features (although this requires some fine tuning) or they are broadened by additional effects such as bulk gas motion in an outflow. The fact that the Fe II lines slightly lag in phase with respect to the companion star can be understood as outflowing gas consistent with a Black-Widow like scenario. Nevertheless, we can not rule out the possibility that blends of various emission lines cause the apparent phase lag of the Fe II emission lines as well as their large width.

3.1 Introduction

EXO 0748−676 was discovered with the European X-Ray Observatory Satellite (EXOSAT, Parmar et al. 1985) in 1985. Soon after the discovery, the detection of type I X-ray bursts from the source (Gottwald et al., 1986) marked it as a Galactic low-mass X-ray binary (LMXB) where a neutron star (NS) is accreting matter from a low-mass companion star. Many LMXBs are known to be transient, alternating periods of quiescence at a relatively low X-ray luminosity ($\sim 10^{32}$ erg s$^{-1}$ in a 0.5-10 keV range) with month to year-long bright X-ray outbursts ($10^{36}-10^{38}$ erg s$^{-1}$). EXO 0748−676 has been continuously in outburst for the 24 years since its discovery: tens of years-long X-ray outbursts have been observed from a number of LMXBs, e.g. KS 1731-260 (Wijnands et al., 2001), GRS 1915+105 and 4U 1755−338 (see Remillard & McClintock 2006b for a review). During outbursts mass accretion proceeds at a high rate forming an extended accretion disc around the accreting compact object. X-rays are emitted from the innermost regions, whereas the optical originates further out in the disk. In LMXBs the disc dominates the optical flux during outbursts, outshining the low-mass companion star. The latter can become visible during quiescence, when the disc is less bright.

A few LMXBs are known where the NS is detected as a pulsar (Chakrabarty, 2005) but for the majority of them the companion star is the only viable source of information regarding the system dynamics. Optical spectroscopy of the companion star can be used to measure the orbital parameters and, under certain conditions (see below), the mass of the accreting compact object. This
measured is interesting in LMXBs since the accretion process can significantly increase the mass of a NS: the maximum mass that a NS can reach is one of the parameters that can distinguish among the existing models for the equation of state (EoS) of those object (Lattimer & Prakash, 2001). The determination of the NS EoS is one of the key goals in the study of NSs and will have strong implication for both astronomy and super-nuclear density matter physics.

The mass of a NS (or a BH) in a non-pulsating LMXB can be measured by solving the system mass function

\[ f(M_D) = \frac{M_X^3 \sin^3 i}{(M_D + M_X)^2} = M_X \frac{\sin^3 i}{(1 + q)^2} = \frac{PK_D^3}{2\pi G} \]  

(3.1)

where \( G \) is the universal constant of gravity, \( M_D \) and \( M_X \) are the masses of the companion and NS, respectively, \( P \) is the orbital period, \( i \) the inclination of the orbital plane, \( K_D \) the amplitude of the radial velocity curve of the companion and where we define \( q \equiv M_D/M_X \). This equation is valid provided that \( f(M_D) \leq M_X \), the mass function provides a lower limit to the mass of the neutron star (Charles & Coe, 2006b).

\( P \) and \( K_D \) can be inferred from the orbital Doppler shift of stellar absorption lines originating in the atmosphere of the companion star, which can be visible in the optical spectra during quiescence. \( f(M_D) \) can be solved for \( M_X \) in eclipsing quiescent LMXBs (van Paradijs & McClintock, 1995a), where \( q \) can be expressed as a function of \( K_D \) and of the projected rotational velocity of the companion star \( v \sin i = \frac{2\pi}{P} R_D \sin i \) (Wade & Horne, 1988a) measured from the broadening of the companion stellar absorption lines (Gray, 1992a). From \( q \) and from the eclipse duration, \( i \) can be obtained.

The LMXB EXO 0748−676 shows X-ray eclipses (Parmar et al., 1986) and, after a more than 20 year-long outburst, it turned into quiescence in September 2008 (Wolff et al. 2008b, Wolff et al. 2008a, Hynes & Jones 2009, Torres et al. 2008). The optical counterpart to the X-ray source was first found by Parmar et al. (1985) and confirmed by the Chandra localisation of EXO 0748−676 at RA= 07h48m33s73, Dec.= −67°45′07″9 (Torres et al., 2008). A search on photographic plates showed that the source was not detected down to \( \sim 23 \) magnitudes when the X-ray emission was off. Spectroscopic observations in the optical during the outburst have been performed by Pearson et al. (2006) and Muñoz-Darias et al. (2009), attempting to get a lower limit on the NS mass from He, C and N emission lines probably originating from the inner, heated face of the companion star. The first spectroscopic study of EXO 0748−676

\[ \sin^2 i \cos^2 (\pi \Delta \phi) = 1 - \left[ \frac{0.49q^{2/3}}{0.6q^{2/3} + 1 + q^{1/3}} \right]^2 \]  

where \( \Delta \phi \) is the eclipse duration (see Horne 1985a). This relation is valid under the assumption that the companion is Roche Lobe filling, which holds for LMXBs.
Optical spectroscopy of EXO 0748–676

Figure 3.1: g’-band light curve determined from the acquisition images. The magnitudes are relative to the bright star USNO-B1.0 0222–0189796. Different symbols refer to different observing nights starting from the night of 2010 January 18/19. In temporal order, the observations of the first to the fourth nights are indicated by black stars, black squares, empty circles and empty squares respectively.

in quiescence was performed by Bassa et al. (2009) two months after the end of the outburst. The spectra, acquired in a 5750-7310 Å wavelength range, were dominated by strong Hα and weaker He emission lines coming from the companion star facing the NS, an indication of irradiation. A weak contribution to the lines was due to optical radiation from a residual accretion disk. No absorption lines were detected, preventing a straightforward solution of the \( f(M_D) \). Nevertheless, the authors could put a lower limit on \( K_D \) and on the NS mass, \( M_{NS} > 1.27 \text{M}_\odot \).

Bassa et al. (2009) determined a minimum temperature for the irradiated companion star of EXO 0748–676 of \( \sim 5000 \) K, the surface temperature of a G type star. We have performed phase-resolved spectroscopic observations of the optical counterpart to EXO 0748–676 after almost one year of quiescence. We attempted to detect absorption lines from the heated companion star by collecting our spectra in the wavelength range (4222-5701 Å) where a G as well as a K type star would show absorption lines. We here report on the results of this study.

3.2 Observations and data reduction

We performed long-slit phase-resolved spectroscopy of the optical counterpart to EXO 0748–676 with the FOcal Reducer and low dispersion Spectrograph
3.2 Observations and data reduction

Figure 3.2: Trailed spectra composed by 73 single spectra of the counterpart to EXO 0748−676, phase binned in 20 bins. The two prominent s-waves are from the H\(\gamma\) and H\(\beta\) lines. Three weak lines consistent with Fe\(\text{II}\) are just visible between 4900 and 5200 Å (see section 3.3.1).

(FORS) instrument on the Very Large Telescope (VLT) \(^2\) (grism 1200g+96 and a 1''0 slit). The orbit was sampled with a total of seventythree 900s long exposures collected between 2010 January 18 (MJD(UTC)=55214) and 2010 January 22, in the wavelength range 4222-5701 Å. We also acquired template spectra from main sequence G type stars (G5V, G9V and G6V). The seeing across the four nights was between ~ 0''8 and ~ 1''2. The detectors were read out with a 2×2 binning, providing a resolution of 2 Å (measured from the width of both arc lines and of the night sky OI line at 5577.338 Å) sampled with a dispersion of 0.73 Å pix\(^{-1}\). The images were corrected for bias, flat-fielded and extracted using the FIGARO package within the STARLINK software and the packages PAMELA and MOLLY developed by T. Marsh. We used dome flats for the flat-fielding and we subtracted the sky continuum by fitting clean sky regions along the slit with a second order polynomial. The spectra were optimally extracted following the algorithm of Horne (1986a) implemented in PAMELA and wavelength-calibrated in MOLLY with a final accuracy of 0.1 Å, using arc exposures taken during daytime. The wavelength calibration was corrected for shifts in the single observation with respect to the position of the sky OI line at 5577.338 Å (Osterbrock et al., 1996a). Each spectrum has been normalised dividing by a first-order polynomial fit of the continuum. The spectra have been phase binned with the \(T_0 = 54776.501663 \pm 0.000068\) MJD/TDB from Bassa et al. (2009), which is the closest in time to our observations and with the orbital period \(P_{\text{orb}} = 0.15933783446\) days from

\(^2\)VLT observing program 085.D-0441(C)
Wolff et al. (2009).

We also analysed sixteen 6 s-long g'-band acquisition images, corrected for bias and flat-fielded with standard routines running in MIDAS. The photometry was performed through point spread function fitting, using DAOPHOT II (Stetson, 1987b). Absolute photometric calibration was not possible due to the lack of observations of g'-band standard stars, but a light curve (Fig. 3.1) of the optical counterpart to EXO 0748−676 was obtained through relative photometry with respect to the reference star USNO-B1.0 0222−0189796. The instrumental magnitude of the reference star was measured with an accuracy of 0.03-0.08 magnitudes across the various images. Relative photometry with respect to two other bright targets have shown that the reference star was not variable during our observations. The light curve was phase-folded with the same ephemeris used to phase-bin the spectra (see above).

3.3 Analysis and results

3.3.1 Individual and trailed spectra

The sole features detected in the individual spectra are the Balmer lines H\(\beta\) (4861.327 Å) and H\(\gamma\) (4340.465 Å), which are observed as strong emission features. We searched for absorption lines in the individual spectra by cross-correlating with template star spectra, but we found no correlation.

As shown in Figure 3.2, more emission features become observable when trailed spectra are constructed. Besides the s-waves associated with the Balmer lines, three weak s-waves are visible in the region between 4900-5300 Å: the position of the first two lines is consistent with a couple of He I lines, at 4921.929 Å and 5015.675 Å, but also with Fe II lines at 4923.92 Å and 5018.44 Å. No He I line matches the position of the third line, which instead can be Fe II at 5169.03 Å (Moore, 1972). This favors an interpretation of the three lines as an Fe triplet as all the three lines are part of multiplet 42.

The variations show only one peak along the orbit. The emission lines are fading away and disappearing between phase \(\sim 0.75\) and \(\sim 0.25\), consistent with an emission region located on the inner face of the companion star. There is no indication of absorption lines in the trailed spectra.

3.3.2 Radial velocity of the Balmer lines

For the H\(\beta\) and H\(\gamma\) lines we have obtained radial velocity curves (see Figure 3.3) by fitting single Gaussians to those lines in each 900 s spectrum, including only significant detections on a 3\(\sigma\) level. The fitted parameters were normalisation, full-width-at-half-maximum (FWHM) and velocity offset of the centroid with respect to the rest frame line wavelength. The 0.1 Å 1\(\sigma\) uncertainty
3.3 Analysis and results

Figure 3.3: Radial velocity curves of the H\(\beta\) (a) and H\(\gamma\) (b) emission lines. The data points are obtained by fitting a Gaussian to each Balmer line in individual 900 s long spectra and selecting significant line detections at a 3\(\sigma\) level. The solid lines show the best fit to the data.

on the velocity offsets due to the wavelength calibration has been added in quadrature to the error on the centroid from the Gaussian fit of each observation. We fitted the radial velocity curve (velocity offset versus phase) for each line with a circular orbit in the form \(v(\phi) = \gamma + K_{\text{em}} \sin(2\pi\phi + \varphi)\). We measured \(\gamma = 54.5 \pm 5.9 \text{ km s}^{-1}\), \(K_{\text{em}} = 306.1 \pm 5.0 \text{ km s}^{-1}\) and \(\varphi = 0.007 \pm 0.004\) from the H\(\beta\), \(\gamma = 32.8 \pm 9.7 \text{ km s}^{-1}\), \(K_{\text{em}} = 312.6 \pm 6.4 \text{ km s}^{-1}\) and \(\varphi = 0.001 \pm 0.007\) from the H\(\gamma\) line. The errors are obtained after we artificially increased the error-bars on the individual measurements such that the fit reduced \(\chi^2\) was 1. The initial reduced \(\chi^2\) was 1.6 for the H\(\beta\) line (45 d.o.f.) and 2.2 for the H\(\gamma\) one (33 d.o.f). The fit of the radial velocity curve of the two Balmer lines provides values consistent within 1\(\sigma\) for \(\varphi\) and \(K_{\text{em}}\), and within 2\(\sigma\) for \(\gamma\). The latter is expected to be the same for all the lines, being the radial velocity of the system center of mass. \(\varphi\) and \(K_{\text{em}}\) instead are not a priori the same for different emission lines, as they could originate from different parts of the irradiated companion star, or in fact regions in the binary.

3.3.3 Averaged spectrum

In order to measure the FWHM of the emission lines, we averaged the spectra in the frame of the companion star. We assumed a circular orbit, shifting the lines by \(v = -K_{\text{em}} \sin(2\pi\phi + \varphi)\), with \(\varphi = 0\). We did not adopt a priori the \(K_{\text{em}}\) obtained from the radial velocity curves of the Balmer lines, since that could be affected by, e.g., asymmetry or variations in the line profile from the individual spectra (as for the H\(\alpha\), Bassa et al. 2009). Moreover, the Balmer lines could originate in a different area than the weaker Fe\(\Pi\) ones and thus
The feature at \( \sim 5577 \, \text{Å} \) is due to non perfect subtraction of the night sky OI line at that wavelength. The two prominent emission lines are from H\( \gamma \) (4340.465 Å) and H\( \beta \) (4861.327 Å). Four weaker lines are marked in the spectrum: the position of the first two is consistent with He\( \text{i} \) lines, at 4921.929 Å and 5015.675 Å, but also with Fe\( \text{II} \) lines at 4923.92 Å and 5018.44 Å. The third line is consistent with the Fe\( \text{II} \) line at 5169.03 Å, which favors an interpretation of the first three lines as an Fe\( \text{II} \) triplet. The fourth weak line can be identified with Mg\( \text{I} \) at 5183.604 Å. The insert shows a zoom-in of the region of the Fe\( \text{II} \) triplet and the Mg\( \text{I} \) line.
3.3 Analysis and results

Table 3.1: a) Results from the fitting of individual emission lines in the average spectrum of EXO 0748−676 (see Figure 3.4) with a Gaussian function. The wavelength of each line in the rest frame $\lambda_0$ (column 1) is frozen in the fit. The last column in the Table indicates the velocity offset of the fitted line centroid respect to $\lambda_0$. There is evidence for the presence of a narrow spike on the red wing of the Fe II(5169.03) line: we fitted it without masking the spike (1) and masking it (2) (see Section 3.3.3 for a discussion). b) Results of the combined multi-Gaussian fit of the three Fe II lines, fitted together forcing the same offset and FWHM in $\text{km s}^{-1}$. The spike affecting Fe II(5169.03) is masked. The $v \sin i_{\text{em}}$ is measured by artificially broadening Arc lines with a Grey profile until reaching the FWHM measured for the EXO 0748−676 lines. This accounts for the instrumental resolution profile. The line smearing due to orbital motion during the integration time is also taken into account.

<table>
<thead>
<tr>
<th>$\lambda_0$ (Å)</th>
<th>FWHM (km s$^{-1}$)</th>
<th>Normalisation (Å$^2$)</th>
<th>Offset (km s$^{-1}$)</th>
<th>Offset (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$\gamma$(4340.465)</td>
<td>267±10</td>
<td>21.9±0.71</td>
<td>33.1±8.08</td>
<td></td>
</tr>
<tr>
<td>H$\beta$(4861.327)</td>
<td>282±7</td>
<td>29.9±0.7</td>
<td>42.5±6.9</td>
<td></td>
</tr>
<tr>
<td>Fe II(4923.92)</td>
<td>246±28</td>
<td>5.6±0.55</td>
<td>3.5±12</td>
<td></td>
</tr>
<tr>
<td>Fe II(5018.44)</td>
<td>366±50</td>
<td>5.7±0.61</td>
<td>-50±21</td>
<td></td>
</tr>
<tr>
<td>Fe II(5169.03)$^1$</td>
<td>410±36</td>
<td>8.4±0.66</td>
<td>20±15</td>
<td></td>
</tr>
<tr>
<td>Fe II(5169.03)$^2$</td>
<td>311±41</td>
<td>6.9±0.77</td>
<td>-15±11</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Best parameters from the Gaussian fit of the faint emission line identifiable with Mg I (5183.604 Å) in the average spectrum (see Figure 3.4). The last column reports the intrinsic line width $v \sin i_{\text{em}}$, measured as for the Fe II lines (see caption Tab. 3.1).

<table>
<thead>
<tr>
<th>$\lambda_0$ (Å)</th>
<th>FWHM (km s$^{-1}$)</th>
<th>Normalisation (Å$^2$)</th>
<th>Offset (km s$^{-1}$)</th>
<th>$v \sin i_{\text{em}}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg I(5183.604)</td>
<td>172±39</td>
<td>2.2±0.4</td>
<td>8±16</td>
<td>98±39</td>
</tr>
</tbody>
</table>
have a different $K_{\text{em}}$. Instead, we proceeded as follows:

- we assumed a range of possible values of $K_{\text{em}}$ ($200 < K_D < 400 \text{ km s}^{-1}$ in steps of 10 km s$^{-1}$). For each $K_{\text{em}}$ value we applied the circular orbital shift and averaged the spectra between phase 0.3 and 0.7 (the range where the weaker emission lines are clearly detected).

- we measured the FWHM of the emission lines in the averaged spectra, fitting a Gaussian function to each line (see Section 3.3.1). An orbital shift close to the real one will result in narrower lines in the averaged spectrum.

- we found the $K_{\text{em}}$ that results in the narrowest lines: for each line, we plotted the width measured from each average spectrum against the $K_{\text{em}}$ of the corresponding orbital shift. The uncertainty on the width was large with respect to its variation among different values of $K_{\text{em}}$. Nonetheless, each line displays a trend indicating a minimum width at $K_{\text{em}} \sim 300 \text{ km s}^{-1}$. The result is consistent with that from the radial velocity curves in Section 3.3.2.

The spectrum in Figure 3.4 is the average of individual exposures comprised between phase 0.35 and 0.7 (where all the emission lines are visible) for $K_{\text{em}} = 300 \text{ km s}^{-1}$. Together with H$\beta$ and H$\gamma$, the averaged spectrum highlights the weak Fe (or He) emission lines.

No absorption lines appear in the averaged spectrum. As for the individual spectra, a cross-correlation of the average spectrum with the standard template spectra does not give a match. Note that we have also constructed an averaged spectrum in the phase interval 0.8 to 0.2 and 0.9 to 0.1, but we did not detect absorption lines from the non-irradiated face of the companion star. Table 3.1 presents the parameters of the best-fitting Gaussian to each line in the averaged spectrum. Each line was fitted for FWHM, normalisation and for the offset $\lambda - \lambda_0$ of the line centroid $\lambda$ with respect to the rest-frame wavelength $\lambda_0$. As we corrected the spectra for the orbital motion only, the lines in the average spectrum are still shifted with respect to their rest-frame wavelength by the systemic radial velocity $\gamma$. The wavelength offset of the H$\beta$ and the H$\gamma$ lines is consistent on a $2\sigma$ level with the values of $\gamma$ derived from the radial velocity curves (see Section 3.3.2). The weighted average of the measures of $\gamma$ from the radial velocity curves and from the offsets of the Balmer lines is $\gamma = 43.8 \pm 3.6 \text{ km s}^{-1}$. The offsets of the Fe$\text{II}$ lines are not consistent with this value, although they agree with each other on a $3\sigma$ level.

In order to understand this difference, we have tested the dependence of the measured line offsets in the averaged spectrum on the choice of $K_{\text{em}}$ and $\varphi$ in the orbital motion correction. If the Fe$\text{II}$ lines originate in different regions
of the companion star, in fact, the two sets of lines will be associated with a different $K_{\text{em}}$ and $\phi$. We found that the offset changes slowly with $K_{\text{em}}$, but is sensitive to variations in $\phi$. The offset of the Fe II lines in the average spectrum is consistent with the measure of $\gamma$ from the Balmer lines if the orbital motion of their source region is shifted in phase by $-0.03 \lesssim \phi \lesssim -0.05$.

As we previously pointed out, the FWHM of the lines (both H$\gamma$, H$\beta$ and the Fe II group) is not affected by changes in $K_{\text{em}}$ of a few tens of km s$^{-1}$ around $\sim 300$ km s$^{-1}$. Unlike the offset, it is also not sensitive to changes of a few percent in $\phi$. In other words, our measure of the FWHM is not affected by a possible small displacement of the Fe II source region with respect to the source region of the Balmer lines. All the lines in the average spectrum have the same FWHM at a 2$\sigma$ level, with the exception of the reddest Fe line, Fe (5169.03 Å), which is significantly broader than Fe (4923.92 Å) at the $>3\sigma$ level. Careful inspection shows a narrow faint emission line on the red end of the 5169.03 Å line (Figure 3.4). The presence of this second peak artificially broadens the Gaussian function used to fit the Fe (5169.03 Å) line, as the fitting routine tries to account for both peaks with the same Gaussian. If this narrow peak is masked or fitted with an additional line, the width of Fe (5169.03 Å) becomes consistent within 1$\sigma$ with the other lines. It must be noted that a second Gaussian introduced to fit the faint emission near the Fe (5169.03 Å) line helps the fit but is not significant itself (the normalisation is approximately equal to the uncertainty on it). After we have verified that the Gaussian fit to the Fe II lines separately provides FWHMs and offsets in agreement with each other, we fitted the triplet together in order to reduce the uncertainty on the parameters. The three Fe lines were forced to have the same FWHM in km s$^{-1}$ and the same velocity offset. The faint emission on the reddest Fe line was masked to avoid artificial broadening. We obtained a FWHM = 304 ± 22 km s$^{-1}$ (reduced $\chi^2 = 0.99, 994$ d.o.f.).

### 3.3.4 Measuring the intrinsic broadening of the emission lines

The observed FWHM of the emission lines is determined by the intrinsic line width broadened by the instrumental resolution profile and by line smearing produced by the motion of the companion during the integration time of one spectrum. Intrinsic saturation effects can also contribute to the width of the emission lines, significantly affecting strong lines like the Balmer ones (Ostherbrock, 1989). On the other hand, if the weak Fe II lines originate on the companion star, their intrinsic width is expected to be dominated by the rotational broadening $v \sin i_{\text{em}}$ (Gray, 1992a). In order to measure the latter from the Fe II triplet, we have artificially smeared and broadened the arc spectra with different values of $v \sin i_{\text{em}}$. The $v \sin i_{\text{em}}$ resulting in smeared arc lines as broad as the FWHM of the Fe II lines is a measure of the rotational broad-
ening. We proceeded as follows: the phase of each EXO 0748−676 spectrum participating in the average in Figure 3.4 was ascribed to one arc spectrum. We smeared the arc spectra by $2\pi T_K \cos(2\pi \phi)/P$ where $T$ is the duration of one exposure (900 s) and $P$ the orbital period. The smeared arcs were then averaged, each one with the same weight as that of the corresponding (same phase) EXO 0748−676 spectrum in the average of Figure 3.4. In this way we have simulated the effect of the smearing due to the orbital motion on the average spectrum. We then broadened the smeared average arc spectrum with a Grey profile for different values of $v \sin i_{\text{em}}$, measuring each time the resulting FWHM in km s$^{-1}$. We find that the measured FWHM of the Fe$\text{II}$ lines corresponds to $v \sin i_{\text{em}} = 255 \pm 20$ km s$^{-1}$.

### 3.3.5 Evidence for Mg$\text{I}$ in emission

The average spectrum displays a weak emission line consistent with Mg$\text{I}$ at 5183.604 Å. The line was not detectable in the single or trailed spectra, but a fit with a single Gaussian function indicate that the line is significant on a 5$\sigma$ level in the average spectrum. Two other Mg$\text{I}$ lines, at 5167.321 Å and 5172.684 Å, belong to the same multiplet with Mg$\text{I}$ (5183.604 Å). The position of Mg$\text{I}$ (5172.684 Å) is consistent with that of the spike on the red wing of Fe$\text{II}$ (5169.03 Å) (see Fig. 3.4), although the detection of the latter is not statistically significant when the prominent Fe$\text{II}$ line is included in the fit. Mg$\text{I}$ (5167.321 Å) could be present but it can not be resolved from Fe$\text{II}$ (5169.03 Å). The FWHM of the Mg$\text{I}$ (5183.604 Å) line is $172 \pm 39$ km s$^{-1}$ (see Table 2) which corresponds to an intrinsic width of $v \sin i_{\text{em}} = 98 \pm 39$ km s$^{-1}$ (measured as we did for the Fe$\text{II}$ triplet in Section 3.3.4). This value is smaller than what we obtained from the Fe$\text{II}$ triplet.

### 3.3.6 Doppler tomography

We employed emission line Doppler tomography to map the observed emission features. Here we used the modulation Doppler tomography method of Steeghs (2003), using the same code that was employed in the Bassa et al. (2009) study. The observed spectra were first phase binned using 30 orbital bins. The underlying continuum was subtracted using a polynomial fit to line-free regions. In Figure 3.5 we show the resulting tomograms for the H$\beta$ line and the two Fe$\text{II}$ lines at 4923.92 and 5169.03 Å. The H$\gamma$ line reconstructions were effectively identical to H$\beta$ and we compare the two Fe$\text{II}$ lines given their apparent difference in intrinsic width. All emission lines reconstructions are consistent with line emission from a region near the mass donor star with no evidence for any extended emission from a residual accretion disc or stream. We find that the line flux is strongly modulated, as expected for an origin on
Figure 3.5: Tomographic reconstructions for the H$\beta$ and for the Fe\textsc{ii} lines at 4923.92 Å and 5169.03 Å. The top-left panel in each case shows the observed line profile as a function of the orbital phase while the top-right panel shows the reconstructed data from the converged maximum entropy solution. The bottom panels show the Doppler maps resolving the emission of each line in a $V_X-V_Y$ plane. The constant and the phase-dependent contribution to the flux are shown in the left and right quadrant respectively (see Steeghs 2003). The color scale indicates the fractional amplitude of the variable map in percent. A Roche lobe model and ballistic stream trajectory is plotted for an assumed system mass ratio of $q=0.25$ and radial velocity semi-amplitude of the companion star $K_2 = 410$ km s$^{-1}$. 
the irradiated face of the companion, and in phase with the observed continuum modulation. Good fits are achieved close to a reduced $\chi^2$ of 1.

The Doppler maps confirm the key attributes we derived in the previous sections using Gaussian fitting. We find that the radial velocity amplitude of the emission ranges from 300-350 km s$^{-1}$, consistent with the $K_{\text{em}}$ values from Section 3.3.3 as well as past estimates of $K_2$. We show in Figure 3.5 the expected location of the donor Roche lobe and gas stream using a mass ratio of $q=0.25$ (consistent with the NS mass range favoured by Özel 2006 and the work of Muñoz-Darias et al. 2009, see also Bassa et al. 2009) and $K_2=410$ km s$^{-1}$. The latter is the lower limit to $K_2$ obtained by Bassa et al. (2009) which is a more stringent constraint compared to what we derived in the previous sections (see the discussion in section 3.5). Again, the line at 5169.03 Å appears somewhat anomalous with a significantly more extended emission distribution, reflecting its observed width. Furthermore, the center of the emission is shifted slightly off the Roche lobe, consistent with the apparent phase shift mentioned previously.

In summary, our Doppler tomograms confirm that the narrow emission lines are consistent with an origin on the irradiated face of the mass donor star, with the exception of the emission feature at 5169.03 Å which is both extended and shifted with respect to the other lines. This is in agreement with the broadening effect observed in the Gaussian fitting of 5169.03 Å (Section 3.3.3). We will discuss this further in Section 3.5.

### 3.4 Summary of the results

The results presented in the previous sections can be summarised as follows:

- The g'-band light curve of the source spans a range of 1 magnitude. The profile is variable, but the errors on the individual magnitudes are large: significant variability at a $3\sigma$ level is detected within the phase interval of 0.007 starting from phase 0.349, with an amplitude of 0.35±0.08 magnitudes (Figure 3.2 top panel ). The morphology of the light curve in the g'-band is similar to that of the r'-band light curve reported by Bassa et al. (2009), albeit the latter is not variable.

- The spectra show emission lines from H$\beta$ and H$\gamma$ and three weaker lines consistent with Fe II (4923.92 Å) or He I (4921.929 Å), Fe II (5018.44 Å) or He I (5015.675 Å) and Fe II (5169.03 Å). Since there is no He I line at the position of the last weak emission feature, we favour an Fe II group interpretation. A weak emission line consistent with Mg I (5183.604) is also detected at a $5\sigma$ level in the average spectrum.
3.4 Summary of the results

- The orbital motion displayed by the emission lines is consistent with them originating close to the surface of the companion star facing the NS. The phasing of the continuum variation is in sync with the strong orbital modulation of the emission line strength, as expected if both are mainly produced by the irradiated companion. Evidence of an irradiated companion star was previously found, both during the X-ray outburst phase (Pearson et al. (2006), Muñoz-Darias et al. 2009) and at the beginning of the quiescent period (Bassa et al., 2009).

- The broad disc component at the base of the emission lines that was detected in the spectra from Bassa et al. (2009) is not detected here. There is no evidence for an accretion disc either from the line profiles or the Doppler tomography.

- The fitting of the radial velocity curves of the Hγ and Hβ lines provides 1σ consistent measures of the radial velocity amplitude of the emission lines K_{em}, whose weighted average is 308.5±3.9 km s^{-1}. The minimum width of the emission lines in the average spectrum is obtained with an orbital-motion correction with K_{em} ~300 km s^{-1}, in agreement with the radial velocity curves estimate. This measurement provides a lower limit on the radial velocity semi-amplitude of the companion star K_2, which is fully consistent with the results of Muñoz-Darias et al. (2009). A more stringent lower limit on K_2 is reported by Bassa et al. (2009) (see discussion in section 3.5).

- The systemic radial velocity γ was measured from the radial velocity curve traced by the Hγ and Hβ lines and from the wavelength offset of the same lines in the orbital-motion subtracted averaged spectrum. The resulting values of γ are in agreement within 2σ, their weighted average being 43.8±3.6 km s^{-1}. The offset of the FeII triplet in the average spectrum, instead, is inconsistent with this value of γ. A phase shift of -0.03/-0.05 of the source region of the FeII lines with respect to the binary axis can account for this discrepancy (see Section 3.5). The Doppler maps also show that the emission of the FeII lines is shifted, particularly for the one at 5169.03 Å. Our measure of the systemic radial velocity is in agreement with the work of Muñoz-Darias et al. (2009), but is more than 5σ apart from the value obtained by Bassa et al. (2009), γ =78.6±3.9 km s^{-1}. Even taking into account that the value of γ is affected by the accuracy of the wavelength calibration (0.023 Å in Bassa et al. 2009 and 0.1 Å for our data) the two measurements differ by more than 4σ. Similar mismatches using VLT data are not unprecedented (see Orosz et al. 2011).
- With the exception of the weak Mg I, the emission lines are very broad. The FWHM of the Fe II lines indicates a $v \sin i_{em} = 255 \pm 22$ km s$^{-1}$, if the broadening results from the rotation of the companion star alone. The Mg I (5183.604 Å) line instead provides a much lower $v \sin i_{em}$ of $98 \pm 39$ km s$^{-1}$.

### 3.5 Discussion

Using medium resolution VLT FORS2 spectra of EXO 0748−676, ranging from 4222 to 5701 Å, we found emission lines indicating that the companion star is still heated by irradiation, as was observed soon after the onset of the quiescent phase (Bassa et al., 2009). We detected H$\gamma$, H$\beta$ and a set of Fe II lines, which is unusual but not unprecedented in LMXBs (Marsh et al., 1994a). We also detect a faint Mg I line. The source of the irradiation is most likely the X-rays associated with the cooling compact object (Degenaar et al., 2009). The slow rate of the NS cooling that has been observed in EXO 0748−676 with XMM, Chandra and Swift (Degenaar et al. 2011, Díaz Trigo et al. 2011) is in agreement with the fact that the companion star is still significantly irradiated, after more than one year of quiescence.

The g'-band light curve of EXO 0748−676 shows evidence for variability between different orbits, in the phase interval of 0.007 starting from phase 0.349. The variability amplitude is 0.35±0.08 magnitudes. This implies a change in the flux heating the companion star, which could potentially be due to a change in a pulsar wind (see below) or to variability in the X-ray radiation, although the latter is hard to explain given the small variations observed in the X-rays (Degenaar et al. 2011, Díaz Trigo et al. 2011). Furthermore, theoretically one does not expect the X-ray flux of the glowing cooling NS to vary on short timescales (Brown et al., 2002). A comparison with the R-band light curve presented in Bassa et al. (2009) shows that the morphology of the light curves is similar, albeit the g'-band one is variable.

Although we can not rule out a disc contribution to the optical continuum, the non-detection of disc line emission is unusual in comparison with typical observations of quiescent LMXB (e.g. Marsh et al. 1994a, Torres et al. 2002a). The disc-instability model that can explain the short outburst of typical X-ray transients (Smak 1971, Dubus et al. 2001) predicts that the disc is present even during quiescence and that an outburst is triggered by a sudden rise of viscosity. The lack of disc lines in EXO 0748−676 suggests instead that the mass transfer has dramatically dropped and might have even stopped since the observations performed by Bassa et al. (2009) at the beginning of the quiescent phase. On the other hand, the disc-instability model might not apply to the case of EXO 0748−676 as it can not easily explain the 20-year long outburst
3.5 Discussion

that the source underwent. The trigger of tens of years long outbursts is not well understood and might have to do with variations in the envelope of the companion star, rather than with instabilities of an accretion disc (Remillard & McClintock, 2006b).

In an attempt to obtain constraints on the NS mass from the emission lines, we determined the rotational velocity obtained from the FWHM of the Fe\textsc{ii} triplet observed in the spectra. If those lines are produced on the companion star surface, their width is expected to be dominated by the effect of rotational broadening $v \sin i_{\text{em}}$ (Gray, 1992a). As also emerged from the tomographic reconstructions, the line emission does not arise from the full inner hemisphere of the companion star, but concentrates close to L1 point. For this reason the $v \sin i_{\text{em}}$ obtained from the Fe\textsc{ii} lines would represent a lower limit to the projected spin velocity of the star $v \sin i$. Due to the shift between the center of light of the Fe emission lines and the center of mass of the companion, the radial velocity semi-amplitude of the emission lines $K_{\text{em}}$ also provides only a lower limit to $K_D$. The combination of the lower limits on $K_D$ and $v \sin i$ provides in turn a lower limit on the NS mass. From the radial velocity curves and from our average spectrum we measured $K_2 \gtrsim 308.5 \pm 3.9$ km s\(^{-1}\) (see Sections 3.3.2 and 3.3.3). From the Doppler maps (which are not influenced by asymmetries in the line profiles, see Bassa et al. 2009) we obtain a higher limit, $K_2 \gtrsim 355$ km s\(^{-1}\). An even more stringent limit is provided in Bassa et al. (2009), $K_2 \gtrsim 405$ km s\(^{-1}\). This was obtained from Doppler tomography of the H\textsc{a} line, which is expected to form closer to the center of mass of the companion star with respect to higher ionization potential lines such as the H\textsc{b} and H\textsc{g}, providing a radial velocity closer to $K_D$ (e.g. Harlaftis et al. 1999, Unda-Sanzana et al. 2006).

The constraints on the mass of the NS in EXO 0748\(−\)676 that can be obtained combining the results of Bassa et al. (2009) with our measure of $v \sin i_{\text{em}}$ show that, if the width of the Fe lines in our spectra is indeed setting a lower limit to $v \sin i$, then the mass of the compact object in EXO 0748\(−\)676 should be $\gtrsim 3.5 \, M_\odot$. This is more than the value of $\sim 3 \, M_\odot$ which is considered to be an upper bound to the mass of a NS. A BH interpretation would be in conflict with the detection of thermonuclear X-ray bursts from the source, which establish that the compact object is a NS (Gottwald et al. 1986). Given the fact that a bursting BH or a 3.5$M_\odot$ NS would be against theories about those objects, we have investigated possible scenarios to solve this incongruity.

Our mass constraint is based on the assumption that the width of the Fe lines provides a measure of the projected rotational velocity of the companion star $v \sin i$, but that might not be the case. An asymmetric irradiation of the companion due, e.g., to the shadowing of a residual accretion disc, could induce currents in the atmosphere trying to re-distribute the heat (Kirbiyik 1982, Wolff et al. 2002). The velocity of the current would add to the width
of the emission lines. Nevertheless, this velocity has to be of the order of the total line broadening in order to give a significant contribution, i.e. a few hundreds km s$^{-1}$. This is more than the sound speed on the surface of a late type star (Frank et al., 2002a).

Another possibility is that the Balmer lines, originating closer to the companion star surface, are broadened by saturation effects (Osterbrock, 1989), while the Fe$^{II}$ triplet, slightly phase shifted, is produced in a stream of residual accreting matter whose velocity causes the observed FWHM. This interpretation requires a bit of fine tuning of two broadening effects and it does not fit well with the lack of any evidence for an accretion disc.

The large width of the Fe lines could also be due to a blend with unresolved lines of other atomic species. This is suggested by the detection of a faint (5σ significance) line consistent with Mg$^{I}$ at 5183.604 Å. As mentioned in Section 3.3.5, the latter belongs to a Mg$^{I}$ multiplet including lines at 5167.321 Å and 5172.684 Å, both very close to the position of the reddest detected Fe$^{II}$ line. Mg$^{I}$ (5172.684 Å) might be identified with the peak next to Fe$^{II}$ (5169.03 Å) that we have masked when measuring the FWHM of the Fe$^{II}$ line. The peak is not significant in the average spectrum, but the anomalous extension and shift of Fe$^{II}$ (5169.03 Å) in the Doppler maps suggest that this narrow feature might be real and present in all the spectra, altering the look of the line in the Tomographic reconstruction. On the other hand, Mg$^{I}$ (5167.321 Å) could be present, but it is not resolved from Fe$^{II}$ (5169.03 Å). While a blend with Mg$^{I}$ can explain the width of Fe$^{II}$ (5169.03 Å), a blend with He$^{I}$ can broaden the other two lines of the Fe$^{II}$ triplet. As in the "stream" scenario, the FWHM of H$\beta$ and H$\gamma$ would instead be determined by saturation effects. The downside of this sketch is that it requires some fine tuning of the width and intensity of the lines of different species in order to produce consistent FWHM and offsets among the three Fe$^{II}$ lines. Other lines from Mg$^{I}$ and He$^{I}$ (at 4387.928 and 4471.68 Å) that are within the wavelength coverage of our observation are not detected, so we have to meet the further requirement that only the lines that overlap with Fe$^{II}$ are strong enough to be observed. Although the Mg$^{I}$ (5183.604 Å) detection supports this scenario, we can not confirm it or rule it out with the resolution and signal-to-noise of our observations.

For this reason, we have considered another possible situation, where the lines are produced in a wind of matter evaporating from the companion star, e.g. due to the action of a pulsar wind and/or the X-ray heating. The emission lines, originating in the wind of evaporated material, are broadened due to the wind velocity. The Balmer lines, produced closer to the companion star surface, display the orbital motion of the irradiated secondary, while the Fe$^{II}$, rising from further out in the wind, display a slight phase delay in the orbital motion as the evaporated material starts to trail the companion star as it moves outwards due to angular momentum conservation. The evaporation
3.6 conclusions

of material could also explain the lack of evidence for emission lines from an accretion disk, as it would quench the accretion. Moreover, the presence of a pulsar wind in addition to the X-ray heating might be responsible for the observed variability in the g'-band light curve, which is possible but rather difficult to produce in terms of variability of the X-ray flux. At last, this “Black-widow like” scenario is consistent with the extended distribution of the line emission in the Doppler maps. The weak point of this outline is that it may be difficult to produce the Mg\textsc{i} (5183.604 Å), which is narrower than the other lines. The weakness of the line did not allow the production of Doppler maps to verify if the source region of this feature is narrow or extended and if it is the same as the Balmer or Fe\textsc{ii} lines. Moreover, it has to be noticed that the pulsar in quiescence has not been found in the radio waveband (private communication M. Burgay).

3.6 conclusions

We performed phase-resolved medium-resolution optical spectroscopy with VLT/FORS2 on the eclipsing LMXB EXO 0748−676, one year and two months after it returned to quiescence. We found evidence for variability in the g'-band light curve and we found that the spectra only present emission lines coming from the region close to the companion star, with no line contribution from a disc. This is unusual compared with typical X-ray transients and could be related to the mechanism that triggers long duration outbursts such as those displayed by the source, which is not yet understood.

The g'-band variability can be explained by a varying X-ray flux or by a variable pulsar wind. X-ray observations show little variations in the flux, as expected from a cooling NS.

The H\textbeta, H\textgamma and Fe\textsc{ii} emission lines in the average spectrum are remarkably broad. Their FWHM is not likely to be dominated by rotational broadening alone as this would lead to a compact object mass inconsistent with a NS. The width of the lines can be explained with bulk gas motion, e.g. the lines could be produced in a wind of material evaporated from the companion star envelope due to X-ray heating, possibly in combination with a pulsar wind. It is also possible that some of the lines are blends of unresolved features. Despite extensive efforts to search for spectral features using multiple methods, we detect no absorption features from the mass donor star. Deeper observations with better resolution might allow to resolve blends and detect more emission lines that could provide a reliable lower limit to the companion star rotational broadening and, in turn, to the NS mass. Moreover, there is still the chance to detect absorption lines from the non-irradiated face of the companion star, which would finally provide a mass estimate for this elusive NS.
Acknowledgments

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Chapter 4

CXOGBS J174444.7–260330: a new long orbital period cataclysmic variable in a low state


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Abstract

We present phase-resolved spectroscopy and photometry of a source discovered with the Chandra Galactic Bulge Survey (GBS), CXOGBS J174444.7−260330 (aka CX93 and CX153 in the previously published GBS list). We find two possible values for the orbital period $P$, differing from each other by $\sim$13 seconds. The most likely solution is $P = 5.69014(6)$ hours. The optical lightcurves show ellipsoidal modulations, whose modeling provides an inclination of $32\pm1^\circ$ for the most likely $P$. The spectra are dominated by a K5 V companion star (the disc veiling is $\lesssim5\%$). Broad and structured emission from the Balmer lines is also detected, as well as fainter emission from HeI. From the absorption lines we measure $K_2 = 117\pm8$ km/s and $v\sin i = 69\pm7$ km/s. By solving the system mass function we find $M_1 = 0.8\pm0.2 {M_\odot}$ for the favored $P$ and $i$, consistent with a white dwarf accretor, and $M_2 = 0.6\pm0.2 {M_\odot}$. We estimate a distance in the range 400 – 700 pc. Although in a low accretion state, both spectroscopy and photometry provide evidence of variability on a timescale of months or faster. Besides finding a new, long orbital period cataclysmic variable in a low accretion state, this work shows that the design of the GBS works efficiently to find accreting X-ray binaries in quiescence, highlighting that the spectra of CVs in a low-accretion state can at times appear suggestive of a quiescent neutron star or a black hole system.

4.1 introduction

We present optical follow-up of the X-ray source CXOGBS J174444.7−260330, discovered in the Galactic Bulge survey (GBS) of Jonker et al. (2011). For the ease of readability, we will refer to the source with its label in the GBS source list, CX93. One of the main goals of the GBS is to detect quiescent X-ray binaries (XRBs) - namely binary systems where a white dwarf (WD), a neutron star (NS) or a black hole (BH) is accreting matter from a companion star - that are suitable for dynamical measurements of the mass of the compact object. Those mass measurements can be done through phase-resolved optical spectroscopy of the donor star, provided that good constraints can be put on the binary inclination. If the system inclination $i$ is known, the mass of the accreting compact object can be obtained by solving the system mass function (see, for instance, Charles & Coe 2006a). This requires measuring the orbital period $P$, the semi-amplitude of the radial velocity curve of the companion star $K_2$ and the ratio between the mass of the donor and that of the accretor, $q \equiv M_2/M_1$. In Roche lobe filling XRBs, with tidally locked companion stars, $q$ is a function of $K_2$ and of the projected rotational velocity of the secondary.

\textsuperscript{1}data from ESO programs 085.D-0441(A) and 087.D-0596(D)
Figure 4.1: 20′′×20′′ finding charts showing the near infrared (J-band) and the optical (R-band) counterpart to CX93, indicated by the black arrows. The left panel is from the variable sources in the Via Lactea (VVV) survey, where the VVV source detections are indicated by circles. Two overlapping circles at the counterpart position correspond to the Chandra position and to that of the NIR source (R.A. = 17h 44m 44s 790, Dec. = −26° 03′ 30″08, with an accuracy better than 0.1″). The right panel is an image from the VIsible Multi-Object Spectrograph (VIMOS).

Prime targets for this study are eclipsing systems, where the inclination can be derived from the eclipse duration based on geometrical arguments only. Among non-eclipsing systems, the inclination can be estimated by modeling the ellipsoidal variation in the optical lightcurve, caused by the distortion of the companion star shape associated with Roche-lobe overflow (care must be taken if other continuum sources contribute to the lightcurves).

Because CXOGBS J174444.7−260330 was initially not identified as a duplicate, it has two labels in the GBS source list, CX93 and CX153 (the offset between the two detections is 3″). The best X-ray source position, from observation CX93, is R.A. = 17h 44m 44s 791(9), Dec. = −26° 03′ 30″3(1) (the 1σ uncertainties, indicated in between brackets, do not include the 90% confidence 0′′6 Chandra boresight error). The source was identified as a quiescent X-ray binary candidate based on preliminary low-resolution spectra of the optical counterpart (Figure 4.1). A near infrared (NIR) counterpart to CX93 was found in the data from the VISTA (Visible and Infrared Survey Telescope for Astronomy) variable sources in the Via Lactea (VVV) survey (Minniti et al. 2009, Catelan et al. 2011, Saito et al. 2011), with magnitude 14.81±0.02 in the J-band, 14.01±0.02 in the H-band and 13.76±0.03 in the K-band. Here we present phase-resolved photometry and optical spectroscopy of the target performed with several instruments. We detected signatures from the mass donor star, which allowed us to measure the orbital ephemeris and constrain...
the mass of the accreting compact object.

4.2 Observations and data reduction

4.2.1 Phase-resolved imaging

CX93 was observed in 2010 Jul. using the Mosaic-2 instrument on the Cerro Tololo Interamerican Observatory 4 m Blanco telescope (Table 4.1). Thirty three 120s-long exposures were collected through the Sloan $r'$ filter. Initial data processing was done by the National Optical Astronomy Observatory (NOAO) Mosaic pipeline (Shaw, 2009). The lightcurves were extracted using the ISIS image subtraction code (Alard & Lupton, 1998; Alard, 1999), which provided clean subtracted images. A variable optical counterpart coincident with the X-ray position of CX93 was clearly identified, despite the fact the variability is only at the level of $\sim$5%. We independently analyzed the images using DAOPhot II (Stetson, 1987a) and obtained comparable lightcurves, although of somewhat poorer quality than those obtained with ISIS. Since ISIS only yields differential count rates, we used DAOPhot II on the best reference image to measure the baseline (non-variable) count rate. This together with the differential count rates from ISIS yielded total count rates as a function of time. We finally converted these to approximate magnitudes using conversion factors supplied by the NOAO pipeline. These are deduced by comparison to USNO B1.0 stars, and have an estimated uncertainty of at least 0.5 magnitudes. The magnitude of CX93 is $17 \pm 0.5$ magnitudes in the $r'$-band.

CX93 was also observed using the Direct CCD Camera on the Henrietta Swope Telescope at Las Campanas Observatory on the night of 2011 Jun. 27/28. A sequence of 60 sec exposures was obtained through a Gunn $r$ filter for about six hours. Bias correction and flat fielding was performed through standard CCD data processing in IRAF. ISIS was used for image subtraction photometry as for the Mosaic-2 data.

4.2.2 Optical spectroscopy

We combined spectroscopic observations from a number of telescopes: the Visible Multi-Object Spectrograph (VIMOS) and the Focal Reducer and Spectrograph (FORS) at the Very Large Telescope, the Inamori Magellan Areal Camera and Spectrograph (IMACS) at the Magellan telescope, the ESO Faint Object Spectrograph and Camera (EFOSC) at the New Technology Telescope

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2IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
Table 4.1: Journal of the observations. The resolution $R$ of the spectra is measured from the width of the night sky lines. The last column list the spectra dispersion $D$.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Date (UT)</th>
<th>#</th>
<th>Exposure (s)</th>
<th>Grism/Filter</th>
<th>Seeing (arcsec)</th>
<th>Slit width (arcsec)</th>
<th>Binning</th>
<th>Sp. range (Å)</th>
<th>$R$ (Å)</th>
<th>$D$ (Å/px)</th>
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<tr>
<td>VIMOS</td>
<td>2011 Apr. 29</td>
<td>2</td>
<td>875</td>
<td>MR-2.2</td>
<td>0.6</td>
<td>1.0</td>
<td>1x1</td>
<td>4879-10018</td>
<td>10</td>
<td>2.50</td>
</tr>
<tr>
<td>IMACS</td>
<td>2011 Jun. 23-26</td>
<td>4</td>
<td>1200</td>
<td>Gri-300-17.5</td>
<td>0.8-1.2</td>
<td>1.0</td>
<td>1x1</td>
<td>4365-6654</td>
<td>4.5</td>
<td>1.28</td>
</tr>
<tr>
<td>FORS</td>
<td>2011 Jul. 4</td>
<td>4</td>
<td>900</td>
<td>1200R+93</td>
<td>0.9-1.4</td>
<td>1.0</td>
<td>2x2</td>
<td>5957-7280</td>
<td>2</td>
<td>0.38</td>
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<tr>
<td>MagE</td>
<td>2011 Aug. 6</td>
<td>1</td>
<td>900</td>
<td>Echelle</td>
<td>1.2</td>
<td>1.0</td>
<td>1x1</td>
<td>3100-11200</td>
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<td>0.47</td>
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<td>Photometry</td>
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<tr>
<td>Mosaic</td>
<td>2010 Jul. 12-18</td>
<td>33</td>
<td>120</td>
<td>Sloan r'</td>
<td>1.3</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Swope</td>
<td>2011 Jun. 27-28</td>
<td>360</td>
<td>60</td>
<td>Gunn r</td>
<td>1.5</td>
<td>–</td>
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</table>
Figure 4.2: Main spectral features from CX93 in the IMACS (top panel), FORS (middle panel) and VIMOS (bottom panel) Doppler-corrected average spectra.
Figure 4.3: Top panel: Mosaic-2 lightcurve. The solid line represents the best fit model assuming ellipsoidal variations plus a single bright spot. Bottom panel: LCO lightcurve, fitted with a pure ellipsoidal modulation model for an inclination of $i = 32.3^\circ$ (dashed line) and $i = 36.2^\circ$ (drawn line). The observations are binned for clarity, but fitting was done on unbinned data.
The mass of the compact object in CX93 (NTT) and the Magellan Echelle (MagE) spectrograph, also at the Magellan telescope. A list of the observations and the instrument settings is given in Table 4.1. The NTT/EFOSC data are not included in the table and in the rest of this work because of the poor quality of the data due to weather conditions. Template spectra of the stars HD163197 (spectral type K4IV) and HD130992 (K3.5V) were also observed with FORS and MagE, respectively. The images were corrected for bias, flat-fielded and extracted using the FIGARO package within the STARLINK software suite and the packages PAMELA and MOLLY developed by T. Marsh. We used sky flats for the flat-fielding and we subtracted the sky background by fitting clean sky regions along the slit with a second order polynomial. The spectra were optimally extracted following the algorithm of Horne (1986b) implemented in PAMELA and wavelength-calibrated in MOLLY with a final accuracy of 0.02 Å for FORS (using arc exposures taken during daytime), 0.04 Å for IMACS, 0.09 Å for VIMOS and ~0.04 Å for MagE. In each spectrum, the wavelength calibration was checked and corrected for shifts with respect to the position of the night-sky OI lines at 5577.338 Å and/or at 6300.304 Å (Osterbrock et al., 1996b). Each spectrum has been normalised dividing by a spline fit to the continuum, with a maximum order of 10. The full MagE spectrum was extracted, but only order 9 (5630-6673 Å) and 10 (6265-7415 Å) were used for our dynamical study of CX93, as they cover the spectral region of the Hα and Ca I, which is rich in absorption features for K type stars and where the signal-to-noise ratio in the spectrum is highest. The MagE spectra show a complex continuum, mainly caused by instrumental response variations across the relevant orders. In order to normalise the spectra, we clipped two ~300 Å-long pieces from the order 9 spectrum (5920-6240 Å and 6310-6630 Å), and one from the order 10 (6300-6750 Å). The regions were selected to keep as many absorption lines as possible in one spectrum. By selecting short pieces from the spectrum we could achieve a good fit to the continuum on each piece with a relatively low-order spline (order 10), avoiding as much as possible the risk of altering the equivalent width of the lines that occurs when using high order splines. The overlap between the orders 9 and 10 allows for a double-check of the results.

4.3 Analysis and results

4.3.1 Spectral features

The spectra of CX93 display a number of absorption lines from the stellar atmosphere of the companion star, but also strong emission lines consistent with Hα and Hβ and with HeI at λ6678.149 and λ5875.618. For each instrument, we combined all the spectra into an average spectrum, after correcting for the Doppler shift of the lines due to the orbital motion (see Section 4.3.3 for the
measurement of the orbital shifts). The top panel of Figure 4.2 shows the average of the IMACS spectra where the Hα and Hβ lines appear as prominent emission features. HeI in emission at 5875.618 Å is next to a blend of the NaI doublet lines in absorption (λ5895.92, λ5889.95) mainly produced by the interstellar medium. The MgI triplet at λ5167, λ5172 and λ5183 is visible, although not resolved. The CaI triplet (λ6102, λ6122 and λ6162) and a blend of stellar lines in absorption at λ6495 are also present.

The Doppler-corrected average of the FORS spectra, in the central panel of Figure 4.2, shows the region of Hα, with better resolution than that of the IMACS spectrum. HeI in emission at λ6678.149 and a forest of absorption lines are visible, in particular from FeII at λ6432.65 and λ6457 and FeI at λ6430.85. Finally, the bottom panel of Figure 4.2 shows a section of the Doppler-corrected average of the VIMOS spectra, displaying the main features in the red part of the spectrum of CX93: the CaII triplet in absorption, at λ8498, λ8542 and λ8662, and a number of emission lines from the Paschen series of hydrogen. A telluric molecular band of water is also present.

In most of the spectra, the Hα emission line appears single-peaked but composite, with a main peak overlapping with at least one side wing. Both components are broad, with FWHM of the order of 350-450 km s\(^{-1}\). The equivalent width (EW) of the line is roughly constant around \(\sim -13/16\) Å across the IMACS and FORS spectra, with no dependence on phase. In the MagE spectrum, taken one month later, it drops significantly to -2.9±0.7 Å. The two VIMOS spectra, collected two months earlier than all the other data-sets, suggest a more active state of the source compared to the IMACS and FORS observations. The EW is -133±1 Å and -140±1 Å in the two spectra. The Hβ line has similar EW to Hα and an even larger FWHM of \(\sim 700\) km s\(^{-1}\).

### 4.3.2 Binary period

The orbital period of CX93 was determined using the Mosaic-2 lightcurve, combined with spectroscopic information. The Swope data provide only loose constraints on the system parameters, which we therefore only used as a consistency check of our results. In order to obtain the best possible accuracy on \(P\), we followed three main steps.

- An initial Lomb-Scargle periodogram of the Mosaic-2 data revealed an apparent period of 0.12 d. Some dispersion was seen when the Mosaic-2 lightcurve was folded on this period indicating that this is the first harmonic. Folding on twice this period yielded an asymmetric double-humped lightcurve (Figure 4.3, top panel). A period of \(P=0.23710(5)\) d was measured by fitting the lightcurve with a sum of two sine waves, with a 2:1 frequency ratio, and amplitudes and relative phases allowed
to vary freely. Error bars were estimated in the usual way from $\chi^2$ totals, after adding an additional error to the Mosaic-2 datapoints to represent unresolved flickering. The Swope data provide a less constrained $P = 0.23(1)$ d, consistent with the Mosaic-2 result. Unfortunately a joint fit to both data sets was not well constrained due to the difficulty in extrapolating the ephemerides across a year (see below), and possible changes in lightcurve morphology.

- The Mosaic-2 $P$ was then used to phase fold the spectroscopic observations and construct an initial radial velocity curve (rvc, the procedure is described in Section 4.3.3, for the final orbital period). The rvc looked consistent with orbital motion of the companion star, and was fitted with a sine wave, measuring $T_0$ in between the time of the spectroscopic observations. We double-checked the measurement of the orbital period leaving it free in the fit, obtaining $P = 0.23710(5)$ d as expected.

- At last, $T_0$ was compared with the time of the phase 0 in the Mosaic-2 lightcurve, $T_M$. We refined the measurement of $P$ by considering that it must be such that the difference $T_0 - T_M$ corresponds to an integer number of orbital cycles. Both the minima in the Mosaic-2 lightcurve potentially correspond to $T_M$, since the $P$ measured above is not accurate enough to unambiguously phase the lightcurve, collected one year earlier than the spectroscopic observations. Depending on the phasing, we find three possible solutions for $P$. If $T_M$ is at the deepest, primary minimum of the Mosaic-2 lightcurve, then $P = 0.237089(3)$ d, with $T_0 - T_M = 14898 \times P$. If $T_M$ corresponds to the secondary minimum, then $P = 0.237169(3)$ d with $T_0 - T_M = 14888 \times P$ or $P = 0.237009(3)$ d with $T_0 - T_M = 14889 \times P$. The rvc fitting favors the first solution, as it is the closest to the best-fitting period. The second solution is less likely but, yielding a $\Delta \chi^2$ of 3.5 with respect to the best-fit $\chi^2$, it has a probability of $\sim 20\%$ to be correct. The last solution is very unlikely, yielding $\Delta \chi^2 \sim 15$.

In conclusion, $P = 0.237089(3)$ d is the statistically most likely orbital period for CX93, although $P = 0.237169(3)$ d can not be ruled out at high confidence.

### 4.3.3 Radial velocity curve

The orbital Doppler shifts of the companion star in CX93 were measured from the absorption lines in the spectra, by cross-correlating with the K4IV template star spectrum acquired with FORS. The emission lines were masked. Since we were using observations from different instruments, the template and each target spectrum were re-binned to the same dispersion and broadened
4.3 Analysis and results

Figure 4.4: Radial velocity curve measured from the absorption lines (top panel) and from the peak component of the Hα emission line (bottom panel). The data are fitted with a circular orbit (solid line), increasing the error bars in order to obtain a reduced $\chi^2$ close to 1.

To the same spectral resolution before the cross-correlation. For MagE, the order 10 and the two parts in which the order 9 was split were cross-correlated separately with the FORS template, and the results were averaged in order to reduce the uncertainty. For all the spectra, the uncertainty on the velocity offsets due to the wavelength calibration has been added in quadrature to the velocity errors from the cross-correlation. The observations were phase folded with the most likely orbital period from Section 4.3.2, obtaining the rvc shown Figure 4.4 (top panel).

The rvc was fitted with a circular orbit of the form $v(\phi) = \gamma + K_2 \sin(2\pi\phi + \varphi)$, providing a large reduced $\chi^2$ of $\sim 13$ (8 degrees of freedom). The uncertainties on the parameters were estimated assuming that the sinusoidal model was correct, and multiplying the errors of the individual velocity shifts by 3 to reach a reduced $\chi^2$ close to 1. $T_0$ was calculated near the middle of the time of the observations and so that $\varphi = 0$, according to the convention of phase 0 at inferior conjunction of the companion star. The period was fixed in the fit. The resulting parameter values are:

$$T_0 = 2455743.1892 \pm 0.0029 \text{ HJD/UTC}$$
$$K_2 = 117 \pm 6 \text{ km s}^{-1}$$
and $\gamma = -69 \pm 6 \text{ km s}^{-1}$, in the rest frame of template star employed for the
cross correlation. A systemic radial velocity of $29.8 \pm 0.4$ km s$^{-1}$ was found for the latter, by fitting a Gaussian function to the H$\alpha$ absorption line and measuring the offset of the line centroid with respect to its rest-frame wavelength. The systemic velocity for CX93 is thus
\[ \gamma = -39 \pm 6 \text{ km s}^{-1}. \]

Figure 4.4 (bottom panel) shows the rvc for the H$\alpha$ line, where the orbital velocities were measured through Gaussian fitting to the line peak in each spectrum. The curve was constructed and fitted as we did above. The orbital motion is close to that of the companion star (from the absorption lines), only slightly leading in phase by $\varphi = 0.08 \pm 0.03$. The fit provides $K_{em} = 58 \pm 6$ km s$^{-1}$, smaller than the radial velocity semi-amplitude we measured from the absorption lines, suggesting an origin of the H$\alpha$ line towards the inner face of the companion. The CX93 systemic velocity is $-45 \pm 4$ km s$^{-1}$, consistent at the 1$\sigma$ level with the result above. Similarly, we measured radial velocity shifts for the H$\alpha$ wing feature. We find variable velocity shifts from $\sim 10$ up to $\sim 600$ km s$^{-1}$ towards the red or the blue, with no clear dependence on the orbital phase.
4.3.4 Rotational broadening and mass ratio

The observed FWHM of the absorption lines in the spectra is determined by the intrinsic line width, expected to be dominated by rotational broadening, broadened by the instrumental resolution profile and smeared by the motion of the companion star during the integration time of one observation. In order to measure the intrinsic line width, namely $v \sin i$, we analysed the MagE spectra, which have the best resolution among our data-sets. We considered all the absorption lines in the spectrum (none of which is known to be strongly affected by thermal or pressure broadening), masking the emission lines. The spectral type of the MagE template, K3.5V, is likely close to that of the companion star in CX93 (see Section 4.3.5). Steeghs & Jonker (2007) showed that a small difference in the spectral type of target and template star do not significantly effect the measurement of $v \sin i$ in close binaries. The integration time smearing on the target spectra was taken into account by artificially smearing the template spectrum by $2\pi TK \cos(2\pi \phi)/P$ km s$^{-1}$, where $T$ is the duration of one exposure on CX93. After that, we broadened the template spectrum with different trial values of $v \sin i$. For each trial value, the template was subtracted from the target spectrum and a $\chi^2$ test was performed on the residuals. Different scalings of the template are tried to account for possible disc veiling\textsuperscript{3}. The broadening that gives the minimum $\chi^2$ is a measure of the actual $v \sin i$. A value of 0.5 for the limb darkening was assumed, appropriate for a main sequence star as we expect for a $\sim 5$ hour orbit. Steeghs & Jonker (2007) tested the effect of the uncertainty on the limb darkening coefficient on $v \sin i$, showing that it is $\sim 1$ km s$^{-1}$ for a difference of 0.25 in the limb darkening. This is negligible with respect to the error on our measurement (see below). Finally, since we subtract template and target spectra acquired with the same instrument, the instrumental resolution profile is not affecting the procedure.

The uncertainty on $v \sin i$ was estimated following the Monte Carlo approach used by Steeghs & Jonker (2007). We copied the target spectrum 500 times, using a bootstrap technique where the input spectrum is resampled by randomly selecting data points from it. The bootstrapping maintains the total number of data points in the spectrum. For each bootstrap copy, one value of $v \sin i$ was measured, corresponding to the minimum $\chi^2$ of the residuals as described above. The distribution of $v \sin i$ obtained from the 500 copies is well described by a Gaussian, whose mean and root-mean-square (rms) provides the optimal subtraction is performed using the optsub command in molly. The routine works on normalized spectra, assuming $F_d = F_s - F_t \ast f$, where $F_s$ is the flux of the target, $F_t$ of the template, $F_d$ is the disc contribution outside the lines and $0 < f < 1$ is a constant, the optimum factor. The routine finds the $f$ that minimizes the structure in the residuals between $F_d$ and a smooth version of $F_d (< F_d >)$, accounting for broad features in the disc spectrum. The disc veiling is $1 - f$.\textsuperscript{3}
the best-fit $v \sin i$ and its $1\sigma$ error. Our final measurement of the rotational broadening is the uncertainty-weighted average of the measures from the first and second piece of the MagE order 9, $v \sin i = 69 \pm 7 \text{ km s}^{-1}$ (Figure 4.5).

Given $v \sin i$ and $K_2$ we could calculate the system mass ratio $q = M_1/M_2$ from the relation $\frac{v \sin i}{K_2} \approx 0.462 q^{1/3} (1 + q)^{2/3}$ (Wade & Horne, 1988b). The uncertainty on $q$ was again estimated with a Monte-Carlo simulation, calculating $q$ for 1000 sets of $v \sin i$ and $K_2$ randomly selected within the $1\sigma$ uncertainty on the parameters. The average of the 1000 simulated measurements provides $q = 0.7 \pm 0.1$, where the uncertainty is the standard deviation of the sample.

### 4.3.5 Companion star spectral type

In order to constrain the spectral type of the mass donor in CX93, we considered a set of 21 high signal-to-noise template spectra of G and K stars of luminosity class V, III and IV, acquired with the William Herschel and the Isaac Newton telescopes between 1992 and 1994. Some of them were previously used for spectral type classification by Casares et al. (1996) and Torres et al. (2002b). We subtracted each template spectrum from the Doppler-corrected average of our FORS observations, performing a $\chi^2$ test on the residuals of the subtraction. The template resulting in the minimum $\chi^2$ provides our best estimate for the source spectral type. The spectra were shifted to the rest frame of the FORS average spectrum, and degraded to match the FORS sampling and the line broadening in the target spectra. The appropriate broadening (accounting for the difference in resolution between the templates and the FORS spectrum and the line broadening intrinsic to the source) was found in a similar manner as we did for measuring $v \sin i$: different broadened versions of each template were subtracted (through optimal subtraction, accounting for veiling) from the CX93 spectrum, until the minimum $\chi^2$ was obtained from the fitting of the residuals. As for $v \sin i$, we assumed a limb darkening of 0.5. The minimum $\chi^2$ is obtained for the K5 V template 61 CYGA, with an optimum factor of 0.98$\pm$0.01, indicating a disc veiling of $\sim 2\%$. It is reasonable to assume an uncertainty of one spectral type when using this procedure. Using the same method described in Ratti et al. (2010) (but adopting standard stellar magnitude in the 2mass J, H and K filters from the 2011 compilation of Mamajek\footnote{http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.dat}) we find that the spectral type K5 V is fully consistent with the J, H and K magnitude of CX93 from VVV, for a reasonable value of the extinction of $A_V = 2.0 \pm 0.6$ ($A_K = 0.23 \pm 0.07$, see Discussion).
4.3 Analysis and results

4.3.6 Ellipsoidal modulations and system inclination

The phase folded Mosaic-2 and Swope lightcurves in Figure 4.3 show variability between the two data-sets. The Swope lightcurve displays pure ellipsoidal modulations, with equal maxima and the deepest minimum at phase 0.5, while the Mosaic-2 one, collected one year earlier, presents asymmetric maxima. We attempted to determine the system inclination by modeling the lightcurves with the XRbinary program written by E.L. Robinson\textsuperscript{5}. The Mosaic-2 Sloan $r'$ and the Swope Gunn $r$ filters were represented by a 5548-6952 Å and by a 6181-7212 Å square bandpass, respectively. In the modeling we assume $K_2$ and $q$ as determined in Sections 4.3.3 and 4.3.4, and that the mass donor is a K5V star (see Section 4.3.5) with an effective temperature of 4500 K (Mamajek 2011). As we did in Section 4.3.2, the Mosaic-2 data were primely used to constraint the inclination, while the Swope observations was kept for consistency checks only, due to the poorer quality of the data. Depending on the phasing, we fitted the Mosaic-2 lightcurve (Figure 4.3, top panel) with two models. For the most likely period, the lightcurve has the deepest minimum at phase 0.5 and the highest maximum at phase 0.25. We modeled this with ellipsoidal modulations plus a single (corotating) hot spot on the outer edge of an otherwise non-luminous disc, centred so that it faces earth at phase 0.25 (which is unusual, see Discussion). This provides a reduced $\chi^2$ of $\sim 4$ (30 d.o.f.) and an inclination of $32.3 \pm 1.3^\circ$.

For the alternative orbital period, the minimum at phase 0.5 is no longer the deepest, which implies heating of the side of the secondary facing the primary. We modeled this assuming irradiation from the primary component. On top of ellipsoidal variations, a disc-edge spot, now at phase 0.75, is again included in the model to account for the asymmetric maxima. Since this model depends on the (unknown) disc geometry, two disc versions were tried, with a height to outer radius ratio of 1 to 12 and 1 to 24. The resulting system inclination is $36.2 \pm 1.3^\circ$ and $34.5 \pm 1.3^\circ$, respectively.

The Swope data, modeled with ellipsoidal modulations only, are consistent with all the values of the inclination determined above. Because the Swope observations were taken close to the spectroscopic ones (one night after the last IMACS pointing), and the disc veiling was $\sim 2\%$ in the spectra, it is safe to assume very little disc contribution to the Swope lightcurve. Its consistency with the inclination estimated from the Mosaic-2 data therefore suggests that the latter are not heavily affected by an accretion disc contribution either (on the effect of a disc contamination on $i$ see Cantrell et al. 2010).

\textsuperscript{5}http://pisces.as.utexas.edu/robinson/XRbinary.pdf
4.3.7 Mass of the stellar components

The mass function $f(M_2) : M_1 \frac{\sin^3 i}{(1+q)^2} = \frac{PK_2^3}{2\pi G} \approx 0.04$ of CX93 is too small to constrain the nature of the primary. However, including our measurements of $i$ and $q$, we can solve it for all dynamical parameters. For the most probable period (see Section 4.3.2), we obtain $M_1 = 0.8 \pm 0.2 \, M_\odot$ and $M_2 = 0.6 \pm 0.2 \, M_\odot$. The uncertainty was obtained with a Monte-Carlo method, as we did for $q$ in Section 4.3.4. For the alternative period the inclination is more uncertain and the masses are reduced to $M_1 \sim 0.6 \, M_\odot$ and $M_2 \sim 0.4 \, M_\odot$.

4.3.8 UV counterpart

We searched for an ultraviolet (UV) counterpart to CX93 in 900 seconds long observations from the Galaxy Evolution Explorer (GALEX). The closest object to the source is a 2σ-detection at an angular distance of 2.2″ from our Chandra position. Even assuming that the detection was real, the position is not consistent with that of CX93 (the 1σ accuracy of the astrometry of GALEX is 0″.4, plus a systematic uncertainty of 0″.2 in Dec). The non-detection of a counterpart in GALEX provides an upper limit to the magnitude of CX93 of $\sim$22 AB magnitudes in the near UV GALEX filter (at 2500 Å, limiting magnitude at 3σ).

4.4 Discussion

We have performed phase resolved optical spectroscopy and photometry of the optical counterpart to CX93, constraining the system parameters. We found an orbital period of more than 5.6 hours (most likely $P = 5.69014(6)$ hours) and an inclination of 32-36° (most likely 32.3 ± 1.3°). The best-estimated masses of the primary and secondary star are $0.8 \pm 0.2 \, M_\odot$ and $0.6 \pm 0.2 \, M_\odot$, although lower masses are possible depending on the phasing of the Mosaic-2 lightcurve. The latter displays minima consistent with ellipsoidal modulations, but asymmetric maxima (this is often called O’Connel effect, see Wilsey & Beaky 2009 for a review). Two values of the period, differing by $\sim$13 seconds, provide an acceptable fit to both the lightcurve and the radial velocity data, causing an ambiguity of half cycle in the phasing. For the most likely period, we could model the lightcurve with ellipsoidal modulations plus a disc spot accounting for the highest maximum, at phase 0.25. The phasing of the disc spot is unusual though, as a mass transfer stream hitting the accretion disc is expected to produce a hot spot that leads the donor. Alternative effects causing the shape of the lightcurve, consistent with the phasing, are tidal interaction of the companion star with the outer disc (Frank et al. 2002b, although the most commonly observed tidal interaction effect, superhumps, can only happen in
systems with \( q < 0.25 \), Hynes 2012) or starspots reducing the light at one maximum (see, e.g., Wilsey & Beaky 2009). The latter are often invoked to explain to the O’Connel effect, but a realistic model of starspots is hard to produce with lightcurve modeling codes, especially when a single band lightcurve is available. Compared to the disc-spot model, the effect of a starspot model on the system parameters would be to increase the inclination, leading to smaller masses.

All our data indicate that the primary is a WD, placing CX93 in the class of cataclysmic variables (CVs). The mass of the donor is consistent with the spectral type favored by our spectroscopic observations (K5 V, typical mass is 0.67 M\(_{\odot}\); Drilling & Landolt 2000), or slightly under-massive for the highest inclination scenario. Under-massive companions are often observed in XRBs and CVs as a result of their accretion history (e.g., Her X–1 and Cyg X–2, see Tauris & van den Heuvel 2006, Knigge 2006). The de-reddened upper limit to the UV flux that we could obtain from the Galex observations (assuming \( A_V \) as derived in section 4.3.5) is rather uncertain, due to possible deviation of the extinction law compared to the standard one we used (from Cardelli et al. 1989b). Still, by comparing WD models from Koester et al. (2005) with our UV upper limit, we conclude that the non-detection of a UV counterpart is consistent with the presence of a 15000-30000 K WD (in agreement with the WD temperature we find for the irradiation model of the Mosaic-2 lightcurve) while a much hotter object would have been detected.

### 4.4.1 Distance and X–ray luminosity

By comparing the typical K-band magnitude of a K5V star (\( M_K =4.42 \), Mamajek 2011) with the observed magnitude \( m_K = 13.76 \pm 0.03 \), and assuming \( A_V = 2.0 \pm 0.6 \) (\( A_K = 0.23 \pm 0.07 \)) as estimated in Section 4.3.5, we obtain the distance \( d = 664 \pm 23 \) pc to CX93. This estimate relies on the assumption that the absolute magnitude of the companion is typical of a normal main sequence star, which is not true for CVs in general (Knigge, 2006). The typical radius of a K5V star is 0.72 R\(_{\odot}\) (Drilling & Landolt, 2000). Using the mass-to-radius relation found by Knigge (2006) for secondary stars in long orbital period CVs, we find that our best mass estimate for the donor, 0.6\( \pm 0.2 \) M\(_{\odot}\), yields a radius of 0.62\( \pm 0.07 \) R\(_{\odot}\) (this is consistent with the Roche lobe radius of the companion \( R_{RL} = 0.62 \) R\(_{\odot}\)) for \( M_1 = 0.8 \) and \( q = 0.7 \). The secondary in CX93 is then fainter than a typical K5V by 0.1 to 0.6 magnitude, allowing a distance of \( \sim 500 \) pc. Further uncertainty to the distance comes from the assumed spectral type. Allowing the spectral type to be off by one, our observations suggest a likely distance between \( \sim 400 \) – 700 pc.

Although seemingly high, the extinction we estimated is consistent with a nearby object. In fact, extinction maps obtained from red clump stars within
VVV, with a resolution of $2' \times 2'$, indicate $E(B-V)=1.67$ ($A_V \sim 5.1$) in the direction of CX93 (Gonzalez et al., 2011). Converting $A_V$ into an hydrogen column density (following Güver & Özel 2009b) yields $N_H = (0.4 \pm 0.1) \times 10^{21}$ cm$^{-2}$. Assuming a power-law spectrum with index 1.6, the 14 counts observed by Chandra from CX93 in the full ACIS range (0.3-8 keV) correspond to an unabsorbed flux of $3.9 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. For $d = 664$ pc the 0.3-8 keV X–ray luminosity of CX93 is $1.8 \times 10^{31}$ erg s$^{-1}$. Compared with typical CVs luminosities ($\sim 10^{31} - 10^{34}$ erg s$^{-1}$) this is consistent with a low accretion state.

4.4.2 The difficult classification of quiescent XRBs

The low X–ray luminosity, the lack of clear signatures of ongoing accretion and the little disc veiling in the optical spectra indicate that CX93 was in a low state during most of our observations. Disc emission is possibly responsible for the wings at the base of the H$\alpha$ line, showing high radial velocities of a few hundred km s$^{-1}$, but the peak of the line traces the donor star (only slightly leading in phase) and can hardly be reconciled with disc motion. The low state and dominance of the companion over the spectra makes the classification of the system in terms of CV subclasses difficult. An intermediate polar scenario, consistent with the presence of little disc, seems to be ruled out by the lack of typical lines from magnetic CVs in the spectra (such as prominent HeII, Williams 1989, Schwarz et al. 2004), but even those lines could be absent if the accretion rate is very low. The complex H$\alpha$ line resembles nova-like systems such as BB Doradus (Schmidtobreick et al., 2012) which do show composite emission features that are not directly from either the secondary star or a remnant disc. Although the dynamics of the line suggests an origin near the tip of the companion star, in fact, the observed FWHM is too broad ($\sim 400$ km s$^{-1}$) to be ascribed to photospheric activity or irradiation of the secondary surface only (although saturation effect might play an important role). CX93 also shows some similarity with the VY Sculptoris subclass of nova-like CVs (NL), which do show extended low accretion states when there can be hardly any evidence of ongoing accretion (see, e.g. the low state of MV Lyrae in Linnell et al. 2005). A dwarf nova scenario also seems viable, with the source ongoing a small outburst at the time of the Mosaic-2 observations, but with the low accretion rate preventing clear accretion features from showing the classification remains tentative.

CX93 also shows that a little level of variability in a quiescence CV can produce spectral features resembling a quiescent BH or NS. Plotting the EW of the Balmer lines detected in the VIMOS spectra against the X–ray to optical flux ratio ($\log(F_X/F_V) \sim -1$, following Patterson & Raymond 1985) provides outlying values for a CV that are suggestive of a more compact accretor. The
4.5 Conclusion

Values are consistent with a normal CV if we consider the IMACS spectra instead. Moreover, it is worth noticing that reference quantities such as the X–ray luminosity and $F_X/F_V$ are not good indicators of the source type for deeply quiescent systems as they are for actively accreting ones. The typical X–ray luminosity for quiescent NS or BH XRBs ($10^{31} - 10^{32}$ erg s$^{-1}$) is in fact consistent with that of a CV in a low state, and $F_V$ is the same for all XRBs when the companion star dominates the optical light. In conclusion, in a quiescent system like CX93 even the nature of the accretor can be mistaken without a complete dynamical study (see also Marsh et al. 1994b). This is important to take into account for projects, such as the GBS, that aim to identify new NSs or BHs.

4.5 Conclusion

We performed a full dynamical study of the GBS source CXOGBS J174444.7$-$260330 (CX93), finding that the source is a nearby ($400 \lesssim d \lesssim 700$ pc) long orbital period ($> 5$ hours) CV, in a state of low accretion rate. One episode of accretion at higher rate was possibly caught in one of our lightcurves, displaying asymmetric maxima that could be fitted with a disc spot. Alternative causes for the asymmetric maxima, such as the presence of starspots on the companion star, are difficult to realistically model. The secondary is likely of spectral type (close to) K5 V and dominates the spectra, which display a disc contribution of $\sim 2\%$. The classification of the source among CV subclasses is difficult. A DN (in particular a VY Sculptoris) or NL system in a low state seems likely, although we can not exclude a magnetic WD accreting at a very low rate. The case of CX93 highlights that CVs in a low accretion state can be hard to distinguish from quiescent XRBs with a NS or BH primary.

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The mass of the compact object in CX93
Chapter 5

Roche lobe overflow onto a compact object from a donor 1.8 times as massive

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Abstract

We present phase-resolved spectroscopy and photometry of the optical counterpart to the X-ray binary IGR J19308+0530. Ellipsoidal modulations in
The mass ratio in IGR J19308+0530

The lightcurve show that the F-type companion star in the system is Roche-lobe filling. The optical spectra are dominated by absorption features from the donor star, with $\sim$10-20% disc contribution to the optical continuum. We measure an orbital period of 14.662±0.001 hours, a radial velocity semi-amplitude for the companion star of $K_2 = 91.4\pm1.4$ km s$^{-1}$ and a rotational broadening of $v \sin i = 108.9 \pm 0.6$ km s$^{-1}$. From $K_2$ and $v \sin i$, given that the donor star is filling its Roche lobe, we derive a mass ratio of $q = M_2/M_1 = 1.78\pm0.04$, which is typically considered to be too large for stable Roche-lobe overflow. Our observations support an inclination of $\sim$50 degrees. The accretor in IGR J19308+0530 is most likely a white dwarf, although a neutron star cannot entirely be excluded.

5.1 introduction

Intermediate-mass X–ray binaries (IMXBs) are binary systems where a compact object - black hole, neutron star (NS) or white dwarf (WD) - is accreting matter from a companion star of spectral type A or F. IMXBs are rarely observed (see, e.g., the catalogue from Liu et al. 2007 and the 2012 version of the RK catalogue Ritter & Kolb 2003$^1$). The majority of accreting WDs in binaries, in fact, belongs to the class of cataclysmic variables (CVs), which have late type secondaries ($M_2 \lesssim M_1$) and $P \lesssim 6$ hours (Knigge et al., 2011). NSs or BHs, instead, are typically observed in X–ray binaries (XRBs) hosting either a massive O-B donor star (high-mass XRBs, HMXBs) driving accretion via stellar wind, or a late M or K dwarf secondary star (low-mass XRBs, LMXBs) accreting via Roche lobe overflow. The reason for the observed rarity of IMXBs especially among NS and WD systems is that, when the companion is more massive than the accretor but not massive enough to have strong winds, wind accretion proceeds at a very low rate and Roche-lobe accretion is thought to be unstable. For NSs and WDs in IMXBs mass flows from the more massive to the lighter star and angular momentum conservation shrinks the orbit, leading to enhanced mass transfer. The bright X-ray binary phase is therefore intense and short-lived, causing an observational bias towards LMXBs, CVs and HMXBs (Tauris & van den Heuvel, 2006). Nevertheless, IMXBs could be a large fraction of the XRB population and have an important role in understanding their evolution (Podsiadlowski et al., 2001). Cyg X–2 and Her X–1 are thought to have started as IMXBs, even though the measured mass ratio is currently $< 1$.

IGR J19308+0530 was discovered by INTEGRAL (Bird et al., 2006b) and observed by Swift (Rodriguez et al., 2008b). An association with the star TYC 486-295-1, classified as an F8 star in the survey by McCuskey (1949b),

$^1$http://physics.open.ac.uk/RKcat/
was made using the *Swift* position (Rodriguez et al., 2008b). This was confirmed using an accurate *Chandra* position of the X-ray source (Ratti et al., 2010). Considering typical parameters of an F8 star, Rodriguez et al. (2008b) suggested IGR J19308+0530 to be a L/IMXB in quiescence or a CV at a distance of $\lesssim 1$ kpc.

Here, we present phase-resolved optical spectroscopy and photometry of IGR J19308+0530, in order to measure the orbital period $P$, the radial velocity semi-amplitude $K_2$ and the projected rotational velocity $v \sin i$ of the companion star, and the system inclination $i$. In a Roche lobe filling system, $K_2$ and $v \sin i$ allow us to infer the ratio $q = M_2/M_1$ between the mass of the secondary and the primary star in the system (Wade & Horne 1988b, see also Gray 1992b) and, knowing $P$ and $i$, to solve the system mass function.

### 5.2 Observations and data reduction

In total twenty-two high-resolution spectra of IGR J19308+0530 were collected. Observations were made on two nights in 2010 Mar., one night in 2010 Apr. and 9 nights in 2010 Jun. using the fiber spectrograph High Efficiency and Resolution Mercator Echelle Spectrograph (HERMES), mounted at the Mercator telescope in La Palma (Raskin et al., 2011). The typical exposure time was 1200 seconds. The spectra have a dispersion of 0.027 Å/pixel at 5000 Å and cover the wavelength range 3770-7230 Å. The fiber aperture is 2′5 on the sky, but the presence of a slicer mimics a narrow slit providing a resolution of $\sim 85000$ irrespective of the seeing. The template star HD185395, of spectral type F4 V (later found to be the closest match to the spectral type of the target, see below) was observed with the same settings for 360 seconds on 2009 Aug. 5. The extraction of the spectra was performed through the dedicated automated data reduction pipeline HermesDRS. For each spectrum we selected two regions for the analysis, one covering the $H\gamma$ and $H\beta$ lines (4280-5250 Å) and one around the $H\alpha$ line (5950-6700 Å), which we will refer to as S1 and S2, respectively. These regions were selected as they are rich in stellar lines, with little contamination from interstellar features. A good fit of the continuum was achieved in each region with a polynomial function of order 9. We normalized the spectra dividing by the polynomial fit.

We also performed time-resolved photometry of IGR J19308+0530, with the 80-cm IAC80 telescope at the Observatorio del Teide in Tenerife equipped with the CAMELOT CCD imager. The observations were obtained during part of three nights between 2010 Jul. 30 and Aug. 02, by cycling through the Sloan $g'$, $r'$, $i'$ and $z'$-band filters. Three consecutive exposures were obtained in each filter, with integration times ranging from 6 to 24 sec depending on the filter and seeing conditions. Standard stars were not taken due to non-
photometric weather. After debiasing and flat-fielding the images using dome flat-field observations, the instrumental magnitudes of IGR J19308+0530 and four comparison stars were computed by means of aperture photometry. Differential lightcurves were then obtained for IGR J19308+0530 with respect to the comparison star TYC 486-968-1. We also extracted lightcurves for TYC 486-968-1 using the other comparison stars. No significant variability was detected in the $i'$-band (r.m.s. $\lesssim 0.006$ mag), whereas for the other bands a larger scatter was observed due to weather conditions (clouds and Calima). The maximum departure from the mean value was of 0.1 mag. Given that the ellipsoidal modulation in IGR J19308+0530 is small in amplitude we decided to model only the $i'$-band lightcurves.

5.3 Analysis and results

5.3.1 Spectroscopy

The spectra are dominated by absorption features from the secondary star. Although no emission line is directly visible, residual emission in the Balmer lines appears when subtracting the spectra one from another, after correcting for the orbital shift of the lines. The emission component is variable in intensity and wavelength and slightly shifted with respect to the absorption line.
5.3 Analysis and results

Figure 5.2: Radial velocity curve from the absorption lines in the IGR J19308+0530 spectra (region S1) and its best fitting sinusoid (solid line). For comparison we plot circular orbits with \( K_2 = 112 \, \text{km} \, \text{s}^{-1} \) (dotted line) and \( K_2 = 140 \, \text{km} \, \text{s}^{-1} \) (dashed line), providing \( q = 1.4 \) and \( q = 1 \) respectively for the observed \( v \sin i \).

We measured the orbital velocity of the companion star in IGR J19308+0530 by cross-correlating the spectra of the target with that of the template star. As the absorption lines are rotationally broadened in the target spectrum, a broadening of 100 km s\(^{-1}\) was applied to the template (see below on rotational broadening), improving the cross-correlation. The Balmer lines and interstellar features were masked. We performed a fit of the velocities versus time with a sine function, with \( K_2 \), the systemic radial velocity \( \gamma \), \( T_0 \), and \( P \) as free parameters. \( T_0 \) was constrained to be near the middle of the time span over which the observations were taken, and such that phase 0 is at the inferior conjunction of the companion star. The best-fitting sinusoid provided a \( \chi^2 \) of 57.6 for the region S1, and 41.76 for S2 (19 d.o.f.). In both cases, the uncertainties on the parameters were estimated assuming that the sinusoidal model was correct, and we scaled the errors on the velocities to reach a reduced \( \chi^2 \) of \( \sim 1 \). The values of \( P \), \( T_0 \) and \( \gamma \) measured in S1 and S2 are consistent at the 1\( \sigma \) level, \( K_2 \) is consistent at the 2 \( \sigma \) level. The error-weighted average of the parameters gives \( P = 0.61092 \pm 0.00003 \) days, \( T_0 = 2455330.8169 \pm 0.0023 \) HJD/UTC, \( K_2 = 91.4 \pm 1.4 \, \text{km} \, \text{s}^{-1} \) and \( \gamma = -18.5 \pm 0.9 \, \text{km} \, \text{s}^{-1} \). Figure 5.2 shows the radial velocity curve (rvc) folded on the above period. The value of \( \gamma \) is in the reference frame of the template star used for the cross-correlation, whose systemic radial velocity is \(-28 \pm 0.9 \, \text{km} \, \text{s}^{-1} \) (Wilson, 1953). The systemic radial velocity of IGR J19308+0530 is therefore \(-46.5 \pm 1.2 \, \text{km} \, \text{s}^{-1} \).

We obtained a set of high signal-to-noise template spectra from the UVES Paranal Observatory Project (UVESPOP, Bagnulo et al. 2003) of A, F and
early G stars of luminosity class V, III and IV. We subtracted each template spectrum from the Doppler-corrected average of the IGR J19308+0530 spectra between orbital phase 0.9 and 0.1. The reason for choosing this range in phase is that the oblate shape of the Roche-lobe filling companion star and the possible presence of irradiation from the compact object could cause asymmetries in the line profiles, which are minimised close to phase 0. We performed a $\chi^2$ test on the residuals of the subtraction: the template resulting in the minimum $\chi^2$ provides our best estimate for the source spectral type. In particular, we adopted the optimal subtraction procedure implemented in MOLLY, where the templates are multiplied by a factor $0 < f < 1$ before the subtraction, representing the fractional contribution of light from the secondary star (1 minus the disc veiling). The factor $f$ is found by minimizing the difference between the residuals and a smoothed version of itself. Before doing the subtraction, the UVESPOP spectra were shifted to the rest frame of the average target spectrum, and degraded to match the sampling and line broadening of the latter.

The procedure favors an F4-F6 V companion star, with a disc veiling of 10 – 20%. The same spectral type and veiling are obtained when considering an average of the target spectra around phase 0.5, suggesting little irradiation on the inner face of the companion star.

To measure $v \sin i$, we compared the spectrum of the template star with the Doppler-corrected average of the IGR J19308+0530 spectra between phase 0.9 and 0.1. The observed full-width at half-maximum (FWHM) of the absorption lines in the target spectra is determined by the intrinsic line width (expected to be dominated by $v \sin i$), broadened by the instrumental resolution profile and smeared by the motion of the companion star during the integration time of one observation. In order to account for the smearing, we made as many copies of the template spectrum as the number of target spectra we used for the average and we artificially smeared each copy of the template by $2\pi TK \cos(2\pi\phi)/P$, where $T$ is the duration of one exposure on IGR J19308+0530 and $\phi$ the phase of one of the IGR J19308+0530 spectra we averaged. After that, we averaged the smeared template and broadened the resulting spectrum with different values of $v \sin i$. For each $v \sin i$, we performed an optimal subtraction of the broadened template from the averaged spectrum of IGR J19308+0530: again the broadening which gives the minimum $\chi^2$ provides a measure of the actual $v \sin i$ (Figure 5.1). A value of 0.5 was assumed for the limb darkening. We masked interstellar features and the lines from the Balmer series.

In order to estimate the uncertainty on $v \sin i$, we included this procedure in a Monte Carlo simulation, following Steeghs & Jonker (2007). We copied each target spectrum 500 times, using a bootstrap technique where the input spectrum is resampled by randomly selecting data points from it. The bootstrapping maintains the total number of data points in the spectrum.
Figure 5.3: $i'$-band CAMELOT lightcurve, folded using the ephemeris from the radial velocity data. The data are from the three observing nights of Jul. 30, Jul. 31 and Aug. 1. The drawn line shows a fit with ellipsoidal modulations plus a disc with a bright disc spot.

For each bootstrap copy, one value of $v \sin i$ is measured as described above. The distribution of $v \sin i$ obtained from the 500 copies is well described by a Gaussian, whose mean and r.m.s. provides the best-fit $v \sin i$ and its 1σ error. As template and target spectra are acquired with the same instrument, the instrumental resolution profile is not affecting our measurement. The weighted average of the results from S1 and S2, consistent at the 1σ level, is $v \sin i = 108.9 \pm 0.6 \text{ km s}^{-1}$. With $v \sin i$ and $K_2$, we calculated the system mass ratio $q = M_2/M_1$ from the relation $\frac{v \sin i}{K_2} = (1+q) \frac{0.49q^{2/3}}{0.6q^{2/3}+\ln(1+q^{1/3})}$ (Horne et al., 1986), obtaining $q = 1.78 \pm 0.04$.

5.3.2 Ellipsoidal modulation and system inclination

Figure 5.3 shows the $i'$-band lightcurve for IGRJ19308+0530 obtained by phase folding the CAMELOT data on the ephemeris determined in Section 5.3.1. The lightcurve displays the typical signature of ellipsoidal variation, with two unequal minima, but in addition asymmetric maxima (O’Connell 1951 and Wilsey & Beaky 2009).

We modeled the $i'$-band lightcurve using the XRbinary program written by E.L. Robinson. A reasonable fit to the data (reduced $\chi^2 \sim 7$, 403 d.o.f.) is obtained with a model assuming an F4V secondary star and including 30% disc contribution to the total light plus a disc hot-spot at phase 0.75. The disc veiling in the model is larger than observed in the spectra, but variability is possible as the photometry was performed one month after the last spectrum.
was acquired. Similar models with different assumptions about the disc properties (disc radius, height and temperature profile) also give reasonable fits. As we have no indications to single out one preferred set of parameters, we do not provide a formal uncertainty on $i$, but an indicative value of $\sim 52^\circ$ as a guide.

5.3.3 Upper limits in the radio waveband

We searched for a radio counterpart to IGR J19308+0530 with a Karl G. Jansky Very Large Array observation at 4.6 and 7.9 GHz (120 MHz bandwidth) (proposal ID 10B-238), taken on 2010 Aug. 19 with the array in its most compact D-configuration. The on-source time was 33 minutes and the data were reduced according to the standard procedures within the Common Astronomy Software Application (McMullin et al., 2007) software package, using the calibrator 3C 286 to set the amplitude scale and J1922+1530 to calibrate the amplitude and phase gains for the target source. IGR J19308+0530 was not detected at either frequency. A 3-sigma upper limit to the source flux of 54 $\mu$Jy/beam was derived.

To search for radio pulsations from a potential pulsar in this system, we used the Westerbork Synthesis Radio Telescope and the PuMa2 backend (Karuppusamy et al., 2008). We observed for 1 hr from both 310–380 MHz (Obs. ID 11205182, 29 Aug. 2012) and from 1300–1460 MHz (Obs. ID 11205210, 31 Aug. 2012). The predicted dispersion measure (DM) for a 300 pc distance along this line-of-sight (see Discussion) is only $\sim 4$ pc cm$^{-3}$ Cordes & Lazio (2002). For each data set, we used the PRESTO software suite (Ransom, 2001) to search a set of trial DMs up to 30 pc cm$^{-3}$. No obvious radio pulsar signal was detected after an acceleration search. From these observations, we can place conservative flux density limits of $S_{350} < 0.9$ mJy and $S_{1400} < 0.4$ mJy for any pulsar present in the system, assuming it is beamed towards us.

5.4 Discussion and conclusion

We performed a dynamical study of the system IGR J19308+0530 through optical spectroscopy and photometry. The optical spectra are dominated by the companion star, with no evidence of irradiation, no emission features visible from the accretion flow besides a partial filling in of the Balmer lines and 10–20% disc contribution to the continuum. The secondary star is most likely of spectral type F4-6 V. Ellipsoidal modulations are detected on the $\sim 14.6$ hour orbit. From phase-resolved spectroscopy we measure an extreme value for the binary mass ratio of $q = 1.78 \pm 0.04$. The lightcurve modeling provides a reasonable fit to the data with a disc+hot-spot model at $i \sim 52^\circ$. Solving the mass function $f(M_2) : M_1 \frac{\sin^3 i}{(1+q)^2} = \frac{PK_2^3}{2\pi G} = 0.03 M_\odot$ with this inclination, we
obtain the following indicative masses: \( M_1 \sim 0.8 \, M_\odot \) and \( M_2 \sim 1.4 \, M_\odot \). The masses are consistent with a WD accretor and an F4V donor (typical mass of \( \sim 1.37 \, M_\odot \), Mamajek’s list 2011\(^2\)). If the inclination is lower, which we cannot exclude based on these data, the masses will increase, allowing a scenario with a NS primary if \( i \lesssim 45^\circ \). However, in this case the companion star would be over-massive for the spectral type, which is unusual for XRB and CVs.

Assuming an F4 V mass donor with a radius equal to that of the Roche lobe for our best estimated masses, the magnitude of the companion is \( M_V = 2.7 \) in the visual band (half a magnitude brighter than for a typical F4 V star, Mamajek 2011). Comparing with the apparent magnitude of IGR J19308+0530 \( (m_V = 10.95 \pm 0.13, \) converted from \( m_{VT} \) in the Tycho catalogue), we estimate a distance range of \( 300 - 450 \) pc, for an extinction between \( N_H = (0 - 2.6) \times 10^{21} \) cm\(^{-2} \) (Dickey & Lockman 1990b, where \( N_H \) is converted into \( A_V \) following Güver & Özel 2009b).

Combining the systemic radial velocity with the source proper motion reported in the UCAC3 catalogue, we computed the Galactic space velocity components of IGR J19308+0530 using the method of Johnson & Soderblom (1987b). Assuming that the Local Standard of Rest (LSR) participates in the Galactic rotation at \( 254 \) km s\(^{-1} \) (Reid et al., 2009b) and a distance of \( 375 \pm 75 \) pc, the derived peculiar velocity is \( 45.3 \pm 2.9 \) km s\(^{-1} \). This rules out a large asymmetric kick from a supernova.

The X–ray luminosity of IGR J19308+0530 measured by Chandra in 2007 (Ratti et al., 2010) is \( 5 \times 10^{29} - 4 \times 10^{30} \) erg s\(^{-1} \), for distance in the above range of \( 300 - 450 \) pc and the corresponding \( N_H \). In the same way, UV Swift observations provide \( 4 \times 10^{30} - 1 \times 10^{31} \) erg s\(^{-1} \) Å\(^{-1} \) at 2500 Å. A scenario where IGR J19308+0530 is not in full contact and the X–rays are from coronal activity of the companion seems unlikely. First, coronal activity usually does not produce prolonged high energy emission, while the source was discovered from a stack of INTEGRAL observations. Second, coronal activity could explain the observed X–ray luminosity only for the earliest spectral type allowed by the observations combined with very little \( N_H \), as for F stars the ratio between the X–rays and bolometric flux is \( \log(L_X/L_{bol}) \lesssim -4.6 \) for \( v \sin i \sim 100 \) (Walter, 1983). Finally, the spectra indicate disc contribution to the continuum, and the emission detected in the Balmer lines shows a slight, variable velocity offset with respect to the radial velocity curve of the companion star which is not expected in case they originate from coronal activity. The emission line component also seems weak for an highly active star. A hot WD of \( \sim 60000 \) K alone could account for the UV emission, but not for \( L_X \) unless thermonuclear burning is happening on its surface. The few intermediate mass

\(^2\) http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.dat
CVs with long orbital period that are known do appear as super soft sources (SSSs), showing soft X–ray spectra possibly due to stable hydrogen burning on the WD (e.g., Kahabka 2002, Kahabka 2006). However, with a luminosity of $10^{36} - 10^{38}$ erg s$^{-1}$, SSSs are much more luminous than what we observe from IGR J19308+0530. As the wind mass loss expected for the secondary spectral type is low ($\sim 10^{-14}$ M$_\odot$ yr$^{-1}$, Cranmer & Saar 2011) wind accretion can not account for the observed X–ray luminosity.

We conclude that IGR J19308+0530 is most likely in contact, consistent with the ellipsoidal modulations observed in the lightcurve. This makes the source particularly interesting among the scarcely populated class of IMXBs since it shows Roche lobe overflow at a low accretion rate $\dot{m}$. This is unusual, as Roche lobe accretion with an intermediate mass companion and such a large mass ratio is typically considered unstable, with an intense and short-lived accretion phase (e.g., Tauris & van den Heuvel 2006). Donor stars of mass around 1.4 M$_\odot$ have thin or non-existent convective envelopes (Verbunt & Zwaan, 1981) which implies that the instability does not proceed on a dynamical timescale. While a convective envelope star would react to mass loss by expanding, a star with a mostly radiative envelope will shrink, slowing down the mass transfer. However, with a mass ratio of 1.8 the radius of the Roche lobe will reduce faster in response to mass transfer than the radius of the companion, triggering a thermal instability (Tauris & van den Heuvel, 2006). Using the binary stellar-evolution code originally developed by Eggleton (Yakut & Eggleton 2005 and references therein), we modeled evolutionary tracks that allow for periods of stable Roche-lobe accretion onto a WD with masses and orbital periods consistent with our findings, although at higher $\dot{m}$ values than implied by the $L_X$ (see also the appendix in Podsiadlowski et al. 2003). The low $L_X$ can be explained if we are observing a short lived phase of low $\dot{m}$, or if the mass transfer is non-conservative (a fully non-conservative scenario requires a mass loss rate from the system of $10^{-10} - 10^{-9}$ M$_\odot$/yr). There is currently no direct evidence in favour of or against the presence of mass loss from the system.

From an observational point of view, an overestimate of $q$ could be due to uncertainties on the limb darkening. However, even assuming a limb darkening of 0 (instead of 0.5) reduces $v\sin i$ by only a few km s$^{-1}$, still providing a high $q$ of $\sim 1.6$.

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Chapter 6

The black hole candidate XTE J1752−226 towards and in quiescence: optical and simultaneous X–ray – radio observations

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Abstract

We present optical, X–ray and radio observations of the black hole transient (BHT) XTE J1752−226 towards and in quiescence. Optical photometry shows that the quiescent magnitude of XTE J1752−226 is fainter than 24.4 magnitudes in the i′-band. A comparison with measurements of the source during its 2009-2010 outburst shows that the outburst amplitude is more than 8 magnitudes in the i′-band. Known X–ray properties of the source combined with the faintness of the quiescence optical counterpart and the large outburst optical amplitude point towards a short orbital-period system \( P_{\text{orb}} \lesssim 6.8 \) h with an M type (or later) mass donor, at a distance of \( 3.5 \lesssim d \lesssim 8 \) kpc. Simultaneous X–ray and radio data were collected with Chandra and the EVLA, allowing constraints to be placed on the quiescent X–ray and radio flux of XTE J1752−226. Furthermore, using data covering the final stage of the outburst decay, we investigated the low luminosity end of the X–ray – radio correlation for this source and compared it with other BHTs. We found that XTE J1752−226 adds to the number of outliers with respect to the ‘standard’ X–ray – radio luminosity relation. Furthermore, XTE J1752−226 is the second source, after the BHT H1743−322, that shows a transition from the region of the outliers towards the ‘standard’ correlation at low luminosity. Finally, we report on a faint, variable X–ray source we discovered with Chandra at an angular distance of \( \sim 2''9 \) to XTE J1752−226 and at a position angle consistent with that of the radio jets previously observed from the BHT. We discuss the possibility that we detected X–ray emission associated with a jet from XTE J1752−226.

6.1 Introduction

XTE J1752−226 was discovered as a transient source in the Galactic Centre region by the Rossi X–ray Timing Explorer (RXTE), on 2009 October 23 (Markwardt et al., 2009b). It was soon proposed to be a Galactic black hole candidate (Markwardt et al., 2009a), i.e., a binary system where a black hole (BH) is accreting matter from a companion star. Most black hole candidates are transient sources (black-hole transients, BHTs) that occasionally
undergo outbursts. During outbursts these sources can show a characteristic evolution through various ‘states’, defined on the basis of their strongly correlated spectral and variability properties (see, e.g., Remillard & McClintock 2006a, Belloni 2010). After the discovery, XTE J1752–226 was monitored by the RXTE, Swift and MAXI satellites: the X–ray behaviour of the source during the outburst matched the typical phenomenological picture for BHTs, confirming XTE J1752–226 as strong accreting black hole candidate (Nakahira et al. 2010, Muñoz-Darias et al. 2010, Shaposhnikov et al. 2010, Curran et al. 2011). Based on the X–ray spectral and timing properties of XTE J1752–226, Shaposhnikov et al. (2010) also report a mass estimate for the BH, \( M_{BH} = 9.8 \pm 0.9 \, M_{\odot} \) and the distance to the source \( d = 3.5 \pm 0.4 \, \text{kpc} \) (although the systematic uncertainties of these estimates could be large).

A bright optical counterpart to XTE J1752–226 was identified by Torres et al. (2009a) based on the Swift position and later confirmed through optical spectroscopy by Torres et al. (2009b). Two radio sources were detected at a position consistent with the optical one (Brocksopp et al., 2010) which were initially interpreted as a decelerated jet and its receding counterpart (Yang et al., 2010). A combination of radio and optical observations with accurate astrometry allowed Miller-Jones et al. (2011b) to locate the radio core of the source, at R.A. = 17\(^{h}\) 52\(^{m}\) 15\(^{s}\) 09509(2), Dec. = -22\(^{\circ}\) 20\(^{\prime}\) 32\(^{\prime\prime}\) 3591(8). This position lies to the southeast of the two jet components previously observed, which were then re-interpreted as two ejection events. The core position was recently confirmed by Yang et al. (2011), who also report on the radio detection of a third jet component.

After transiting through all the canonical states of a BHT, XTE J1752–226 faded towards quiescence in July 2010 (Russell et al., 2012). The quiescent state of BHTs was initially considered as an extension towards low luminosities \((10^{30}-10^{33} \, \text{erg s}^{-1})\) of the ‘hard state’, i.e. a spectral state where the X–ray spectrum is dominated by a power-law component with index \( \Gamma \sim 1.5 \). Later, a number of BHTs were found to show softer spectra in quiescence compared to the hard state, suggesting that the former can be considered a state on its own (e.g., Jonker et al. 2004a, Tomsick et al. 2004). Still, because of their low luminosities at all wavelengths, it has been challenging to collect high quality spectral data to constrain the properties of quiescent BHTs.

The hard state is also associated with the presence of radio emission, with a flat or slightly inverted spectrum that, owing to the high brightness temperature, is generally thought to originate from a compact jet. The X–ray emitting accretion flow and the radio emitting jet are known to be intimately connected: Gallo et al. (2003) and Corbel et al. (2003) found that several BHTs follow a correlation between the X–ray and radio luminosity \((L_X \, \text{and} \, L_R \, \text{respectively})\) in the form \( L_R \propto L_X^{0.7} \). The power-law index was later refined to \( L_R \propto L_X^{0.6} \) (Gallo et al., 2006). The correlation was initially thought to be universally
Figure 6.1: Top panel: $i'$ band light curve from the optical counterpart to XTE J1752−226, including our IMACS observations (black dots), and the measurements obtained by Russell et al. (2012) with the Faulkes telescopes (empty circles) and by Corral-Santana et al. (2010a) with the WHT/ACAM (cross), showing the XTE J1752−226 optical rebrightening. Central panel: X–ray light curve from our Chandra observations (black dots) and RXTE/PCA observations from Russell et al. (2012) (stars). The 3-20 keV count rate provided by the authors has been converted into 1-10 keV fluxes using the HEASARC tool WebPIMMS, assuming a power-law spectrum with a photon index of 1.6 or 1.4 (spectral information from Russell et al. 2012 and Shaposhnikov et al. 2010). Bottom panel: GHz radio light curve including our EVLA and VLBA observations (black dots) and the hard-state observations reported by Brocksopp et al. (2009). The dotted lines across the radio and X–ray light curves highlight the temporal correspondence of the data in the two energy bands. Note that the X–ray and radio light curves cover a shorter time range than the $i'$-band light curve in the top panel.
valid for all BHTs, but in recent years a number of outliers have been found (see Calvelo et al. 2010 for an updated compilation of sources). For most of the outliers it is not established yet whether they follow the correlation at a lower normalization or a correlation with a different slope. The work of Jonker et al. (2010) and Coriat et al. (2011) on the outlier H1743−322 has shown that a reconnection of the the ‘outliers branch’ with the standard correlation is also possible: H1743−322 in fact lies on a steeper correlation than $L_R \propto L_X^{0.6}$ at high luminosity (Jonker et al., 2010), but undergoes a transition back to the canonical correlation as the luminosity decreases below $\sim 10^{34}$ erg s$^{-1}$ (Coriat et al., 2011). This indicates a change-over between two accretion regimes when the source moves from a high-luminosity to a low-luminosity hard state. Following the X–ray – radio correlation across a broad range in luminosity for other BHTs may show whether similar transitions are a common feature among this class of sources and provide new elements to our understanding of the accretion mechanism at different accretion rates, including in the low-luminosity quiescent regime. It may also help us understand why different sources follow different X–ray – radio correlations.

Here, we report on contemporaneous Chandra X–ray and Expanded Very Large Array (EVLA) radio observations of XTE J1752−226 aimed at following the X–ray and radio light curves and establishing the X–ray – radio correlation during the final part of the decay towards quiescence. We also present one Very Long Baseline Array (VLBA) detection and optical observations of XTE J1752−226 in quiescence, providing information about the system’s orbital period and distance.

### 6.2 Observations, data reduction and results

#### 6.2.1 Chandra X–ray observations

We observed XTE J1752−226 with the Chandra satellite using the back–illuminated S3 CCD–chip of the Advanced CCD Imaging Spectrometer (ACIS) detector.
Figure 6.2: 0.3-7 keV Chandra/ACIS-S images from observation 11035 and 11036 (left panel and right panel respectively). The data are Gaussian smoothed with a kernel radius of 2. The finding charts show 6 unidentified sources detected by Chandra close to XTE J1752−226 (see also Table 6.3), labeled S1 to S6 (with a question mark if the detection is uncertain). The dashed line shows the position angle of the jet component named A by (Yang et al., 2010) at the time of its last detection, with respect to XTE J1752−226 (-50.9±0.1 degrees, Miller-Jones et al. 2011b). This is consistent with the position angle of S2 (-52±7 degrees) with respect to XTE J1752−226.

(Garmire 1997) on four occasions during the decay towards quiescence (see Figure 6.1 and Table 6.1). During all the observations the ACIS–S3 detector was windowed, providing a frame time of 0.4104 s. We have reprocessed and analysed the data using the CIAO software developed by the Chandra X–ray Center. Since, by design, the source position falls near the optical axis of the telescope, the size of the point spread function is smaller than the ACIS pixel size. Therefore, we follow the method of Li et al. (2004) implemented in the CIAO 4.3 tool acis_process_events to improve the image quality of the ACIS data.

In our analysis we have selected events only if their energy falls in the 0.3–7 keV range. All data have been used, as background flaring is very weak or absent in all data. The last observation (ID 11056) has been performed with the datamode set to VFAINT. This means that pulse height information in a 5x5 pixel region around the event is telemetered down, allowing for a more rigorous cleaning of background events caused by for instance cosmic rays.

1http://cxc.cfa.harvard.edu/ciao4.3/
Table 6.2: Best fit parameters of the X–ray spectra of XTE J1752−226. PL refers to power law. All quoted errors are at the 68 percent confidence level. $N_H$ was fixed in all instances to $5 \times 10^{21}$ cm$^{-2}$.

<table>
<thead>
<tr>
<th>Obs ID</th>
<th>PL index</th>
<th>Unabs. 0.5–10 keV flux</th>
<th>Goodness percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>11053</td>
<td>1.6±0.5</td>
<td>$ (7.0 \pm 2.0) \times 10^{-14} $</td>
<td>0</td>
</tr>
<tr>
<td>12310</td>
<td>1.6±0.1</td>
<td>$ (6.4 \pm 0.6) \times 10^{-13} $</td>
<td>91</td>
</tr>
<tr>
<td>11055</td>
<td>1.9±0.5</td>
<td>$ (1.0 \pm 0.2) \times 10^{-14} $</td>
<td>20</td>
</tr>
<tr>
<td>11056</td>
<td>1.7±0.2</td>
<td>$ (1.4 \pm 0.2) \times 10^{-14} $</td>
<td>11</td>
</tr>
<tr>
<td>55+56a</td>
<td>1.8±0.2</td>
<td>$ (1.3 \pm 0.1) \times 10^{-14} $</td>
<td>10</td>
</tr>
</tbody>
</table>

*a Fit using the spectra of 11055 and 11056 combined.

Using wavdetect we detected XTE J1752−226 in each of the observations. We selected a circular region of 10″ radius centred on the accurately known source position (Miller-Jones et al., 2011b) to extract the source counts for the first two observations (Obs IDs 11053 and 12310). The longer, deeper, exposures of the last two observations revealed faint sources near the position of XTE J1752−226 (Figure 6.2). Therefore, we used a smaller extraction radius of 1.5″. In order to correct the source flux in these latter two observations for the small extraction radius, we used the arfcorr command in CIAO. For all four Chandra observations, we used a circular region with a radius of 10″ on a source-free region of the CCD to extract background counts. The redistribution response file is the same for the source and background region but we have made auxiliary response matrices for the source region of each of the observations separately. The net, background subtracted, source count rate for each observation is given in Table 6.1.

Using xspec version 12.4.0ad (Arnaud 1996) we fit the spectra of XTE J1752−226 using Cash statistics (Cash 1979) modified to account for the subtraction of background counts, the so called W–statistics2 for all four observations. We used an absorbed power–law model (pegpwlw in xspec) to describe the data. Due to the relatively low number of detected counts, we fixed the interstellar extinction during the fits to $5 \times 10^{21}$ cm$^{-2}$ found by Curran et al. (2011). The power-law index and normalisation were allowed to float. The results of our spectral analysis are listed in Table 6.2. We note that the goodness percentage is in all cases far from the nominal 50%. However, by visually inspecting the spectra there is no clear reason to reject the fits. Possibly the low number of counts is responsible for the discrepant goodness values.

2see http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/manual/
6.2.2 Quiescent X–ray emission from XTE J1752–226

The X–ray spectra we acquired are dominated by a power-law component, indicating that the source was in a hard spectral state at the time of the observations. As shown in Table 6.2, the power-law index \( \Gamma \) is \( \sim 1.6 \) in the first two observations (11053 and 12310), while the last two observations (11055 and 11056) present a slightly softer spectrum (although \( \Gamma \) is consistent with a constant value across the observations at the 1\( \sigma \) level). The light curve in Figure 6.1 shows the unabsorbed X–ray flux from XTE J1752–226, from our Chandra observations at the beginning of the quiescent phase and from RXTE observations performed earlier in the outburst. The unabsorbed flux on 2010 Jul. 12 was the faintest observed from this source since the beginning of the outburst, \((7.0\pm2.0)\times10^{-14}\) erg s\(^{-1}\) in the 0.5-10 keV range. In the following week XTE J1752–226 experienced a re-brightening by (nearly) one order of magnitude, reaching \((6.4\pm0.6)\times10^{-13}\) erg s\(^{-1}\) on 2010 Jul. 20. Six days later, on Jul. 26, the source had faded again down to \((1.0\pm0.2)\times10^{-14}\) erg s\(^{-1}\). The flux level at the time of our last observation, on 2010 Aug. 02, is consistent (within 2\( \sigma \)) with that shown on Jul. 26 (see Table 6.2), suggesting a flattening of the light curve. Despite the large errorbars, the flux level in the last two observations is in fact inconsistent with a constant decay after the 2010 Jul. 20 flare. This supports the conclusion that the source has reached quiescence (see discussion in Section 6.3).

6.2.3 New Chandra sources in the vicinity of XTE J1752–226

Figure 6.2 shows the two deepest images we acquired with Chandra, 11055 and 11056 (see Table 6.1). Six unidentified sources are detected in the vicinity of XTE J1752–226, labeled S1 to S6 (see also Table 6.3). The closest to XTE J1752–226 is CXOU J175214.8-222030 (S2), detected only in the observation 11055 with 10 net counts at an angular separation of \( \sim 2''9 \) from XTE J1752–226. The source position provided by wavdetect defines a position angle with respect to XTE J1752–226 of \( \sim -52\pm7 \) degrees. The significance on the flux measurement from wavdetect is 4.1 \( \sigma \). In the 0.3-7 keV band, the probability of finding the source by chance is less than 3\( \times10^{-15} \), corresponding to more than 8 \( \sigma \) in Gaussian statistics. S2 is not significantly detected by wavdetect in any other of our Chandra observations, although visual inspection of the deepest one, 11056, shows a faint source close to the position of S2 in 11055. Considering a 1'' radius circle (Chandra \( \sim 95\% \) encircled energy radius) centred by eye on this source provides \( \sim 10 \) counts in the 0.3-7 keV band. The estimate of the background is such that, from Poisson statistic only, the probability that the source is due to a statistical fluctuation of the background...
Table 6.3: New Chandra sources detected in the vicinity of XTE J1752–226 and their candidate counterparts in the $i'$-band. Labels in column 1 refer to Figure 6.2. The uncertainty on the X-ray positions is dominated by the 0.6 \degree boresight error of Chandra. The count rate is that measured by wavdetect on the deepest Chandra image, 11056, for all the sources but S2. For the latter, the counts are measured on the image 11055. The last two columns report the position of optical sources detected within the Chandra error circle (see text in Section 6.2.6). The accuracy on the optical position is 0" 05 on both R.A. and Dec.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>CXOU J175215.1-222035</td>
<td>17$^h$52$^m$15$^s$.19</td>
<td>$-22^\circ20'35''.4$</td>
<td>$(2.6\pm0.5)\times10^{-4}$</td>
<td>$17^h 52^{m} 15^{s} 2$</td>
<td>$-22^\circ20'34''.5$</td>
</tr>
<tr>
<td>S2</td>
<td>CXOU J175214.8-222030</td>
<td>17$^h$52$^m$14$^s$.91</td>
<td>$-22^\circ20'31''.4$</td>
<td>$(5.8\pm1.3)\times10^{-4}$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>S3</td>
<td>CXOU J175215.4-222023</td>
<td>17$^h$52$^m$15$^s$.46</td>
<td>$-22^\circ20'23''.9$</td>
<td>$(5.6\pm0.8)\times10^{-4}$</td>
<td>$17^h 52^{m} 15^{s} 42$</td>
<td>$-22^\circ20'24''.3$</td>
</tr>
<tr>
<td>S4</td>
<td>CXOU J175215.0-222010</td>
<td>17$^h$52$^m$15$^s$.06</td>
<td>$-22^\circ20'10''.9$</td>
<td>$(8.8\pm1.0)\times10^{-4}$</td>
<td>$17^h 52^{m} 15^{s} 10$</td>
<td>$-22^\circ20'11''.4$</td>
</tr>
<tr>
<td>S5</td>
<td>CXOU J175215.9-222001</td>
<td>17$^h$52$^m$16$^s$.01</td>
<td>$-22^\circ20'02''.25$</td>
<td>$(4.3\pm0.7)\times10^{-4}$</td>
<td>$17^h 52^{m} 16^{s} 05$</td>
<td>$-22^\circ20'11''.0$</td>
</tr>
<tr>
<td>S6</td>
<td>CXOU J175215.4-222036</td>
<td>17$^h$52$^m$15$^s$.49</td>
<td>$-22^\circ20'37''.0$</td>
<td>$(2.1\pm0.5)\times10^{-4}$</td>
<td>$17^h 52^{m} 15^{s} 50$</td>
<td>$-22^\circ20'37''.2$</td>
</tr>
</tbody>
</table>
is less than $10^{-14}$. By considering the same 1″ radius circle, we calculated 95% confidence upper limits to the count rate of S2 in all the observations where it was not detected. The upper limits are summarized in Table 6.4. Count rates were transformed into unabsorbed fluxes by assuming $N_H = 5 \times 10^{21}$ cm$^{-2}$ and a power-law spectrum with a photon index of 1.6 (similarly to the X-ray spectrum of the jet feature observed by Corbel et al. 2005 in H1743-322).

The source CXOU J175215.4-222036 (S6) is also detected only once, in the deepest observation 11056. The 4 counts collected in 11055 at the source position do not provide a significant detection, as there is a Poissonian probability of 13% to detect as many counts from S6 if the source was at the same flux level as in 11056.

### 6.2.4 Optical observations

We collected three observations of XTE J1752−226 in the i′ and I (CTIO) bands, with the Inamori-Magellan Areal Camera and Spectrograph (IMACS) at the Magellan Baade telescope in Cerro Las Campanas on 2009 Nov. 2 (5 s exposure, seeing 0′′.8), 2010 Aug. 31 (3 exposures of 180 s each, seeing 1′′.3) and 2011 May 13 (300 s-long deep exposure plus 5 s-long exposure for astrometry, seeing 0′′.7). The images were corrected for bias and flat-fielded with standard routines running in MIDAS.

An astrometric solution was obtained (using MIDAS) against entries from the third U.S. Naval Observatory CCD Astrograph Catalog (UCAC3; Zacharias et al. 2010), considering only sources that are not saturated on the CCD and appear stellar and unblended. The astrometric solution was fitted for the reference point position, the scale and the position angle, obtaining root-mean-square (rms) residuals of $\sim 0′′.03$ for the 2009 Nov. 2 and 2011 May 13 images, and $0′′.05$ for the 2010 Aug. 31 exposure. The 300 s exposure on 2011 May 13 was astrometrically calibrated using the 5 s one as a secondary catalogue. The final astrometric solution was calculated on stars with UCAC3 fit model magnitudes in the 14-16.5 range, for which the positional accuracy of UCAC3 is estimated to be $0′′.01$ (Zacharias et al., 2010). In addition, the systematic uncertainty in tying the UCAC3 stars to the International Celestial Reference System (ICRS) is 0.005″ (Zacharias et al., 2010). For the accuracy of our stellar positions we adopt the linear sum of the residuals of the astrometry and the accuracy of the catalogue (as the latter is potentially a systematic error): the resulting positional accuracy at 1σ across different observations ranges between $0′′.046$ and $0′′.065$ on both right ascension and declination.

The photometry was performed through point spread function (psf) fitting, using DAOPHOT II (Stetson, 1987c) running within MIDAS. The absolute photometry of three comparison stars labeled C1, C2, C3 in Miller-Jones et al.

3http://www.eso.org/sci/software/esomidas/
Figure 6.3: Finding charts: the position of XTE J1752−226 (from radio observations in Miller-Jones et al. 2011b) is indicated by the arrow and further highlighted by the white dot in the rightmost finding chart, where no counterpart to XTE J1752−226 is detected. The error-circles in the same finding chart indicate the position of nearby unidentified Chandra X–ray sources, labeled as in Figure 6.2. As we are using our astrometric solution in order to over-plot the X–ray positions on the finding charts, the error-circles in the figure account for the accuracy of Chandra and of our astrometry on the optical images, added linearly. The resulting 90% confidence radius is 0′′.68. The Chandra position of XTE J1752−226 is indicated by the thin black error-circle. The black band on the central finding chart is caused by a bad column on the IMACS CCDs.
Table 6.4: Constraints on the flux from CXOU J175214.8-222030 (S2 in Figure 6.2). The count rate is calculated within 1\arcsec (\sim 95\% encircled energy radius) around the position of S2. Upper limits are at the 95\% confidence level. A power-law spectrum with photon index 1.6 is assumed (see text), and $N_H = 5 \times 10^{21}\text{cm}^{-2}$.

<table>
<thead>
<tr>
<th>Obs ID</th>
<th>Observing Date</th>
<th>Unabs. 0.3-7 keV flux (erg s$^{-1}$cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11053</td>
<td>2010 Jul. 12</td>
<td>&lt;17.8\times10^{-15}</td>
</tr>
<tr>
<td>12310</td>
<td>2010 Jul. 20</td>
<td>&lt;5.1\times10^{-15}</td>
</tr>
<tr>
<td>11055</td>
<td>2010 Jul. 26</td>
<td>4.6\times10^{-15}</td>
</tr>
<tr>
<td>11056</td>
<td>2010 Aug. 2</td>
<td>&lt;2.6\times10^{-15}</td>
</tr>
</tbody>
</table>

(2011b) (with $i'$-band magnitudes of 13.62, 14.53 and 14.38 respectively) was used to determine the $i'$-band photometric calibration. The photometry of the 2010 Aug. 31 image could not be calibrated due to the lack of observations of photometric standard stars in the I (CTIO) filter.

### 6.2.5 Optical outburst amplitude of more than 8 magnitudes

Figure 6.3 shows $30'' \times 30''$ finding charts from our $i'$ and I-band observations, where the optical counterpart to the radio core of XTE J1752–226 (R.A. = $17\text{h} 52\text{m} 15\text{s} 09509 \pm 0.00002$, Dec. = $−22\degree 20' 32'' 3591 \pm 0.0008$, Miller-Jones et al. 2011b) is indicated by arrows. The first observation, from 2009 Nov. 2 (Figure 6.3, left panel), was taken during the first part of the 2009 X-ray outburst, when the source was in a low-hard spectral state (Nakahira et al. 2010, Muñoz-Darias et al. 2010). Accurate astrometry of this image has been used by Miller-Jones et al. (2011b) in order to locate the radio core of XTE J1752–226. The $i'$-band magnitude of XTE J1752–226 measured with our psf photometry in this observation is $16.29 \pm 0.01$, consistent with the measurement obtained from aperture photometry by Miller-Jones et al. (2011b). The second observation (Figure 6.3, middle panel) was performed on 2010 Aug. 31, and shows the fading of the source towards quiescence, after the optical rebrightening occurred on 2010 Aug. 8 (Corral-Santana et al. 2010a, Corral-Santana et al. 2010b). In the third observation (Figure 6.3, right panel), taken on 2011 May 13 after almost one year of quiescence, the optical counterpart to XTE J1752–226 it is not detected anymore down to a limiting magnitude of $24.4$ (3 $\sigma$ upper limit) in the $i'$ filter. Close neighbours to the optical counterpart are visible in the last two finders. One of them is within the Chandra error circle, at \sim 0''4 to the X-ray position. Nonetheless, the association with
XTE J1752–226 is ruled out by the radio position and by the variability observed from the actual optical counterpart to the source. The psf photometry is able to resolve the counterpart to XTE J1752–226 from those nearby stars in the observation taken during outburst, when those are outshone by the target’s light. A comparison of the magnitudes measured from our first and last observations shows that the drop in magnitude from outburst to quiescence is more than 8 magnitudes.

### 6.2.6 Optical counterparts to unidentified Chandra sources

The 2011 May 13 finding chart in Figure 6.3 shows the position of some of the unidentified X-ray sources detected by Chandra during our observations ((S1, S2, S3, S6, see Section 6.2.2). Other two unidentified sources nearby (S4, S5) are shown in Figure 6.4. There is no clear $i'$-band counterpart to the faint X-ray source S2 detected close to XTE J1752–226, although there is a star near the edge of the 90% Chandra error-circle (0''.6 radius), at 0''.7 from the X-ray position (the 90% uncertainty on the optical position is 0''.08). A brighter star is located a bit further, at $\sim$1''.10. Unfortunately, none of our optical images is close in time to the Chandra observation 11055, where this source was brightest in the X-rays. For both S1 and S5, a faint source lies on the edge of the Chandra error-circle. S6 can be associated with a bright star, while S3 has two faint optical counterpart candidates, partly blended together. Two faint optical sources are also consistent with the position of S4. The position of the best candidate counterpart(s) to each Chandra source is reported in Table 6.3.

### 6.2.7 Radio observations: EVLA

The new Expanded Very Large Array (EVLA; Perley et al., 2009) was used to monitor the decay of the outburst of XTE J1752–226 from 2010 April 15 through 2010 August 2, under program codes AM1039 and SB0329. With the newly-operational wideband 4–8 GHz receiver system, we were able to observe simultaneously in two independent 128-MHz sub-bands (each comprising 64 channels of width 2 MHz) to obtain spectral information at every epoch. To avoid the radio frequency interference (RFI) known to exist below 4.5 GHz, and yet achieve the widest feasible frequency separation, the two sub-bands were centred at 4.6 and 7.9 GHz. Once the source was no longer detected in an individual sub-band, no spectral information could be derived. We then switched the frequency setup in order to achieve the maximum possible sensitivity, observing over a contiguous bandwidth of 256 MHz centred at 8.4 GHz. Throughout our observing campaign, the array was in its most compact ‘D’ configuration, with an angular resolution at frequency $\nu$ of 12''(6 GHz/$\nu$).
Data reduction was carried out using the Common Astronomy Software Application (CASA; McMullin et al., 2007). The data were initially averaged down by a factor of 10 from the default 1 s integration time to make the data sets more manageable. Baseline corrections were performed and bad data arising from shadowing, instrumental issues, or RFI were edited out before beginning the calibration. Bandpass and flux density calibration was carried out using 3C 286, setting the flux scale according to the coefficients derived at the VLA in 1999 (Perley, 1999). Amplitude and phase gains were derived for all calibrator sources, referencing the target source XTE J1752–223 to the calibrator J1820–2528. OQ 208 was used as an unpolarized calibrator to derive the polarization leakage terms and 3C 286 was used to calibrate the polarization position angle. Finally, the calibration was applied to the target source, which, following frequency-averaging by a factor of 8, was then subjected to several rounds of imaging and self-calibration. Measured flux densities for XTE J1752–223 are given in Table 6.5.

### 6.2.8 Radio observations: VLBA

One epoch of VLBA data was also taken during the decaying hard state of XTE J1752–223, on 2010 June 17, under program code BM346. We observed
Table 6.5: A journal of the EVLA observations

<table>
<thead>
<tr>
<th>Observation date</th>
<th>MJD(^1) (days; UTC)</th>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Flux density (mJy beam(^{-1}))</th>
<th>Spectral index (\alpha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 Apr 15</td>
<td>55301.43 ± 0.01</td>
<td>4.6</td>
<td>128</td>
<td>1.33 ± 0.04</td>
<td>-0.7 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>55301.43 ± 0.01</td>
<td>7.9</td>
<td>128</td>
<td>0.88 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>2010 May 19</td>
<td>55335.29 ± 0.01</td>
<td>4.6</td>
<td>128</td>
<td>0.43 ± 0.05</td>
<td>-0.5 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>55335.29 ± 0.01</td>
<td>7.9</td>
<td>128</td>
<td>0.32 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>2010 May 31</td>
<td>55347.31 ± 0.02</td>
<td>4.6</td>
<td>128</td>
<td>0.18 ± 0.03</td>
<td>-0.3 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>55347.31 ± 0.02</td>
<td>7.9</td>
<td>128</td>
<td>0.21 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>2010 Jul.13</td>
<td>55390.17 ± 0.02</td>
<td>4.6</td>
<td>128</td>
<td>&lt; 0.10</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>55390.17 ± 0.02</td>
<td>7.9</td>
<td>128</td>
<td>&lt; 0.12</td>
<td>-</td>
</tr>
<tr>
<td>2010 Jul.20</td>
<td>55397.23 ± 0.10</td>
<td>8.4</td>
<td>256</td>
<td>0.075 ± 0.020</td>
<td>-</td>
</tr>
<tr>
<td>2010 Jul.26</td>
<td>55403.16 ± 0.07</td>
<td>8.4</td>
<td>256</td>
<td>&lt; 0.078</td>
<td>-</td>
</tr>
<tr>
<td>2010 Aug.02</td>
<td>55410.20 ± 0.10</td>
<td>8.4</td>
<td>256</td>
<td>&lt; 0.048</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^1\) the MJD is at the mid-point of the observation. The errorbar reflects the observation length.

\(^2\) upper limits are on the 3\(\sigma\) level.
with nine VLBA antennas (the Pie Town antenna was out of the array owing to a broken rail). We observed at 8.4 GHz in dual circular polarization, with the maximum available recording rate of 512 Mbps, corresponding to 64 MHz of observing bandwidth per polarization. The observations were phase referenced to the nearby calibrator source J1755–2232, from the third extension to the VLBA Calibrator Survey (Petrov et al., 2005, VCS-3;) and located 0.76° from XTE J1752–223. We switched between target and calibrator with a cycle time of 3 min, substituting the VCS-5 (Kovalev et al., 2007) check source J1751–1950 for every eighth scan on the target. By observing a range of bright calibrator sources at differing elevations, for 30 min at the start and end of the observing run (aka geodetic blocks), we could better solve for unmodeled clock and tropospheric phase errors. The geodetic blocks were analysed using the Astronomical Images Processin System (AIPS) task DELZN, thereby improving the success of the phase transfer. Data reduction was carried out according to standard procedures within AIPS. The flux density of the phase reference source decreased substantially on the longer VLBA baselines, most probably due to scatter broadening. When fringe fitting for the phase reference source, no good solutions were found for the Mauna Kea (MK) and Saint Croix (SC) stations, and all data from these stations had to be discarded. XTE J1752–226 was marginally detected, at a level of $0.25 \pm 0.08 \text{ mJy beam}^{-1}$ at the known source position (Miller-Jones et al., 2011b).

6.2.9 Upper limits to the radio quiescent flux

Assuming a radio spectrum of the form $S_\nu \propto \nu^\alpha$, our simultaneous detections in the 4.6 and 7.9 GHz-bands show a spectral index $\alpha$ consistent with 0 at the 1σ level for the observations of 2010 May 31. On May 19 the spectral index was consistent with both 0 and -1 at the 2σ level, while on Apr. 15 $\alpha$ was inconsistent with 0 and consistent with -1 at the 3σ level. This can be due to the presence of an optically thin ejection event during the source hard state. The EVLA light curve in Figure 6.1 shows the fading of the radio counterpart to XTE J1752–226 at the end of the outburst. After May 31 (MJD 55347) the source is detected only once, corresponding to the X-ray re-brightening observed by Chandra (see Section 6.2.2). The most stringent upper limit to the quiescent radio flux of XTE J1752–226 was obtained on 2011 Aug. 2, when the 3σ upper limit to the flux density at 8.4 GHz was $<0.048 \text{ mJy beam}^{-1}$ (Table 6.5).

\(^4\text{http://www.aips.nrao.edu/index.shtml}\)
6.2 Observations, data reduction and results

6.2.10 The X–ray – radio correlation

We performed quasi-simultaneous ($\lesssim 0.5$ days apart) Chandra-EVLA observations on 2010 Jul. 13, 20, 26 and Aug. 2. Moreover, Russell et al. (2012) reports RXTE/PCA observations that are less than 0.6 days apart from our EVLA pointings on 2010 Apr. 15, May 19 and May 31 and from our VLBA detection on 2010 Jun. 17. Furthermore, two radio observations of XTE J1752–226 during the hard state, performed on 2009 Oct. 31 and Nov. 1 with the Australia Telescope Compact Array (ATCA), are reported by Brocksopp et al. (2009). Quasi-simultaneous RXTE detections (Russell et al., 2012) provides us with a total of ten X–ray – radio observations (see dashed lines in Figure 6.1) that we can use to investigate the behaviour of XTE J1752–226 on the X–ray – radio correlation for the hard state of BHTs. As shown by Jonker et al. (2004a), the non-linearity of the X–ray – radio correlation makes the normalization dependent on the distance. In order to compare XTE J1752–226 with other sources, we calculated the X–ray (1–10 keV) and GHz radio luminosity assuming a distance of 3.5 kpc as well as a the typical distance of 8 kpc to the Galactic Centre (see discussion on the distance in Section 6.3.). When converting the monochromatic radio flux density into a radio luminosity, we multiplied by a frequency of 5 GHz, under the assumption that the spectrum is flat in the GHz range. This assumption leads to an underestimate of the luminosity for the observation taken on 2010 Apr. 15, when the spectrum was consistent with optically thin synchrotron emission (see Section 6.2.9 and below). The choice of the 5 GHz frequency has the purpose of comparing with the most updated $L_X$–$L_R$ plot, reported by Calvelo et al. (2010). Figure 6.5 shows the X–ray – radio correlation that we obtained for XTE J1752–226 together with data from Calvelo et al. (2010) for GX 339–4, 4U 1543–47, 1E1740.7–2942, A 0620–00, GS 1354–64, XTE J1118+480 and V404 Cygni, all of which follow the ‘canonical’ X–ray – radio correlation, GRS 1915+105, which may or may not be an outlier (see Coriat et al. 2011) and the ‘outliers’ XTE J1550–564, XTE J1650–500, GRO J1655–40, Cygnus X–1, Swift J1753.5–0127, GRO J0422+32, RXS 1758–254, XTE J1720–318 and H1743–322. For the latter, we have used the hard-state measurements from the work of Coriat et al. (2011). Observations of XTE J1908+094 from Jonker et al. (2004a) and recent radio upper limits from Miller-Jones et al. (2011a) for GRO J0422+32, XTE J1118+480, GRO J1655–40, GS 2000+451, XTE J1908+094, XTE J1859+226 and V4641 Sgr are also included.

Three of our radio observations did not result in a detection and provide upper limits to the radio flux. The upper limits are consistent with both a standard as well as an under-luminous correlation. On the other hand, the six points at an X–ray luminosity above $10^{35}$ erg s$^{-1}$ are clearly under-luminous
in radio with respect to the standard correlation. The intermediate point at \( L_X \sim 10^{33} - 10^{34} \text{ erg s}^{-1} \) (depending on the distance) is located much closer to the standard correlation than the higher luminosity ones, resembling the behaviour of H1743–322. For a distance of 8 kpc, the \( L_X \sim 10^{34} \text{ erg s}^{-1} \) point falls very well on the standard correlation while the higher luminosity points are located in the region of the (known) ‘outliers’. For this distance a transition from the ‘outliers region’ towards the canonical correlation seems to occur around the same luminosity as for H1743–322. Excluding the ATCA detections, for which no uncertainty was reported, a fit to the five remaining detections with a single power-law is very poor (\( \chi^2 = 85, 3 \text{ d.of.} \)) and gives \( L_R \propto L_X^{0.51 \pm 0.04} \). Slightly better fits are obtained with two power-laws, one including the most luminous point and not the faintest, with an index \( b = 0.87 \pm 0.08 \) (\( \chi^2 = 27, 2 \text{ d.of.} \)) and one including the least luminous detection but not the brightest, with \( b = 0.46 \pm 0.07 \) (\( \chi^2 = 23, 2 \text{ d.of.} \)). Still, the fit is poor due to the scatter between the few points. Moreover, the fitted slope of the correlation on the outliers branch relies on the 2010 Apr. 15 observation, for which we are likely under-estimating the radio luminosity and which is not a good representative of the hard state. The fact that the spectral index \( \alpha \) was negative indicates contamination from an optically thin ejection event. Despite this, the observations reported by Brocksopp et al. (2009) confirm that XTEJ1752–226 lies on the outliers branch at high luminosity.

6.3 Discussion

We have observed the BHT XTEJ1752–226 towards the end of its 2009-2010 X–ray outburst, with the purpose of exploring the quiescent properties of the source and, in particular, the low-luminosity end of the X–ray – radio correlation. To this end we performed four simultaneous EVLA and Chandra observations, plus three EVLA observations and one VLBA observation that are simultaneous to RXTE pointings. After a short re-brightening, XTEJ1752–226 reached a minimum X–ray flux level of \((1.6 \pm 0.4) \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \) (0.5-10 keV) on 2010 Jul. 26. At this same flux level the source was found again one week later, in our last Chandra pointing. The EVLA observations towards quiescence provide one detection corresponding to the X–ray re-brightening, and allow us to set an upper limit to the quiescent 8.5 GHz radio flux of <0.048 mJy beam\(^{-1}\).

We also observed the source with the Magellan/IMACS instrument in the optical i’-band, almost one year after the end of the X–ray outburst. We could not detect the source down to a limiting magnitude of 24.4.
Figure 6.5: X–ray radio correlation for XTE J1752−226 assuming a distance of 8 and 3.5 kpc (large black dots and empty circles, connected by dotted lines; see text in Section 6.2.10). The most updated set of sources on the correlation, from Calvelo et al. (2010), is plotted for comparison. The data for H1743-322 are from a dedicated paper by Coriat et al. (2011). Observations of IGR J17091-3624 in the hard state from (Rodriguez et al., 2011), of XTE J1908+094 from Jonker et al. (2004a) and recent radio upper limits from Miller-Jones et al. (2011a) are also included, for GRO J0422+32, XTE J1118+480, GRO J1655−40, GS2000+451, XTE J1908+094, XTE J1859+226 and V4641 Sgr. For clarity we do not show the uncertainty on the source distances, but see Miller-Jones et al. (2011a) and (Rodriguez et al., 2011). The slope of the standard correlation $L_R \propto L_X^{0.6}$ is shown by the dashed line. The data-point indicated by the dashed arrow is from the observation of 2010 Apr. 15, when the radio spectrum was consistent with optically this emission from an ejection event.
6.3.1 Distance

With the available data it is not possible to put solid constraints on the source distance. However, some indication of a reasonable distance range can be obtained by combining known empirical relations. Maccarone (2003) found that the transition from the hard to soft state at the end of a BHT outburst occurs at a bolometric luminosity that is around the $\sim 2.2\%$ of the Eddington luminosity $L_{Edd}$ (with an uncertainty of 40%). Assuming a typical BH mass of $10\, M_\odot$ we can compute $L_{Edd}$ and, following Maccarone (2003), the luminosity of XTE J1752$-$226 at the time of the transition from the soft to the hard state. Comparing this luminosity with the RXTE/PCA flux at the time of the transition we can obtain an estimate of the source distance. Russell et al. (2012) and Shaposhnikov et al. (2010) show that the RXTE count rate from the source was 100 counts per second in the first hard state observation after the soft-to-hard state transition. The corresponding bolometric X-ray flux (for the bolometric correction we follow Maccarone 2003) is $\sim 2.7 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$, from which we obtain a distance of $\sim 9.1 \pm 4.5$ kpc. This is consistent at the 2σ level with the distance of $3.5 \pm 0.4$ kpc claimed by Shaposhnikov et al. (2010) on the basis of the source spectral and timing properties in X-rays. The above methods are both rather uncertain. Their agreement between 3.5 and 9 kpc suggests that XTE J1752$-$226 is in the Galactic bulge or closer to us, but the boundaries of a likely distance range are hard to define. For this reason, we choose two nominal values: the 3.5 kpc from Shaposhnikov et al. (2010) (which is probably a conservative lower limit, as will be shown below) and the distance of 8 kpc typically assumed for a source in the Galactic bulge. Further in the discussion we will show that a consistent scenario for the multi-wavelength properties of XTE J1752$-$226 emerges within this distance interval, although, given the uncertainties on the relations we used, the extremes of this range are only indicative.

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5As the transition requires several days, during which the source flux varies by a factor of $\sim 2$, it is not straightforward to establish what is the luminosity at the transition to be used in the method of Maccarone (2003). This uncertainty on the time of the transition is included in the 40% uncertainty on the ratio with the Eddington luminosity indicated by the author. We have tested that, whatever observation we consider during the state transition of XTE J1752$-$226, we indeed measure consistent distances within 1σ.

6Note that the $N_H$ towards XTE J1752$-$226 $(0.5 \times 10^{22}$ cm$^{-1}$) is close to the Galactic one in the direction of the source $(0.45 \times 10^{22}$ cm$^{-1}$,Dickey & Lockman 1990b). As the Galactic latitude of XTE J1752$-$226 is $b=2.1$ degrees, the observed $N_H$ implies a lower limit to the source distance that is consistent with the 3.5 kpc limit derived from the X-ray spectral and timing source properties (assuming a vertical dimension of the dust Galactic plane of $\sim 0.12$ kpc, e.g. Greenberg et al. 1987).
6.3 Discussion

6.3.2 Companion star

The upper limit we measured on the quiescent i’-band magnitude makes a giant companion star in XTE J1752−226 very unlikely, as the source should be located outside of our Galaxy. For \( N_H = 5 \times 10^{21} \text{ cm}^{-2} \) we obtain an extinction coefficient in the i’-band \( A_{i'} \approx 1.54 \) (following Güver & Özel 2009b and the extinction laws in Cardelli et al. 1989b). For a G5 III star the absolute magnitude is \( M_i \approx -0.27 \) (Drilling & Landolt 2000, later spectral types are brighter, aggravating the problem). Given our observed magnitude \( m_i \gtrsim 24.4 \) and according to the definition of the distance modulus \( 5 \log d(\text{pc}) - 5 = m_i - M_i - A_i \) we conclude that the distance of a giant would be \( d \gtrsim 300 \text{ kpc} \).

An ultra-compact binary scenario, i.e. with a white dwarf donor, is also ruled out by the detection of Hydrogen lines in the optical spectra in outburst (Torres et al., 2009a). Thus, the companion star in XTE J1752−226 is most likely a main sequence or sub-giant star. Given our limit on the i’-band magnitude, the indications we found on the source distance confine the spectral type of the companion star to a type M or later: a distance of 8 kpc gives an absolute magnitude for the secondary \( M_i \gtrsim 7.6 \) (reddening has been considered as above) which is true for a main sequence star later than M2 (Drilling & Landolt, 2000). If \( d = 3.5 \text{ kpc} \), our i’-band non-detection implies that the spectral type has to be later than M5.

6.3.3 Orbital period

Since XTE J1752−226 most likely hosts a main sequence secondary star, we expect the source to follow the relation found by Shahbaz & Kuulkers (1998) between the V-band outburst amplitude \( \Delta V \) and the orbital period \( P_{\text{orb}} \) (note the caveats mentioned by Miller-Jones et al. 2011c and below). A comparison of the limit to the quiescent i’-band magnitude (\( \gtrsim 24.4 \) mag) with observations in outburst indicates an outburst amplitude \( \Delta i > 8 \) magnitudes. The corresponding \( \Delta V \) depends on the spectrum of the disc, which dominates the optical emission in outburst, and on the spectrum of disc+companion star in quiescence. We can provide an upper limit to the orbital period by assuming that the disc is dominating both in outburst and in quiescence. van Paradijs & McClintock (1995c) found that, on average, \( B-V \sim 0 \) for the accretion disc in a low mass X-ray binary. If \( V-I \) is also \( \sim 0 \), \( \Delta V = \Delta i > 8 \) magnitudes and, according to the correlation of Shahbaz & Kuulkers (1998), \( P_{\text{orb}} \lesssim 6.8 \text{ h} \). As pointed out by Miller-Jones et al. (2011c), the correlation of Shahbaz & Kuulkers (1998) does not include the effect of the inclination. High inclination systems (such as MAXI J1659−152) are fainter in the optical during outburst because only a small fraction of the disc surface is visible when the disc is seen edge on. As XTE J1752−226 probably hosts a BH, the lack of eclipses
or dips still allows for quite a high inclination (\(\sim 80\) degrees, Horne 1985b). For this reason, although the large outburst amplitude points towards a lower inclination, we can not exclude a significant inclination effect on the Shahbaz & Kuulkers (1998) correlation. If this is the case, the orbital period of XTE J1752−226 would be even shorter than what we are calculating.

Independent support of our estimate of the distance and the orbital period comes from the correlation between \(P_{\text{orb}}\) and the luminosity at the peak of an outburst \(L_{\text{peak}}\) found by Wu et al. (2010). The flux at the peak of the outburst of XTE J1752−226 was \(\sim 8 \times 10^{-9}\) erg s\(^{-1}\) cm\(^{-2}\) in the 1-10 keV range (RXTE/PCA from Russell et al. 2012), which gives \(0.01 L_{\text{Edd}} \lesssim L_{\text{peak}} \lesssim 0.05 L_{\text{Edd}}\) for a distance \(3.5 \lesssim d \lesssim 8\) kpc and a 10 M\(_{\odot}\) BH. Using the correlation of Wu et al. (2010), this gives \((0.9 \pm 0.08) < P_{\text{orb}} < (6.5 \pm 1.8)\) h, consistent with the upper limit we derived from the optical outburst amplitude. For \(d \sim 6\) kpc, \(P_{\text{orb}} \sim 2.4\) h, comparable to the shortest orbital period known for a BHT (MAXI J1659−152, Kuulkers et al. 2011, Kennea et al. 2011). For \(3.5\) kpc, the period is much shorter than the shortest known for a BHT, trespassing into the ultra-compact systems regime. The presence of hydrogen in outburst, however, rules out a hydrogen deficient donor. The distance to the source is, therefore, probably larger than \(3.5\) kpc. The luminosity at the peak of the outburst would also be low at \(3.5\) kpc with respect to typical BHTs. Nonetheless, given the uncertainties on the methods we used, we can not rule out such a low distance.

In summary, the spectral and timing properties of XTE J1752−226 and the X-ray luminosity at the transition from soft to hard state indicate a distance of roughly \(3.5 \lesssim d \lesssim 8\) kpc, which translates into consistent estimates of the orbital period from two independent methods: the optical outburst amplitude and the X-ray outburst peak luminosity. The methods also suggest that \(3.5\) kpc is a conservative lower limit and the source is likely to be further than that.

### 6.3.4 The X-ray–radio correlation

Using the indications we found on the source distance, we have calculated the X-ray and radio luminosity of XTE J1752−226 in order to compare the X-ray–radio correlation for this source with other BHTs. Figure 6.5 shows the correlation for a distance of \(3.5\) and \(8\) kpc. The behaviour of XTE J1752−226 resembles that of H1743−322, where a transition from the region of the ‘outliers’ to the standard correlation occurs when \(L_X\) decreases. For \(d=8\) kpc, XTE J1752−226 seems to experience the transition close to the same luminosity where it occurs for H1743−322, while for \(d=3.5\) kpc it transits at a lower luminosity. The transition was covered with many observations in the case of H1743−322 (Coriat et al., 2011) and interpreted as a switch from a radiatively efficient accretion mechanism (on the ‘outliers’ branch) to a radia-
tively inefficient one (on the ‘standard’ correlation). It is possible that many BHTs are located on one branch or the other for the full range of luminosity covered within one outburst, or, in other words, that the hard state can be associated with a different accretion flow for different sources. On the other hand, the similarity between XTE J1752−226 and H1743−322 suggests that the ‘switching’ behaviour of the latter may be shared by other outliers. It is worth noting that, based on our data, it is also possible that XTE J1752−226 does not ‘return’ to the \( L_R \propto L_X^{0.6} \) correlation but crosses it at low luminosities. Either way, XTE J1752−226 is the first BHT found to show evidence of a transition similar to that of H1743−322. More data will be needed in order to confirm this result and to probe the low luminosity end of the X–ray – radio correlation better, for XTE J1752−226 and for other BHTs.

### 6.3.5 X–ray detection in quiescence?

The X–ray flux XTE J1752−226 on 2010 Jul. 26 and Aug. 2, when we observed it with *Chandra* for the last time, was \((1.4\pm0.2)\times10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \) (0.5-10 keV, corresponding to a luminosity of \( L_X \sim 8 \times 10^{31} \text{ erg s}^{-1} \) for a distance of 8 kpc). The fact that we observed consistent flux levels in our last two observations suggests that the source had reached its quiescent level. Nonetheless, it is also possible that we found the source on a temporary plateau and that it further faded after our observations. The optical counterpart to XTE J1752−226 was far from reaching its quiescent level at the time of our last *Chandra* pointing: the source flux dropped by more than 3-3.5 magnitudes in the \( i' \)-band after that moment, until it disappeared below 24.4 mag on 2011 May 3 (see Figure 6.1). In the case that we measured the quiescent X–ray flux level, this indicates that the decay of the outburst phase towards quiescence had an ‘inside-out’ development, starting with the fading of the X–ray source only later followed by the optical. Moreover, assuming we measured the quiescent X–ray flux, the quiescent luminosity for our estimate range of distances implies an orbital period longward of 10 hours, if XTE J1752−226 follows the trend between orbital period and quiescent X–ray luminosity reported by Garcia et al. (2001) and Gallo et al. (2008). Instead, if the true quiescent luminosity is lower than measured, then the inferred orbital period would be shorter and more compatible with the orbital period inferred above.

### 6.3.6 X–ray detection of a jet?

Finally, using our deep *Chandra* observations we discovered unidentified faint sources in the vicinity of XTE J1752−226. In particular, we detected faint X–ray emission at \( \sim 2'' \)9 from the source on 2010 Jul. 26 (source S2 in Figure
6.2 and Table 6.3). No clear optical counterpart corresponds to the X–ray position.

A possible scenario is that S2 was a transient event aligned by chance with XTE J1752−226. A flare from an unseen background star is unlikely, as the X–ray flux is too high with respect to the optical one. The ratio between X–ray and visual flux for a stellar flare, in fact, is typically \( \log\left(\frac{F_X}{F_V}\right) \lesssim -2 \). Given the observed X–ray flux from S2, the V-band magnitude of an unseen stellar counterpart should be \( \lesssim 18.7 \), meaning \( \lesssim 19.2 \) in the i’-band \((V-I=-0.47\) for an O5 star, increasing towards later types, Drilling & Landolt 2000). An object with this magnitude would be visible in our deep R-band observation.

A chance alignment with an unknown background AGN, binary system or with some peculiar transient event is also rather unlikely due to the rarity of such events, but it can not be ruled out. Nonetheless, the proximity to XTE J1752−226, the position angle (see below) with respect to the BHT core compared to that of the radio jet ejections (Yang et al. 2010, Miller-Jones et al. 2011c, Yang et al. 2011), the morphology and the variability of S2 can also be interpreted as X–ray emission coming from a relativistic jet launched by XTE J1752−226.

Radio observations earlier in the outburst resolved two jet components from XTE J1752−226 (Yang et al. 2010, Miller-Jones et al. 2011b) probably ejected during the outburst at the time of the hard-to-soft transition, in January 2009 (Homan, 2010). A third one was recently identified by Yang et al. (2011). Besides the radio emission, relativistic jets from BHTs have been found to emit also in the X–rays, at large scales and long after the ejection event (the most extreme case is the BHT XTE J1550-564, Corbel et al. 2002, Tomsick et al. 2003, Kaaret et al. 2003). In the BHT H1743-322 (Corbel et al., 2005) Chandra observations revealed X–ray emission associated with ejecta previously detected in the radio, at an angular separation of a few arcseconds from the core of the source. Both the radio and X–ray radiation are thought to be synchrotron emission from particles accelerated by shocks within the jet.

The position for S2 from our Chandra observation 11055 indicates a position angle of \(-52 \pm 7\) degrees, which is consistent at the 1\(\sigma\) level with the position angle of the radio jets, \(50 \pm 0.6\) degrees (Miller-Jones et al. 2011b, Yang et al. 2011). Although not significantly detected by WAVDETECT, fainter emission along the jet direction is visible in observation 11056 too (Figure 6.2). The upper limits to the X–ray flux from S2, obtained from the non-detections in the observation 11056 and in the ones previous to 11055 (see Section 6.2.2) are high enough that S2 may have had a constant flux level (or possibly re-brightened) between 2010 Jul. 20 (observation 12310) and 2010 Jul. 26 (observation 11055), while it has faded by at least a factor of \(\sim 1.8\) in the following seven days, until 2010 Aug. 2 (observation 11056). An X–ray brightening can be caused by a shock in the jet either caused by the collision of consecutive jets.
traveling at different velocities, by the interaction of the ejecta with the interstellar medium (ISM) or by renewed energization related to the X-ray flare from the core of XTE J1752–226 occurred around 2010 Jul. 20 (observation 12310). Fender et al. (2004) proposed a similar scenario for the neutron star X-ray binary Cir X–1, where X-ray flares from the source core were causing re-brightening of radio emitting components 2′-2′′5 downstream in the jets, on a timescale of few days. Although this interpretation has been put into question by recent observations of Cir X–1 (Miller-Jones et al., 2012), evidence of a flow of energy through astrophysical jets was found for other objects, such as the NS X-ray binary Sco X–1 (Fomalont et al., 2001) and several active galactic nuclei (e.g. Tingay et al. 1998). For a distance of 8 kpc, and assuming the date of observation 12310 as the starting time (MJD 55397.07034), the velocity of a shock propagating from the core of XTE J1752–226 to S2 would be \( \beta \gtrsim 0.999c \) (for details on the calculation see Fender et al. 2004). Although highly relativistic shocks within the jets were found for other sources (for Sco X–1, the jets velocity was 0.32-0.57c, but energy appeared to move from the core to the radio lobes at \( \beta \gtrsim 0.95c \), Fomalont et al. 2001) the limit we find for XTE J1752–226 is even higher than the extreme case of Cir X–1, where \( \beta \gtrsim 0.998c \). If XTE J1752–226 lies at 3.5 kpc, the velocity would still be \( \beta \gtrsim 0.994c \). Such high values would imply that the jets are very close to the line of sight, with an inclination of less than \( \sim 12^\circ \) at 3.5 kpc and less than \( \sim 5^\circ \) at 8 kpc. As XTE J1752–226 did show several X-ray flares during the last part of the outburst, an X-ray and/or radio re-brightening of the source core prior to our Chandra observation 12310 could be responsible for the re-energization of S2, leading to smaller velocities for the energy flowing in the jets. A scenario for XTE J1752–226 with very low inclination and highly relativistic shocks traveling in the jets would be consistent with the high proper motion measured from the resolved radio jets (\( \sim 58\text{ mas}d^{-1} \), Yang et al. 2011) and with the fact that no receding jet was detected so far. As pointed out by Yang et al. (2011), XTE J1752–226 is a promising Galactic superluminal source candidate.

Another plausible scenario is that the X-ray emission from S2 is caused by interaction of a previously launched jet with the ISM, or by the collision of two consecutive ejections. Evidence for deceleration of the radio jets launched close to the hard-to-soft transition due to the ISM was already presented by Miller-Jones et al. (2011b). The authors found that the motion of the jets was best fit by a combination of a pure ballistic model describing the initial phase after the ejection, followed by a Sedov model further out with respect to the source core. Extrapolating this model to the time of our detection of S2, the jets should have traveled to a distance of \( \sim 1'' \) away from the core of XTE J1752–226. This is less than half the separation we observe between XTE J1752–226 and S2. If S2 is related to the ejections reported by Yang
et al. (2010) and Miller-Jones et al. (2011b), this result indicates that the jets deceleration did not continue according to the Sedov model due to, e.g., density variations in the ISM. Denser coverage would be needed in order to single out a specific interpretation. At last, we note that the variable, unidentified Chandra source S6 also lies on the jet line, albeit on the side opposite S2, at a distance of \(\sim 7.4\) from the core of XTE J1752−226. Although it is possible that the X-ray emission we observed from S6 is associated with a receding jet from XTE J1752−226, the source position corresponds to that of a bright star detected in the optical, with a 0.25% probability of chance coincidence. An association with the optical candidate counterpart is thus likely.

6.4 Conclusion

We performed multi-wavelength observations of XTE J1752−226 in quiescence and during the last phase of the outburst decay towards quiescence, with the IMACS instrument in the optical i’-band, with the Chandra satellite in the X–rays, and with the EVLA and VLBA in the radio band. We found that the i’-band counterpart to the source is fainter than 24.4 magnitudes, while the quiescent radio flux is <0.048 mJy beam\(^{-1}\) at 8.4 GHz. The quiescent X–ray flux as measured from our last Chandra observations is \((1.4\pm0.2)\times10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) (0.5-10 keV), although we can not rule out a later further dimming of the source.

We presented independent indications that the distance towards XTE J1752−226 is likely between \(\sim 3.5\) and \(\sim 8\) kpc, in agreement with previous estimates based on the X–ray spectral and timing properties of the source. We showed that such a distance leads to a coherent picture where XTE J1752−226 has a short orbital period of \(P_{\text{orb}} \lesssim 6.8\) h and the companion star is later than an M type main sequence star. Combining our EVLA pointings with simultaneous Chandra observations and published RXTE data acquired during the outburst, we could investigate the X–ray – radio correlation for XTE J1752−226 in comparison with other BHTs. We found indications that XTE J1752−226 behaves similarly to H1743−322, a BHT that is under-luminous in radio with respect to the ‘standard’ relation \(L_R \propto L_X^{0.6}\) when above a critical luminosity of \(\sim 5 \times 10^{-3}L_{\text{Edd}}(M/10M_\odot)\), but undergoes a transition towards the standard correlation as the luminosity decreases. This transition was interpreted as a switch from a radiatively efficient accretion mechanism to a radiatively inefficient one. Given that a similar transition occurs in XTE J1752−226, suggests that such changes in the accretion mechanism are not due to some exceptional property of H1743−322 but may be shared by other BHTs. Our deep Chandra observations also detected several unidentified X–ray sources in the vicinity of XTE J1752−226, for some of which we found i’-band counterparts. One of the
6.4 Conclusion

X–ray sources is variable and is probably associated with re-energization of jets from XTE J1752−226 or with the interaction of the ejecta with the ISM.

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Summary
(Samenvatting)

X–ray binaries (XRBs) and cataclysmic variables (CVs) are binary systems consisting of a normal star and a compact object - a neutron star (NS) or black hole (BH) for XRBs or a white dwarf (WD) for CVs. The compact object captures material from the companion star, in a process called mass accretion (Figure 6.6). In this process, a large amount of energy is radiated from the accreting material, mostly as X–ray emission. XRBs and CVs are, in fact, the most luminous X–rays sources in the Galaxy (Figure 6.7).

In the chapters of this thesis I presented observations of XRBs and CVs in the X–rays and radio energy bands, but mostly in optical (visible) and near infrared (NIR) light. These observations were tailored to measure the mass of the compact object in the binary. Although challenging to obtain, such measurements are important to address a number of astrophysical questions. For example, the formation and evolution of the binary population is complex and not fully understood. Tracing the currently poorly constrained mass distribution of NSs and BHs can provide constraints to theoretical models in this field. Similarly, measurements of massive NSs can rule out theories about the composition of these objects (which is unknown), as a different composition implies a different value for the maximum possible mass.

Dynamical mass measurements

A reliable method to measure masses in XRBs and CVs is based on the observation of the companion star and the application of Kepler’s laws (dynamical mass measurements). In practice, one needs to perform phase-resolved spectroscopy of the companion star, i.e. collecting several spectra of the latter spread across its orbit around the compact object. In the spectra, we can detect absorption lines from elements in the atmosphere of the star (Figure 6.8). While the latter moves in its orbit, the wavelength at which absorption lines are detected is shifted due to the Doppler effect, offering a way to trace
the projected velocity of the star and measure the binary orbital period.
In compact accreting systems such as those we are targeting, accretion causes
the companion star to be tidally locked with the orbit, meaning that the angular
velocity of rotation and revolution is the same (the same happens with the
moon and the Earth). Thanks to this, the mass ratio between the companion
star and the compact object can be expressed as a function of the maximum
projected orbital velocity of the star, measured as explained above, and of
another measurable quantity, which is the width of the absorption lines. The
lines are broadened by the rotational velocity of the companion star around
its own axis.
Once the orbital period and the mass ratio are known, only one more param-
eter is needed in order to measure the masses, which is the inclination of the
plane of the orbit with respect to the line of sight. The inclination is best
measured in eclipsing systems, where it can be inferred from the eclipse du-
ration based on geometrical arguments only. Unfortunately eclipsing systems
are rare. In non-eclipsing systems, a method to constrain the inclination is the
modelling of ellipsoidal modulations, which are small variations in the luminos-
ity of the secondary star due to the fact that its shape is deformed compared
to a sphere. This deformation is caused by the gravitational field of the ac-
cretor (Figure 6.6). However, as shown in Chapter 4 and 5, the modelling can
be uncertain because of further effects modulating the luminosity, such as star.
spots on the companion star or emission from the accreting material. Since dynamical mass measurements rely on the observation of the companion star, they are usually performed when the XRB or CV is in ‘quiescence’, meaning that the rate of mass transfer is relatively low. The reason is that, when the accretion rate is high (in ‘outburst’), the accretion flow around the compact object emits light from the X–rays to the NIR and typically out-shines the companion star at all wavelengths (best candidates for dynamical mass measurements are systems with a companion star of late spectral type, which are faint). As a consequence of the need to perform observations in quiescence, the measurements of compact object masses also often provides useful information about XRBs and CVs at low luminosity.

**Optical/NIR counterpart identification**

The first step to find suitable candidates for dynamical mass measurements is to determine the optical or NIR counterpart to an X–ray source, namely to find the star that corresponds to the X–ray emission. This is done by matching the X–ray target coordinates with those of stars detected in the optical/NIR
Figure 6.8: Optical spectrum of the XRB IGR J19308+0530. Many absorption lines are visible, due to elements in the stellar atmosphere of the companion star (lines from Fe, Ca and H are labeled). The absorption feature labeled as IS is caused by interstellar material in between us and the source.

light. Since optical images collected with telescopes do not come with standard celestial coordinates attached to them, one has to first accurately determine the coordinates of the stars in the observed field (i.e. performing astrometry on the field), which is not as trivial as it might seem. Moreover, most of the X–ray satellites measure positions with a rather low level of accuracy, so that the same X–ray source could correspond to multiple stars in visible light. In order to obtain a secure association, one needs to target the source with the Chandra X–ray satellite, which provides the best positional accuracy currently achievable in the X–rays. This was done in Chapter 2, which is dedicated to the identification of the optical counterpart to a sample of recently discovered X–ray sources. The Chapter also shows how the identification of the optical counterpart is useful for the classification of X–ray sources. XRBs and CVs, in fact, can be grouped in several classes with different characteristics. Also they are not the only objects emitting X–rays in the sky, and the X–ray observation alone is often not enough to determine the nature of a source.
Three dynamical studies of quiescent XRBs/CVs

Chapter 3, 4 and 5 present examples of dynamical studies performed on an XRB or a CV in quiescence. The source analysed in Chapter 3, EXO 0748−676, is in principle the ideal target for the purpose of measuring a potentially high NS mass. However, we could not obtain an accurate mass measurement for this object, due to the unexpected conditions that we found in the system. The NS in the binary turned out to be unusually hot at the time of our observations, and was irradiating and heating up the inner face of the companion star. As a result, the spectra did not show absorption lines from the stellar atmosphere of the latter, but were dominated by emission lines from Hydrogen and Helium due to irradiation. This prevented us from performing straightforward dynamical mass measurements.

Moreover, we found that the observed emission lines were too broad to originate on the companion star surface. This suggested evaporation of material from the heated face of the mass donor, possibly due to the X−ray emission and/or to a pulsar wind from the NS. In a famous X−ray source known as ‘the black-widow pulsar’, a similar effect has almost completely blown the companion star away.

The sources studied in Chapter 4 and 5, CXOGBS J174444.7−260330 and IGR J19308+0530 respectively, are both low accretion rate systems that never showed an outburst. In both cases the optical spectra were dominated by the companion star. We could trace the orbital Doppler shift of the mass donor absorption lines, obtaining a measurement of the orbital period $P$ and of the mass ratio, $q$.

In the case of IGR J19308+0530 we measured $q \sim 1.8$, which is extremely high compared to what theory usually predicts for this type of XRB ($q \lesssim 1$). With $q \sim 1.8$, one would normally expect a short-lived (and thus unlikely to observe) phase of very high accretion rate and high X−ray luminosity. However, we observe a faint and quiescent system. A possible way to reconcile our observations with theory is that accretion is kept stable by mass loss from the binary, i.e. not all the mass that is lost by the companion star ends up on the compact object (accretion is not conservative). The peculiarity of IGR J19308+0530 makes it interesting as an extreme case to be reproduced by binary evolution theories, and drives attention on non-conservative mass transfer, which is neglected in most theoretical models.

For both IGR J19308+0530 and CXOGBS J174444.7−260330 the modelling of ellipsoidal modulations was difficult, but allowed to establish that the compact object is most likely a WD. This provides an example of the difficulty of knowing the nature of the compact object in an XRB without dynamical mass measurements, as in both cases preliminary clues favoured a NS or even a BH.
Our observations of CXOGBS J174444.7−260330 also show that the state of quiescence is not stable as it is often thought to be, but sporadic episodes of higher accretion rate and small outbursts can occur. This has to be taken into account for all the surveys aiming to spot NS and BH XRBs, since it causes WD systems to sporadically show features resembling those of more massive accretors.

**Quiescence in X–rays and radio**

XRBs are known sources of powerful jets of ultra-relativistic particles, which are detected in the radio waveband due to synchrotron radiation. Observations show that the radio and X–ray luminosity of XRBs correlate across several orders of magnitude, suggesting a coupling between the X–ray emitting accretion flow and the radio emitting jets. The physics underlying the correlation is not yet understood, but its study can potentially provide insights about the energy balance of the accretion process. The BH sources for which the X–ray - radio correlation has been studied can be divided into two groups: the ‘standard’ systems (the first sources found to show a correlation are in this group) for which $L_R \propto L_X^{0.6}$, and the so-called ‘outliers’, showing a steeper correlation similar to that of NS systems at high luminosities. The two ‘flavours’ of the correlation have been associated with different regimes of accretion. In Chapter 6 we present simultaneous observations of the BH XRB XTE J1752−226 in X–rays and radio, performed at the end of its 2009-2010 outburst in order to probe the X–ray - radio correlation towards low luminosities. We found evidence of a change in the slope of the correlation for this source, which seems to switch from the outlier group to the standard correlation as the luminosity decreases. Before our research was published, a similar transition had been observed for one other BH system only, H1743−322. Our result is important as it suggests that a switching behaviour on the X–ray - radio correlation is not a peculiarity of H1743−322, but could be shared by many XRBs at low luminosities.

With *Chandra* observations, we also detected a variable X–ray source in the vicinity of XTE J1752−226, aligned with the direction of ultra-relativistic radio jets previously observed from the binary. The observations were consistent with re-energization of a previously launched jet, producing the X–ray emission. This is an interesting find, as very few cases of X–ray emission from jets are known (e.g., Sco X-1, Cir X-1, XTE J1550-564).

We also performed deep observations in the optical, but we did not detect the counterpart to XTE J1752−226, which is thereby too faint for dynamical mass measurements.
Samenvatting

Röntgendubbelsterren en cataclysmische variabelen zijn dubbelstersystemen die bestaan uit een normale ster en een compact object - een neutronenster of zwart gat in een röntgendubbelster, of een witte dwerg in het geval van een cataclysmische variabele. Het compacte object ontvangt materiaal van zijn begeleider in een proces dat massa-accretie heet (Figuur 6.6). Bij dit proces komt een grote hoeveelheid energie vrij, die voornamelijk wordt uitgezonden als röntgenstraling. Röntgendubbelsterren en cataclysmische variabelen zijn zelfs de helderste bronnen van röntgenlicht in onze Melkweg (Figuur 6.7).

In dit proefschrift presenteer ik waarnemingen van röntgendubbelsterren en cataclysmische variabelen op verschillende golflengtes: in röntgen- en radiolicht, maar voornamelijk in het zichtbaar en nabij-infrarode (NIR) deel van het spectrum. Deze waarnemingen zijn ontworpen om de massa’s van de compacte objecten in deze dubbelstersystemen te meten. Deze massa’s zijn lastig te meten, maar erg belangrijk voor het beantwoorden van een aantal prangende vragen in de sterrenkunde. Zo zijn er bijvoorbeeld de formatie en evolutie van dubbelsterren, een complex en nog niet volledig begrepen proces. Het bepalen van de - op dit moment nauwelijks bekende - massaverdeling van neutronensterren en zwarte gaten kan helpen om grenzen aan te geven voor de theoretische modellen in dit veld. Ook de structuur en samenstelling van neutronensterren zijn nog onbekend. Omdat verschillende modellen een andere maximale massa voorspellen, kan het meten van de massa’s van de zwaarste neutronensterren helpen de juiste theorie te vinden.

Dynamische massabepaling

Een betrouwbare methode om de massa’s van de compacte objecten in röntgendubbelsterren en cataclysmische variabelen te meten is de zogeheten dynamische massabepaling. Deze methode is gebaseerd op het observeren van eigenschappen van het dubbelstersysteem, zoals de baanperiode en de massaoverhouding van het compacte object en zijn begeleidende ster, en het toepassen van de wetten van Kepler. De eigenschappen van het dubbelstersysteem kunnen worden afgeleid uit waarnemingen van spectra van de begeleider in verschillende fases in de baanperiode. In deze spectra zoeken we naar absorptielijnen die worden veroorzaakt door elementen in de atmosfeer van de ster (Figuur 6.8). Als de ster beweegt in zijn baan rond het compacte object veranderen de golflengtes waarop we deze lijnen waarnemen door het Dopplereffect. Dit geeft ons een manier om de snelheid van de begeleidende ster, zoals die wordt geprojecteerd in onze kijkrichting, en de baanperiode van het dubbelstersysteem te meten. In dit soort compacte systemen waarin massa-overdracht
plaatsvindt zorgt het accretieproces ervoor dat de rotatie van de begeleidende ster om zijn eigen as gebonden is aan zijn rotatie rond het compacte object (net zoals de Maan in dezelfde tijd om zijn eigen as en om de Aarde draait). Dankzij dit effect kan de massaverhouding van de ster en het compacte object worden uitgedrukt als een functie van de maximale baansnelheid van de ster zoals geprojecteerd in onze kijkrichting (gemeten uit de maximale Dopplerverschuiving van de absorptielijnen in het spectrum) en de rotatiesnelheid van de ster. Die laatste leiden we af uit de breedte van de absorptielijnen, die wijder worden doordat de ster om zijn eigen as roteert. Als we de baanperiode en de massaverhouding van het systeem kennen hebben we nog maar één extra parameter nodig om de massa’s te bepalen. Dit is de hoek die het vlak waarin de baan van het dubbelstersysteem ligt maakt met de kijkrichting vanaf de Aarde (de ‘inclinatie’). De inclinatie is het eenvoudigst te meten in systemen waarin een eclips te zien is: dan is hij op puur geometrische grond te berekenen. Helaas zijn er maar weinig eclipsrende systemen. Als de ster en het compacte object niet voor elkaar langs bewegen is er een andere methode om de inclinatie te bepalen. Dit is door middel van het modelleren van zogeheten ‘ellipsoïdale modulaties’, kleine variaties in de helderheid van de begeleidende ster die worden veroorzaakt doordat de ster wordt vervormd in het sterke zwaartekrachtsveld van het compacte object (Figuur 6.6). Zoals ik in Hoofdstuk 4 en 5 laat zien zijn er echter ook andere effecten die de helderheid van het systeem kunnen veranderen, zoals sterrevlekken op de begeleider of licht dat afkomstig is van het materiaal dat van de ster naar het compacte object stroomt. Dit maakt het afleiden van de inclinatie via deze methode erg onzeker. Aangezien dynamische massabepalingen afhankelijk zijn van observaties van de begeleidende ster, worden ze meestal uitgevoerd wanneer de röntgendubbelster of cataclysmische variabele in ‘rusttoestand’ is. Dit houdt in dat er relatief weinig massa wordt overgedragen van de ster naar het compacte object. Wanneer de massa-overdracht sneller gaat (het systeem is dan ‘in uitbarsting’), zendt de accretieschijf rond het compacte object zoveel licht uit dat hij op alle golflengtes helderder is dan de begeleidende ster. Dit maakt het observeren van die ster vrijwel onmogelijk, zeker omdat de beste kandidaten voor dynamische massabepaling een begeleider hebben van een laat spectraal type. Dit type sterrren is vrij lichtzwak. Omdat het noodzakelijk is om de dubbelstersystemen te observeren in hun rusttoestand leveren deze metingen ook nuttige informatie op over röntgendubbelsterren en cataclysmische variabelen die weinig (röntgen)licht uitzenden.

Identificatie van röntgendubbelsterren in zichtbaar/nabij infrarood licht

De eerste stap op weg naar het vinden van geschikte kandidaten voor dy-
namische massabepalingen is het identificeren van de tegenhangers van röntgenbronnen in zichtbaar of NIR licht, oftewel het vinden van de ster die hoort bij de röntgenstraling. Dit doen we door de coördinaten van röntgenbronnen te vergelijken met die van sterren die zijn gedetecteerd in zichtbaar of NIR licht. Aangezien de opnames die afkomstig zijn van optische telescopen normaal gesproken geen hemelcoördinaten bevatten, is het noodzakelijk om eerst nauwkeurig de posities te bepalen van de sterren in het geobserveerde veld (‘astrometrie toevoegen aan een afbeelding’). Dit is niet zo triviaal als het misschien lijkt. Daar komt nog bij dat de meeste röntgensatellieten de posities van röntgenbronnen niet erg nauwkeurig meten, zodat één röntgenbron samen kan vallen met meerdere sterren en niet duidelijk is welke ster echt bij de röntgenbron hoort. Om zeker te weten dat we de juiste tegenhanger vinden gebruiken we de Chandra röntgensatelliet, die de meest nauwkeurige posities geeft die op dit moment beschikbaar zijn. Dit beschrijf ik in Hoofdstuk 2, dat gewijd is aan het identificeren van de optische tegenhangers van een groep recentelijk ontdekte röntgenbronnen. Dit Hoofdstuk toont ook aan hoe het identificeren van optische tegenhangers kan helpen bij het classificeren van röntgenbronnen. Röntgendubbelsterren en cataclysmische variabelen blijken in verschillende klassen te kunnen worden ingedeeld op grond van de optische straling die ze uitzenden. Daarbij komt dat deze objecten niet de enige bronnen van röntgenlicht in het heelal zijn, en alleen het röntgenlicht is meestal niet voldoende om een bron te classificeren.

**Studie van drie röntgendubbelsterren of cataclysmische variabelen in rusttoestand**

In Hoofdstuk 3, 4 en 5 presenteer ik waarnemingen van drie verschillende röntgendubbelsterren of cataclysmische variabelen in rusttoestand. De bron die wordt geanalyseerd in Hoofdstuk 3 is EXO 0748-676. Dit systeem bevat vermoedelijk een zware neutronenster en is dus in principe een ideaal doelwit om een hoge massa te meten. We konden echter geen nauwkeurige dynamische massabepaling uitvoeren door de onverwachte omstandigheden in deze röntgendubbelster. De neutronenster in dit systeem bleek op het moment van onze waarnemingen een ongewoon hoge temperatuur te hebben, en bestraalde en verhitte de kant van de begeleidende ster die naar hem toe was gekeerd. Dit zorgde ervoor dat er in de spectra van de ster geen absorptielijnen te zien waren. In plaats daarvan werden de spectra overheerst door emissielijnen van waterstof en helium, veroorzaakt door de bestraling vanaf de hete neutronenster. Hierdoor was het niet mogelijk om een dynamische massabepaling uit te voeren. Bovendien bleek dat de emissielijnen te breed waren om afkomstig te zijn van het oppervlak van de begeleidende ster. Dit suggereert dat materiaal verdampd aan de kant die naar de neutronenster is gericht, mogelijk door de röntgenstral-
ing en/of door een pulsarwind afkomstig van de neutronenster. In een ander bekend dubbelstersysteem, de ‘black-widow pulsar’, is de begeleidende ster door een vergelijkbaar effect bijna volledig weggeblazen. In Hoofdstuk 4 en 5 bestuderen we de bronnen CXOGBS J174444.7-260330 en IGR J19308+0530. In beide systemen wordt weinig massa overgedragen en ze zijn nooit in uitbarsting gedetecteerd. De optische spectra van deze bronnen worden gedomineerd door de begeleidende ster, zodat we de Doppler-verschuiving van absorptielijnen in de steratmosfeer als functie van zijn baan om het compacte object kunnen traceren. Hiermee meten we de baanperiode $P$ en de massaverhouding $q$. Voor IGR J19308+0530 meten we een massaverhouding $q \sim 1.8$, wat extreem hoog is vergeleken met wat door de theorie voorspeld wordt voor dit type röntgendubbelsterren ($q \lesssim 1$). Bij een waarde van $q \sim 1.8$ verwachten we een kortdurende fase waarin juist erg veel massa-overdracht plaatsvindt en de bron heel helder is in röntgenlicht. Omdat deze fase zo kort duurt is het onwaarschijnlijk dat we deze toevallig waarnemen. Bovendien zien we een lichtzwak systeem in de rusttoestand. Een mogelijke oplossing om onze waarnemingen en de theorie met elkaar in overeenstemming te brengen is dat het accretieproces gestabiliseerd wordt doordat de massa die de begeleidende ster verliest niet alleen op het compacte object terecht komt, maar ook gedeeltelijk ontsnapt aan het dubbelstersysteem (‘non-conservatieve accretie’). IGR J19308+0530 is een extreem geval en het zou interessant zijn om te onderzoeken of theorieën die de evolutie van dubbelsterren beschrijven zo’n systeem kunnen reproduceren. Ook richt het de aandacht op non-conservatieve massa-overdracht, een fenomeen dat in de meeste theorieën tot nu toe genegeerd wordt. Voor zowel IGR J19308+0530 als CXOGBS J174444.7-260330 was het modelleren van de ellipsoidale modulaties moeilijk, maar het heeft ons in staat gesteld om te concluderen dat beide systemen waarschijnlijk een witte dwerg bevatten. Dit laat zien hoe moeilijk het is om te achterhalen wat het compacte object in een röntgendubbelster is zonder een dynamische massa-bepaling uit te voeren: voor beide systemen was het eerdere vermoeden dat ze een neutronenster of zelfs een zwart gat bevatten. Onze observaties van CXOGBS J174444.7-260330 laten ook zien dat de rusttoestand niet zo stabiel is als vaak gedacht wordt. Sporadische episodes met hogere accretiesnelheden en kleine uitbarstingen kunnen ook voorkomen. Voor studies die gericht zijn op het vinden van neutronensterren en zwarte gaten is het belangrijk om hier rekening mee te houden, omdat het betekent dat systemen die een witte dwerg bevatten zich soms gedragen als systemen met een zwaarder compact object.

Röntgen- en radiowaarnemingen van de rusttoestand

Röntgendubbelsterren staan er om bekend dat ze een bron zijn van krachtige stromen (‘jets’) van ultra-relativistische deeltjes. Omdat deze deeltjes syn-
chrotronstraling uitzenden zijn de jets zichtbaar op radiogolflengtes. Uit observaties is gebleken dat er een verband is tussen de radio- en röntgenlichtkracht van deze bronnen, zowel bij hoge als bij lagere lichtkracht. Dit suggereert dat de jet (die radiolicht uitzendt) op de een of andere manier gekoppeld is aan de accretiestroom (die het röntgenlicht produceert). De natuurkunde achter deze correlatie kennen we nog niet, maar het bestuderen ervan kan inzicht verschaffen in de energiebalans van het accretieproces. De systemen met zwarte gaten waarvoor dit verband tussen radio- en röntgenemissie bestudeerd is kunnen in twee groepen worden verdeeld. De eerste groep bestaat uit de ‘standaard’ systemen (de eerste bronnen waarin de correlatie ontdekt is valen in deze groep) waarvoor geldt dat de radiolichtkracht schaalt met de röntgenlichtkracht als \( L_R \propto L_X^{0.6} \). De tweede groep, de zogenaamde ‘uitschieters’, bevat bronnen die een steiler verband laten zien. De helling van deze correlatie is vergelijkbaar met die van heldere neutronenstersystemen. De twee vormen van deze correlatie worden in verband gebracht met verschillende snelheden van het accretieproces. In Hoofdstuk 6 presenteren we XTE J1752-226, een röntgendubbelster met een zwart gat waar we gelijktijdige röntgen- en radiowaarnemingen van hebben. Deze zijn gedaan aan het eind van de uitbarsting van deze bron in 2009-2010, zodat we de röntgen-radiocorrelatie kunnen testen bij lagere lichtkracht. We vinden bewijs voor een verandering van de helling van de correlatie in deze bron, die lijkt te veranderen van een ‘uitschieter’ in een ‘standaard’ systeem als zijn lichtkracht afneemt. Zo’n overgang was maar één keer eerder gezien, in het zwarte gat H1743-322. Ons resultaat is belangrijk omdat het laat zien dat deze overgang van de ene naar de andere groep niet uniek is voor H1743-322. Het is mogelijk dat meer röntgendubbelsterren dit gedrag vertonen als hun lichtkracht omlaag gaat. In de waarnemingen van Chandra detecteerden we ook een variabele röntgenbron dichtbij XTE J1752-226, in dezelfde richting als ultra-relativistische jets die eerder zijn waargenomen in dit systeem. Een mogelijke verklaring is dat een eerder gelanceerde en uitgedoofde jet opnieuw energie heeft ontvangen en daarom röntgenlicht uitzendt. Dit is een interessante vondst, aangezien er maar weinig gevallen bekend zijn van röntgenlicht dat afkomstig is van jets (een paar voorbeelden zijn Sco X-1, Cir X-1 en XTE J1550-564). We hebben ook diepe optische waarnemingen gedaan, maar geen tegenhanger van XTE J1752-226 gevonden. De bron is dus te lichtzwak om een dynamische massabepaling uit te voeren.
References

Aleksandrovich, N. L., Aref’ev, V. A., Borozdin, K. N., Syunyaev, R. A.,
Software and Systems V, vol. 5, p. 17
Bagnulo, S., Jehin, E., Ledoux, C., Cabanac, R., Melo, C., Gilmozzi, R., ESO
Notes in Physics, Springer Verlag, Berlin, p. 53
391, L108
Brandt, S., Budtz-Jørgensen, C., Chenevez, J., 2006, The Astronomer’s Tele-
gram, 778, 1
Brandt, S., Budtz-Jørgensen, C., Gotz, D., Hurley, K., Frontera, F., 2007,
The Astronomer’s Telegram, 1054, 1
Brocksopp, C., Corbel, S., Tzioumis, T., Fender, R., 2009, The Astronomer’s
Telegram, 2278, 1
Brocksopp, C., Yang, J., Corbel, S., Tzioumis, T., Fender, R., 2010, The
Astronomer’s Telegram, 2438, 1
Corral-Santana, J. M., Casares, J., Rodríguez-Gil, P., 2010a, The Astronomer’s Telegram, 2804, 1
Corral-Santana, J. M., Rodríguez-Gil, P., Guerra, J. C., Casares, J., 2010b, The Astronomer’s Telegram, 2818, 1
Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., Hessels, J. W. T., 2010, Nat, 467, 1081
Homan, J., 2010, The Astronomer’s Telegram, 2387, 1
Horne, K., 1986a, PASP, 98, 609
Horne, K., 1986b, PASP, 98, 609
Jonker, P. G., Galloway, D. K., McClintock, J. E., Buxton, M., Garcia, M.,
Kaaret, P., Corbel, S., Tomsick, J. A., Fender, R., Miller, J. M., Orosz, J. A.,
Kahabka, P., 2006, Advances in Space Research, 38, 2836
125
Kennea, J. A., Pagani, C., Markwardt, C., Blustin, A., Cummings, J., Nousek,
J., Gehrels, N., 2005, The Astronomer’s Telegram, 599, 1
439, 317
Körding, E., Rupen, M., Knigge, C., Fender, R., Dhawan, V., Templeton, M.,
Muxlow, T., 2008, Science, 320, 1318
Kuiper, L., Jonker, P. G., Torres, M. A. P., Rest, A., Keek, S., 2008, The
Astronomer’s Telegram, 1774, 1
J. van Paradijs, & E. P. J. van den Heuvel, ed., X-ray binaries, p. 175 - 232,
p. 175
Li, J., Kastner, J. H., Prigozhin, G. Y., Schulz, N. S., Feigelson, E. D., Getman,
Linnell, A. P., Szkody, P., Gänsicke, B., Long, K. S., Sion, E. M., Hoard,
Lutovinov, A., Walter, R., Belanger, G., Lund, N., Grebenev, S., Winkler, C.,
2003, The Astronomer’s Telegram, 155, 1
Markwardt, C. B., et al., 2009b, The Astronomer’s Telegram, 2258, 1

Moore, C. E., 1972, A multiplet table of astrophysical interest - Pt.1: Table of multiplets - Pt.2: Finding list of all lines in the table of multiplets


Nakahira, S., et al., 2010, PASJ, 62, L27+


Negueruela, I., Smith, D. M., Chaty, S., 2005, The Astronomer’s Telegram, 470, 1


O’Connell, D. J. K., 1951, Publications of the Riverview College Observatory, 2, 85


Özel, F., 2006, Nat, 441, 1115

Parmar, A. N., White, N. E., Giommi, P., Haberl, F., 1985, IAU Circ, 4039


Perley, R., et al., 2009, IEEE Proceedings, 97, 1448
References

Remillard, R. A., 1999, Memorie della Societa Astronomica Italiana, 70, 881
Revnivtsev, M. G., et al., 2004, Astronomy Letters, 30, 382
Smak, J., 1971, Acta Astronomica, 21, 15
p. 143
Torres, M. A. P., Steeghs, D., Jonker, P. G., Thompson, I., Soderberg, A. M., 2009b, The Astronomer’s Telegram, 2268, 1
Walter, R., et al., 2004, The Astronomer’s Telegram, 229, 1
Watson, M. G., et al., 2008, VizieR Online Data Catalog, 349, 30339


Williams, R. E., 1989, AJ, 97, 1752


Wilson, R. E., 1953, Carnegie Institute Washington D.C. Publication, 0


Zacharias, N., et al., 2010, AJ, 139, 2184


Zolotukhin, I., 2009, The Astronomer’s Telegram, 2032, 1
Publications

Refereed publications - First author


Other refereed publications


Astronomer’s telegrams

Ratti, E.; Steeghs, D.; Jonker, P. G. Optical observations of the field containing SGR 0418+5729 ATel #2169 (08/2009)

Miller-Jones, J. C. A.; Madej, O. K.; Jonker, P. G.; Homan, J.; Ratti, E. M.; Torres, M. A. P. X-ray and radio observations of the re-brightening event in MAXI J1659-152, ATel #3358 (05/2011)

Press release

‘How black holes change gear’, released by SRON and Royal Astronomical Society
Acknowledgments
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[Quando la prima creatura vivente e’ comparsa, io ero li’, in attesa. Quando l’ultima creatura vivente morira’, il mio lavoro sara’ finito. Metterò le sedie sui tavoli, spegnerò le luci e chiuderò a chiave l’universo dietro di me prima di andarmene]

(Death in ‘The Sandman’, N. Gaiman)