Different manifestations of accretion onto compact objects

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Introduction

In this thesis I discuss phenomena that occur in systems that are referred to as low-mass X-ray binaries. These systems emit radiation over a large range of wavelengths but here I focus only on the X-ray emission. In this chapter, I briefly explain what these systems are, I introduce some of the main phenomena that arise in them and I discuss the methods by which these systems are studied.

1.1 Low-Mass X-ray binaries

Most of the stars in our universe occur in binary systems, i.e., systems of two stars in orbit around a common center of mass. If one of the members of these systems is a compact object (neutron star or black hole), and the system components are sufficiently close to exchange matter causing them to become very bright in X-rays, then they are called X-ray binaries. Compact objects are formed by supernova explosions; I note, however, that it has also been suggested that neutron stars can be formed from the accretion-induced collapse of a white dwarf (Whelan & Iben 1973), and that black holes might be the result of the merger of two neutron stars (King 2006), events whose signature in terms of supernova phenomenology is uncertain.

X-ray binaries can be divided into high-mass X-ray binaries (HMXBs) and low-mass X-ray binaries (LMXBs) depending on the mass of the companion star. The companion to the X-ray source in HMXBs is a luminous star of spectral type O or B with mass typically larger than 10 M$_\odot$, necessarily be-
longing to a young stellar population as these types of stars do not live longer than about $\sim 10^7$ years. In LMXBs the companion is a faint star of mass lower than 1 $M_\odot$ and tends to belong to a much older stellar population, with ages that can be hundreds of millions of years.

In this thesis, I concentrate on the study of the LMXBs (see Figure 1.1 for an artist’s impression) in which mass transfer from the companion star to the compact object is due to Roche-lobe overflow, i.e., material from the companion star that passes beyond the so called Roche-lobe radius flows onto the compact object. Since the Roche-lobe radius is a function only of the orbital separation and the masses of the two stars, the onset of Roche-lobe overflow requires that either the envelope of the companion star expands (due to stellar evolution), or that the binary separation shrinks (as a result of orbital angular momentum losses). In any case, due to conservation of angular momentum the gas cannot fall directly onto the compact object and so it spirals in, forming a rotating disk around the compact object. This process is called accretion and the disk is known as an accretion disk.

The most powerful phenomena we observe from LMXBs are directly related to these accretion disks, as a large amount of gravitational energy is released when the matter approaches the compact object. This causes the inner accretion disk to reach temperatures as high as $10^7$ Kelvin and therefore to emit in (thermal) X-rays. So, the analysis of the X-ray emission from these sources is a fundamental tool we have to study the properties of compact objects and accretion disks. These sources become therefore, very good natural laboratories in which to test theories of gravity in extreme conditions (e.g. general relativity), and where to study physics of ultra-dense matter, in particular the equation of state (i.e., the mathematical description of the relations between temperature, pressure and density of matter) of neutron stars, where densities are thought to be higher than those in atomic nuclei.

1.2 Instrumentation and techniques

In this thesis I study low-mass X-ray binary systems by means of energy spectra and time variability analysis. The combination of these two methods has proven to be very useful in describing the X-ray behavior of LMXBs. Below, I briefly describe the instruments and techniques used.

1.2.1 The Rossi X-ray Timing Explorer

All the results presented in this thesis are based on data obtained with the Rossi X-ray Timing Explorer (RXTE, Bradt et al. 1993). It was launched
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Figure 1.1: Artist’s impression of a low-mass X-ray binary. The image was produced with the program BinSim (v0.8.1) developed by Rob Hynes.

on December 30th, 1995 and, at the time this thesis goes to press, is still operating. Figure 1.2 shows a schematic view of the satellite.

There are three scientific instruments on board the satellite, namely the All Sky Monitor (ASM; Levine et al. 1996), the High Energy X-ray Timing Experiment (HEXTE; Gruber et al. 1996; Rothschild et al. 1998) and the Proportional Counter Array (PCA; Zhang et al. 1993; Jahoda et al. 2006).

The ASM observes ∼80% of the sky each orbit with a spatial resolution of 3′ × 15′, it operates in the 1.5–12 keV range and has a time resolution of 1/8 seconds. The ASM plays an important role in identifying state transitions and outbursts from transient sources, allowing us to trigger follow-up observations with other instruments within a few hours. The instrument also permits us to monitor the long-term intensity and behavior of the brightest X-ray sources (see, e.g., Chapters 4 & 8 and Figure 1.6 in this Chapter).

The HEXTE has a field of view of ∼1° and operates in the 15–200 keV range. It consists of two photon counter detectors, each having an area of ∼800 cm², an energy resolution of 18% at 60 keV, and a time resolution of 10 μs. Due to the large field of view and the lack of spatial resolution, background estimation can be an issue. This problem is solved by making both clusters oscillate (“rock”) between on and off source positions (1.5° or 3° from the
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XTE Spacecraft

![Diagram of the XTE spacecraft, with instruments labeled.](image)

Figure 1.2: Diagram of the XTE spacecraft, with instruments labeled.

source), every 16 or 32 seconds. The data from this instrument have been used in this thesis mainly to better estimate the X-ray luminosity of sources.

The PCA is the main instrument on board RXTE. It is a pointed instrument, co-aligned with the HEXTE and having the same collimated field of view of $\sim 1^\circ$. It consists of five Proportional Counter Units (PCUs) with a total collecting area of $\sim 6250 \text{ cm}^2$, operates in the 2–60 keV range, has a nominal energy resolution of 18% at 6 keV and, most importantly for this thesis, a maximum time resolution of $\sim 1\mu$s. With the exception of regions near the center of the Galaxy, the source density on the sky is low enough to provide sufficient positional resolution and avoid source confusion.
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Figure 1.3: Typical power spectrum of a pulsar light curve. The high power represents the pulsar spin frequency ($\nu_s \sim 442$ Hz, in SAX J1748–2021, Chapters 4).

1.2.2 Timing analysis

The main tool I use for studying the timing properties of an X-ray source is the Fourier power spectrum of the count rate time series, in which data are transformed from the time to the frequency domain. This technique is particularly needed when the counting noise dominates the time series and it is only possible to study the averaged properties of the timing phenomena. It is not the aim of this introduction to give an extensive overview of how Fourier techniques are used in X-ray variability studies. For that, I refer to the “bible” by van der Klis (1989). Below, I briefly describe the main procedures.

For the Fourier timing analysis I use data from the PCA (recorded in Event, Good Xenon and/or Single Bit modes, Jahoda et al. 2006). Data are split up into blocks of equal time length and for each block the Fourier power spectrum is calculated. These power spectra are then averaged (generally per observation – I refer to Appendix I in Chapter 6 for a discussion on this). The frequency resolution is equal to the inverse of the time duration of each block. The maximum frequency in the resulting power spectrum is called the Nyquist frequency and is half the inverse of the time resolution of the data (generally, the time resolution I have used is $125 \mu s$, which allows the study of variability up to 4096 Hz).

Highly coherent signals, like pulsations, appear as a single frequency-bin spikes while aperiodic structures are spread over more frequency elements. Broad structures are usually called ‘noise’, while narrow–peaked features are called ‘quasi-periodic oscillations’ (QPOs). In Figure 1.3 I show an example of a power spectrum in which a clear spike appears at the spin period of the accreting millisecond pulsar SAX J1748–2021 (the spin frequency of this
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pulsar is $\nu_s \sim 442$ Hz, see Section 1.5.3 for a brief introduction to millisecond pulsars). In Figure 1.4 I show a typical power spectrum where noise (labeled with VLFN, $L_{\text{b2}}$, $L_{\text{b}}$, $L_{\text{hHz}}$) and QPOs ($L_{\ell}$ and $L_{u}$) are present.

Figure 1.4: Typical averaged power spectrum where noise (VLFN, $L_{\text{b2}}$, $L_{\text{b}}$, $L_{\text{hHz}}$) and QPOs ($L_{\ell}$ and $L_{u}$) are present (this is a representative power spectrum from the Atoll source 4U 1636–53, see Chapter 6).

As can be seen in Figure 1.4, the power spectrum consists of a superposition of different components. Unfortunately, there is no physical model that describes all these components consistently, as the real processes behind the X-ray variability are still poorly understood. In order to have a unified phenomenological description of these timing features within a source and among different sources and source types, I fit noise and QPOs with a function consisting of one or multiple Lorentzians, each denoted as $L_i$, where $i$ determines the type of component. The characteristic frequency ($\nu_{\text{max}}$) of $L_i$ is denoted $\nu_i$. $\nu_{\text{max}}$ is the frequency where the component contributes most of its variance per logarithmic frequency interval and is defined as $\nu_{\text{max}} = \sqrt{\nu_0^2 + (\text{FWHM}/2)^2} = \nu_0\sqrt{1+1/4Q^2}$ (Belloni et al. 2002b). For the quality factor $Q$, I use the standard definition $Q = \nu_0/\text{FWHM}$. FWHM is the full width at half maximum and $\nu_0$ the centroid frequency of the Lorentzian.

I note that a Lorentzian is the Fourier power spectrum of an exponentially damped sinusoid, and although the multi-Lorentzian model usually gives good fits (but see Chapter 8 for exceptions), the original signal can still be different from a damped oscillation. Our choice of this over other models (such as a combination of power law and Gaussian functions) is motivated by the fact that the multi-Lorentzian model gives the possibility to identify and fol-
low the characteristics of power spectral components as they evolve in time and as a function of spectral state using only one type of function (i.e., a Lorentzian). This also allows us to compare the characteristics of different components. I particularly refer the reader to Chapter 8 for an example. The combination of the multi-Lorentzian model with excellent sampling of the 2 brightest outbursts of the black hole XTE J1550–564, allowed us to follow the characteristics of QPOs and noise components in novel ways.

**Other techniques used**

In a few cases in my thesis I use other techniques, in addition to Fourier ones, in particular Lomb-Scargle periodograms (Lomb 1976; Scargle 1982; Press et al. 1992) as well as the phase dispersion minimization technique (PDM - see Stellingwerf 1978). The Lomb-Scargle technique is ideally suited to look for sinusoidal signals in unevenly sampled data. The phase dispersion minimization technique is well suited to the case of non-sinusoidal time variation covered by irregularly spaced observations.

**1.2.3 Spectral analysis: Colors**

In the best case scenario the X-ray energy spectrum of a given source can be described by the combination of one or more physically motivated mathematical functions, or models. However, the physical reality of these models is still uncertain and in many cases the data can be satisfactorily described by different models, making the results of such spectral analysis inconclusive. In this thesis I use another method, the so called color analysis, which makes use of color-color diagrams and hardness–intensity diagrams. This method is more sensitive to subtle changes in the X-ray spectra as it does not need to assume a certain model.

To calculate the colors, the X-ray spectrum is divided into energy bands. A color is defined as the ratio of count rates in two different energy bands. Different bands are typically chosen for neutron stars and black holes, which have different spectral variability characteristics.

To calculate X-ray colors, in this thesis I always use the 16-s time-resolution Standard 2 mode data of RXTE (see Section 1.2.1). For neutron stars I define soft and hard color as the 3.5–6.0 keV / 2.0–3.5 keV and 9.7–16.0 keV / 6.0–9.7 keV count rate ratio, respectively, and the intensity as the 2.0–16.0 keV count rate. For black hole systems, soft and hard color are the 6.0–16.0 / 2.0–6.0 keV and 16.0–20.0 / 2.0–6.0 keV count rate ratio, respectively and the intensity is the count rate in the 2.0–20 keV band. To correct for the gain changes (i.e., changes in the high voltage setting of the PCUs, Jahoda et al. 2006) as well as
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the differences in effective area between the PCUs themselves, we normalize our colors by the corresponding Crab Nebula color values that are closest in time but in the same RXTE gain epoch (see Kuulkers et al. 1994; van Straaten et al. 2003, see table 2 in Chapter 6 for average colors of the Crab Nebula per PCU). By applying this normalization, I assume that the spectrum of the Crab is constant, and that the energy spectrum from the source studied is similar to that of the Crab. In Figure 1.5 I show examples of a color–color and a hardness–intensity diagram for the atoll source 4U 1608–52.

Figure 1.5: Color–color (left) and hardness–intensity (right) diagrams for the transient atoll source 4U 1608–52. Grey points represent the 16 seconds average color and black points the average color per observation (where an observation covers 1 to 5 consecutive satellite orbits. Usually, an orbit contains between 1 and 5 ksec of useful data separated by 1–4 ksec data gaps). Colors and intensities are normalized to the Crab Nebula.

1.3 Long term X-ray variability of LMXBs

In the context of X-ray variability at time scales of hours, days and up to years, low-mass X-ray binaries can be divided into two main classes: the so called persistent and transient sources. The persistent ones are those which have been “on” since the beginnings of X-ray astronomy while transient sources are those which are generally “off” (in what is called quiescent state) but occasionally show outbursts during which the count rate can increase by several orders of magnitude.

In Figure 1.6 I show the long-term variability of the persistent sources Serpens X-1 and 4U 1820–30 (top and middle panel, respectively) and of the transient source Aql X-1 (bottom panel). As can be seen, a persistent source can show almost no variability (Serpens X-1) or alternatively strong variabil-
1.3 Long term X-ray variability of LMXBs

ity (4U 1820–30) in their X-ray count rate, or something in between (see, e.g., Figure 7.2 in Chapter 7).

![Figure 1.6](image)

**Figure 1.6**: The long-term variability of three LMXBs as observed with the All Sky Monitor on board RXTE. Each point represents the 1–day average measurement of the count rate. The top panel shows a persistent source which has a roughly constant count rate (Serpens X-1), the middle panel shows a persistent source with a $\sim 170$ days quasi-periodic variability (4U 1820–30) and the bottom panel shows a transient source (Aql X-1).
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In the case of transient sources, outburst are usually unpredictable, except in a few sources, in which it is possible to predict the beginning of the outbursts within a few tens of days. Not all outbursts from the same source reach the same intensity or last for the same amount of time.

1.4 Black hole states

The X-ray spectral properties of black holes can be classified into two main components: when a hard, non-thermal, power-law component with photon index in the range 1.5–2 dominates the energy spectrum, it is said that the source is in its low/hard state (or just low state – LS); when a soft, thermal, black-body like component with temperature \( kT \lesssim 1 \text{ keV} \) dominates, then the source is in its high/soft state (or just high state – HS). In between the low and the high states, there is the intermediate state which links both extremes and where complex behavior, including sometimes large flares in intensity, occur. This intermediate state can be usefully subdivided into the Soft Intermediate State (SIMS) and the Hard Intermediate state (HIMS) based mainly on the X-ray time variability (see, e.g., a discussion in Belloni et al. 2005). On the left panel of Figure 1.7 I schematically show the roughly square pattern in the hardness–intensity diagram that typical black hole candidates tend to trace out during an outburst. The solid line shows the track the source follows during outburst. For an example of an outburst that shows all these states I refer to the work of Belloni et al. 2005 (see also Figure 8.1 in Chapter 8).

In both LS and HIMS, the power spectrum is dominated by a strong broad band noise (up to 60% fractional rms) and sometimes QPOs. The SIMS shows power spectra without the broad band noise component that are dominated by a weak power law, on top of which several QPOs are present. The HS power spectra are similar to those of the SIMS, although the variability might be weaker and generally no QPOs are present. In all these cases, the broad and peaked features are found at low characteristic frequency (< 100 Hz), however, sometimes weak high frequency QPOs (100–450 Hz) are also found in the HIMS and SIMS. On the right panel of Figure 1.7, I plot representative power spectra for the high state, soft and hard intermediate states and low state.

Of course, the behavior of black hole sources in the hardness–intensity diagram is not always as smooth and as clear as that shown in the left panel of Figure 1.7, nor are the power spectral components as clear as those shown in the right panel. For a general description of how the power spectral components vary as a function of source state I refer to the recent reviews by Homan & Belloni (2005) and van der Klis (2006). In Chapter 8 I study the black hole
1.5 Neutron star phenomenology

1.5.1 States and power spectra

Hasinger & van der Klis (1989) classified the neutron star LMXBs based on the correlated variations of the X-ray spectral and rapid X-ray variability properties. They distinguished two sub-types of LMXBs, the Z sources and the atoll sources, whose names were inspired by the shapes of the tracks that they trace out in an X-ray color-color diagram on time scales of hours to days. The Z sources are the most luminous (above $10^{38}$ erg s$^{-1}$); the atoll sources cover a much wider range in luminosities. For each type of source, several spectral/timing states are identified, which are thought to arise from qualitatively different inner flow configurations (e.g. presence or absence of a corona, structure of accretion disk, jets).

In this thesis I study only atoll sources. The main three states are the extreme island state (EIS), the island state (IS) and the banana branch, the latter subdivided into lower-left banana (LLB), lower banana (LB) and upper banana (UB) states (see Figure 1.8). The hardest and lowest luminosity ($L_x$) state is generally the EIS, which shows strong low-frequency noise. The IS is spectrally softer than the EIS and its power spectrum is characterized by broad features and a dominant band-limited noise (BLN) component which becomes stronger and lower in characteristic frequency as the flux decreases and the spectrum gets harder at $> 6$ keV. In order of increasing $L_x$, I encounter the LLB, where the so called “twin kHz QPOs” are first observed, the LB, where dominant band limited noise at 10 Hz occurs and finally, the UB, where the (power law) very low frequency noise (VLFN) dominates at $< 1$ Hz. In the banana states, some of the broad features observed in the EIS and the IS become narrower (peaked) and occur at higher frequency. The twin kHz QPOs can be found in LLB (at frequencies in excess of 1000 Hz), only one is seen in the LB, and no kHz QPOs are detected in the UB. In Figure 1.8 I show a schematic color color diagram and representative power spectra for the EIS, IS, LLB and the UB states.
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Figure 1.7: Left: Schematic hardness–intensity diagram for a typical black hole source outburst. The solid line shows the track the source follows during outburst (courtesy of M. Klein-Wolt). Right: Representative power spectra for black hole states (see also Chapter 8). The main states are the high state (HS), soft intermediate state (SIMS), hard intermediate state (HIMS) and the low state (LS).
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Figure 1.8: Left: Schematic color–color diagram for a typical atoll source. The solid line shows the track the source follows from state to state, and the dashed line indicates the direction in which the X-ray luminosity increases (courtesy of M. Klein-Wolt). The main states are the extreme island state (EIS), the island state (IS) and the banana branch, the latter subdivided into lower-left banana (LLB), lower banana (LB) and upper banana (UB) states. Right: Representative power spectra for the EIS, IS, LLB and the UB states.
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1.5.2 Thermonuclear burning on the neutron star surface

Unstable burning

Observationally, thermonuclear X-ray bursts (also called Type-I X-ray bursts) manifest as a sudden, unpredictable and rapid (1 to 10 seconds) increase in the X-ray intensity of accreting neutron stars. The rise is generally followed by a smooth and approximately exponential decay which lasts from a few seconds to several minutes. As matter accumulates on the surface of the neutron star, it is compressed and heated until the temperature and density at the base of the accreted layer become large enough that the fuel ignites in a “burning spot”, and the matter burns unstably consuming the available fuel as the burning spot spreads rapidly over all the neutron star surface in matter of seconds. Time-resolved spectral analysis of this type of bursts shows that the rise and the exponential decay can be interpreted as heating resulting from the initial fuel ignition, followed by cooling of the ashes once the available fuel is exhausted.

Although X-ray bursts were known since the 1970s, it was not until the RXTE era that highly coherent (burst) oscillations associated with thermonuclear bursts were discovered (see Figure 1.9 for a typical burst with burst oscillations). These oscillations have frequencies between 45 and 620 Hz, fractional rms amplitudes between 5 and 20% and have been detected in bursts from 14 sources so far (Strohmayer & Bildsten 2006; Galloway et al. 2006). As the burst evolves, the frequency of these oscillations generally increases by a few Hz as it reaches an asymptotic value, which has been found to be stable (within ~ 1 Hz) for a given source. This asymptotic frequency is an excellent estimate of the spin frequency (within ~ 1 Hz) for a given source as has been confirmed by the detection of burst oscillations at the spin frequency in the accreting millisecond pulsars SAX J1808.4–3658 and XTE J1814–338 (Chakrabarty et al. 2003; Strohmayer & Bildsten 2003).

Marginally stable burning?

Revnivtsev et al. (2001) discovered a new class of quasi-periodic oscillation in the persistent emission (i.e. not during Type-I bursts) from three neutron star X-ray binary sources. These new QPOs have frequencies in the milli-Hertz range, are usually seen before a Type-I X-ray burst but not immediately after, and their properties differ from those of the other QPOs found in neutron star systems (e.g., energy dependence, see also van der Klis 2006). Although Revnivtsev et al. (2001) could not discard an interpretation related to disk instabilities, they conclude that the mHz QPO is likely due to a special mode of nuclear burning on the neutron-star surface. This interpretation is strength-
Figure 1.9: X-ray burst lightcurve (histogram) and dynamical power spectrum illustrating the typical frequency evolution of a burst oscillation (contours). The left axis marks the frequency of the oscillations and the right one the PCA count rate. This figure is courtesy of D. Galloway (see also Galloway et al. 2006).

ened by the results of Yu & van der Klis (2002), which suggest that the inner edge of the accretion disk slightly moves outward as the luminosity increases during each mHz cycle due to stresses generated by radiation coming from the neutron star surface. Based on numerical simulations, Heger et al. (2007) show that the mHz QPOs might be explained as the consequence of marginally stable nuclear burning on the neutron star surface. These authors find that the burning is oscillatory only close to the boundary between stable burning and unstable burning (i.e., Type-I X-ray bursts).

In Figure 1.10 I show a representative light curve where mHz oscillations are present before the occurrence of an X-ray burst and not after. These oscillations when present, can be seen directly in the light curve.

Confirming that these oscillations are related with a special mode of nuclear burning on the neutron–star surface is of great interest, as it would be the first time (except for the highly coherent pulsations in accreting millisecond pulsars) that a feature of the persistent X-ray variability has been identified.
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Figure 1.10: Light curve of a data segment in which the mHz QPOs are present prior to the occurrence of an X-ray burst. Before the X-ray burst occurs, the oscillations are clear from the light curve while after the burst they seem to disappear. Fourier analysis confirms this.

to originate from the neutron star surface rather than the accretion disk. To further investigate this, I am analyzing RXTE archival data of more than 40 neutron star binary systems to look for similar signals. In the cases in which mHz QPOs are present, I am studying their interactions with X-ray bursts. In Chapter 2 I present the first results, in which I show that the mHz QPO frequency constitutes the first identified observable that can be used to predict the occurrence of X-ray bursts. This result confirms that the mHz QPO phenomenon is intimately related with the processes that lead to a thermonuclear burst.

1.5.3 Millisecond pulsars

Radio pulsars are highly magnetized ($\gtrsim 10^8$ Gauss) rotating neutron stars which emit a collimated beam of radio waves. The youngest radio pulsars are observed to rotate rapidly, up to 100 times per second. This rapid rotation combined with the high magnetic field strength ($10^{12}-13$ Gauss) of the neutron star produces beamed radio emission at the magnetic poles, and since the magnetic poles “are fixed” on the neutron star, the beams spin at the frequency of the neutron star ($\nu_s$). After a radio pulsar is born it slows down as it loses energy until $\nu_s$ is so low (lower than a few tenths of Hz) that the pulsar mechanism is not able to produce detectable radio emission anymore and it is said that the pulsar has died. This process takes millions of years, depending on the initial spin frequency and magnetic field strength of the neutron star.

If it is true that new pulsars have frequencies not higher than $\sim 100$ Hz, and that their spin frequency decreases with time, then how is it possible that
there are radio pulsars with much higher spin frequencies than 100 Hz, the fastest now being 716 Hz? (Hessels et al. 2006). In the early 1980s, Alpar et al. (1982) and Backer et al. (1982) explained these fast pulsars as follows: if a radio pulsar is born in a binary system which does not get disrupted by the supernova explosion in which the neutron star is formed, it is possible that the companion star or the binary orbit evolves in such a way that at a certain moment the companion star fills its Roche lobe. When this happens, matter is exchanged from the companion to the neutron star, spinning it up by the transfer of angular momentum. When accretion stops the system is left with neutron star that rotates at several 100 Hz and appears again as a radio pulsar. This neutron star has a weak magnetic field (~ 10^8 Gauss, in contrast to the 10^{12−13} Gauss in the young pulsars). It is thought that the accretion is responsible for reducing the magnetic field strength, however, the process for this is as yet uncertain (Bhattacharya & van den Heuvel 1991).

If the neutron stars in X-ray binaries are rapidly rotating as predicted by Alpar et al. (1982), we could, in principle, see pulsations in X-rays as well. The first observational indication that neutron stars in low-mass X-ray binaries rotate rapidly came in 1996 with the discovery of millisecond oscillations (with frequencies that usually show drifts) during thermonuclear X-ray bursts (see Section 1.5.2), but it was not until 1998 that the first accreting millisecond X-ray pulsar was discovered (Wijnands & van der Klis 1998a). Since then a total of 9 (and even 10 if we consider Aql X-1 as an accreting millisecond pulsar – see discussion in Chapter 3) have been found out of a sample of more than 150 neutron star LMXBs known up to date. These systems are known as Accreting Millisecond X-ray pulsars (AMXPs, also referred to as AMPs in the literature) and are thought to be accretion-powered; gas coming from the accretion disk couples to the star’s magnetic field and gets channeled, forming “hot spots” perhaps at the magnetic poles, which can be seen in X-rays. These hot spots are fixed on the neutron star surface and therefore rotate with the spin frequency of the neutron star.

An important and not yet resolved issue is why most neutron star LMXBs do not show persistent pulsations in their X-ray emission. Several theoretical efforts have been made to explain this, the main question remaining whether the pulsation is hidden from the observer (e.g. there is a scattering medium that washes out the coherent beamed pulsations) or not produced at all (e.g., because the magnetic field is too weak to channel the accreting matter). So, given that pulsations were only seen from a few sources, in the literature (up to now) the neutron star systems were sub-classified into pulsating and non-pulsating ones. The recent discovery of HETE J1900.1–2455 showed that this classification might not cover all systems. This was the first AMXP which did
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not show persistent pulsations throughout the outburst, but only during the first $\sim 2$ months. Sudden increases in the amplitude of the pulsations were apparently triggered by thermonuclear X-ray bursts; the amplitude decreased steadily on timescales of days after the bursts (Galloway et al. 2007). This source was also different from the other AMXPs, as it has been in outburst for more than 2.5 years\(^1\), while typical AMXP outbursts last for no more than a few weeks or months. This difference suggested that the accumulation of matter on the surface was burying the magnetic field (Galloway et al. 2007) and therefore extinguishing the pulsations. If the accumulation of matter is the key process that buries the magnetic field, then this result could explain why most of neutron star LMXBs do not show pulsations.

We are searching the full RXTE public archive data for coherent pulsations. In Chapters 3 & 4 I report on the discovery of episodes of intermittent coherent millisecond X-ray pulsations in two X-ray transients. These pulsations appear and disappear on timescales of hundreds of seconds and can be identified as occurring at the spin frequency of the respective sources. These short time scales cannot be explained by the burying scenario proposed for the intermittent AMXP HETE J1900.1–2455. Another important conclusion of our discoveries is that irrespective of the physical mechanisms behind the pulsations, it is now clear that a strict division between pulsating and non-pulsating neutron star sources cannot be made. It is possible that all sources pulsate occasionally, although the recurrence times could be very long.

\(^{1}\)At the time of submitting the thesis to the printer, the source was still active.
1.6 Outline

In this thesis I present a study of different manifestations of accretion onto compact objects, studying periodic as well as aperiodic variability.

In Chapter 2 I report on the discovery of systematic frequency drifts in the frequency of the Millihertz QPOs. They constitute the first identified observable that can be used to predict the occurrence of X-ray bursts. Furthermore, our observational results confirm that the mHz QPO phenomenon is intimately related with the processes that lead to a thermonuclear bursts.

In Chapters 3 and 4 I report on the discovery of episodes of intermittent coherent millisecond X-ray pulsations at the spin frequency of the X-ray transients SAX J1748–2021 and Aql X-1. These findings provide new input for models: irrespective of the physical mechanisms behind the pulsations, it is now clear that there is not a strict division between pulsating and non-pulsating neutron star sources as it was thought before; it is possible that all sources pulsate occasionally although the recurrence times could be very long.

In Chapter 5 I report on the low-luminosity island state of the ultra-compact atoll source 4U 1820–30. I compare the frequencies of the variability components found in the power spectra with those in other atoll sources. These frequencies were previously found to follow a universal scheme of correlations; these correlations are frequency-shifted in the case of the variability measured in some accreting millisecond pulsars. Our results show that 4U 1820–30 is the first atoll source which shows no significant pulsations but has a significant shift in the frequency correlations compared with 3 other non-pulsating atoll sources.

In Chapter 6 I report on the time variability of the atoll source 4U 1636–53 in the banana state and, for the first time with RXTE, in the island state. I find that the so called “hectohertz QPO” shows a behavior different from that of other spectral components, indicating that the mechanism that sets its frequency differs from that for the other components, while the amplitude setting mechanism is common. I also show that a previously proposed interpretation of the narrow low-frequency QPO frequencies in different sources (in terms of harmonic mode switching) is not supported by our data, nor by some previous data on other sources and more importantly, that the frequency range that this QPO covers is found not to be related to source spin, angular momentum or luminosity.
1. Introduction

In Chapter 7 I report on the X-ray source 1E 1724–3045 in the globular cluster Terzan 1. I study the flux transitions observed between February 2004 and October 2005 and conclude that they are due to changes in the accretion rate. I confirm the atoll nature of the source and report on the discovery of kHz QPOs.

Finally, in Chapter 8 I report on all 5 outbursts observed with RXTE from the black hole candidate XTE J1550–564. I investigate how the frequency, coherence and strength of each power spectral component evolve in time and as a function of spectral state and find that it is generally possible to follow the time evolution of the different power spectral components as they shift in frequency and vary in strength and coherence. Using this information I identify the different components and find frequency–frequency relations within the data of this source. I compare these relations with similar ones that I have used in Chapters 6 & 7.