Accretion states and thermonuclear bursts in neutron star X-ray binaries
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Citation for published version (APA):

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Accretion states of neutron stars: luminosity, variability and spectra of atoll sources.

Manuel Linares and Michiel van der Klis


Abstract

The X-ray spectrum of neutron stars that accrete from low-mass companions varies on a wide range of timescales. We study in this work the most numerous class of neutron star low-mass X-ray binaries, the so-called atoll sources. Using more than a decade of *Rossi X-ray Timing Explorer* data, we perform a systematic study of the luminosity, timing and spectral properties of nine atoll sources across different source states. We include the hard X-ray emission in our spectral fits in order to obtain broadband luminosities. We measure the cutoff of the flat-topped variability spectrum over more than two decades in frequency, as well as the frequencies of the kilohertz quasi-periodic oscillations. We show that soft states can have luminosities as low as 1% of the Eddington luminosity, while the luminosity of hard states can be as high as 15% Eddington. State transitions, which feature large changes in variability frequencies, occur at fairly constant luminosities within each of the studied sources. Nevertheless, the state transition luminosity can be different in a given source at different epochs, and differs by more than one order of magnitude among different systems. The transient systems within our sample can mimic the canonical behavior of black hole transients during an outburst. However, we show that contrary to black holes they can transit from the hard to the soft state at luminosities lower than those of the soft to hard transition.
5. Accretion states of atoll sources

By comparing the spectral and timing properties in each source we find an anticorrelation between the hardness of the X-ray spectrum and the variability frequencies. Furthermore, we show that for constant variability frequency, luminosity and hardness are positively correlated across different sources. This luminosity-hardness correlation is clearly at odds with the common perception that harder sources are less luminous, and holds for luminosities between 0.5% and 30% Eddington. We put these new results in the context of models of accretion flows around compact objects, and propose an explanation for the luminosity-frequency decoupling and the luminosity-hardness correlation that involves changes in the inner disk temperature.

5.1 Introduction

Low-mass X-ray binaries (LMXBs), the most numerous class of bright X-ray sources, are powered by accretion from a low-mass donor star onto a neutron star (NS) or a black hole (BH). Mass is transferred through Roche lobe overflow and forms an accretion disk (Pringle & Rees 1972; Shakura & Syunyaev 1973) that often extends down to deep in the gravitational potential well, a few Schwarzschild radii from the center. Other forms of accretion flow are known to exist in LMXBs, and are essential to interpret those observations that show only traces of the predicted thermal emission from the accretion disk. Their structure and radiative properties are still a matter of debate (Narayan 1996; Blandford & Begelman 1999; Falcke et al. 2004) yet it is generally agreed that Compton up-scattering of thermal photons contributes considerably to the emerging spectrum.

Twenty years ago Hasinger & van der Klis (1989) found two classes of NS LMXBs when studying the correlation between their X-ray spectra and variability: “Z” and “atoll” sources. Named after the shapes they trace out in color-color diagrams (Sec. 5.2), these two classes differ in their luminosity; near the Eddington limit \(^1\) (at luminosity \(L_{\text{Edd}}\)) in Z sources and below \(\sim 50 \% \ L_{\text{Edd}}\) in atolls. Moreover, atoll sources can show harder X-ray spectra, which usually change on longer timescales than in Z sources. Three exceptional systems have exhibited both Z and atoll source behavior (Cir X-1, Oosterbroek et al. 1995; XTE J1806–246, Wijnands & van der Klis 1999b and most recently XTE J1701–462, Homan et al. 2007) suggesting that mass accretion rate, \(\dot{M}\),

\(^1\)The Eddington luminosity depends among other parameters on the composition of the accreting matter (Lewin et al. 1993). For a 1.4\(M_\odot\) NS, at a gravitational redshift of 1 + \(z = 1.31\), \(L_{\text{Edd}} = 1.6(2.7) \times 10^{38} \ \text{erg s}^{-1}\) for solar composition (pure helium). While keeping in mind that the nature and composition of the donor star are uncertain in many LMXBs, we use throughout this paper a value of 2.5 \(\times 10^{38}\) erg s\(^{-1}\).
is the main parameter that sets the different behaviors of Z and atoll sources. The fundamental question remains, however, of which processes make Z and atoll sources different and how precisely their differences arise.

Atoll sources show multiple X-ray variability components in their power spectra, ranging from millisecond to kilosecond timescales, which change in strength and frequency within every studied source, giving rise to different timing states. Kilohertz quasi-periodic oscillations (kHz QPOs), present in both Z and atoll sources, produce the fastest luminosity variations in accreting systems and have received wide attention since they were discovered (van der Klis et al. 1996; Strohmayer et al. 1996a). Several broad and peaked components are present at lower frequencies, between millihertz and several hundred Hertz. In a way analogous to BH X-ray binaries, the energy spectra of atoll sources can be classified into three broad classes or spectral states: hard states, soft states and intermediate states (Sec. 5.3 for more details and the relation with the traditional “banana” and “island” terminology). Since the first studies of X-ray spectra and variability of NS-LMXBs (Hasinger & van der Klis 1989) some timing properties (such as the frequency, strength or mere presence of certain variability components) have been found to correlate with spectral indicators (such as colors or hardness ratios, Sec. 5.2.2), suggesting that spectral and timing states are intimately related.

The X-ray luminosity of transient and persistent atoll sources varies considerably on timescales longer than about one day. The role of luminosity in setting (or being set by) the spectral and variability properties outlined above (i.e. the precise relation between timing/spectral states and luminosity) has remained elusive during the last two decades. For instance, although in a given source the kHz QPO frequency correlates with X-ray intensity (or count rate) within less than ~1 hr (Strohmayer et al. 1996b), these two quantities are not correlated on longer timescales Ford et al. (1997); Méndez et al. (1999). This is known as the parallel track phenomenon, as the combination of short time scale correlation, observational windowing and long term lack of correlation gives rise to parallel lines in a frequency versus intensity diagram. Ford et al. (2000) showed that in different sources kHz QPOs can have the same frequencies at 2–50 keV luminosities that differ by more than two orders of magnitude. This creates patterns in a frequency versus luminosity diagram reminiscent of (but covering a much wider range in luminosity than) the parallel lines from a single source. The physical origin of both phenomena may or may not be the same. It should be noted that Méndez et al. (1999) and Ford et al. (2000) used the 2–16 keV and 2–50 keV energy ranges in their works, respectively, and therefore could not discard the possibility that a variable and sizable fraction of the bolometric flux was being radiated outside that energy band. More re-
recently, Gladstone et al. (2007) analyzed the ~2–50 keV spectra of a sample of atoll sources and suggested that these show two types of spectral transitions, one that follows a vertical track on a color-color diagram and occurs at 2% of the Eddington luminosity and a diagonal one at 10% Eddington. By studying two transient atoll sources Lin et al. (2007), proposed a hybrid spectral model to explain the emission in different states, and discussed the implications for $M$ and the radiative efficiency in the hard state.

During more than a decade the Rossi X-ray Timing Explorer (RXTE) has accumulated a wealth of data from many LMXBs. The broad band spectral coverage (from ~2 to 200 keV) together with the unprecedented range of variability timescales accessible to RXTE (~10 yr to ~1 µs) make this a unique dataset to study accretion physics in LMXBs. Using these data we performed a systematic and homogeneous analysis of the luminosity, timing and spectral properties of a sample of atoll sources in order to investigate the relations between these properties. We find that, while the broadband luminosity and the variability frequencies are decoupled on timescales longer than one week, the hardness of the energy spectrum is in one-to-one correspondence with the variability frequencies in each source, which shows up as a global anticorrelation between spectral hardness and variability frequencies that breaks down in both soft and hard states. Furthermore, we find a positive correlation between luminosity and spectral hardness at given variability frequency. We present these results in Section 5.3 and discuss the main implications of this work in Section 5.4. Section 5.2 and Appendix A describe our analysis method.

5.2 Observations and Data Analysis

5.2.1 Atoll sources

With the main goal of investigating how spectral and timing states relate to luminosity, we compiled a sample of atoll sources that satisfy the following requirements: i) they present different states, as witnessed by previous work; ii) they have been extensively observed with RXTE, allowing a detailed study of their properties in the different states and state transitions, iii) their distance is well constrained and therefore a good estimate of their bolometric luminosity is achievable and iv) together they cover a wide range in luminosity. This yielded a total of nine sources. We used all RXTE pointed observations, taken over more than a decade, that were publicly available at the start of this project. We list the sources that form our sample in Table A.1, together with a summary of their properties and the RXTE datasets used in this work.
5.2 Observations and Data Analysis

5.2.2 Spectral analysis and bolometric luminosity

We extracted the Crab normalized and dead time corrected count rate (intensity) in the 2.0–16.0 keV energy band, in 16 s bins. We searched for type I X-ray bursts and instrumental spikes or dropouts in the resulting 16 s lightcurves and excluded these events from the subsequent spectral and timing analysis.

In order to obtain a model independent measurement of the spectral properties we calculated colors (hardness ratios) using four contiguous energy bands, in 16 s steps and then averaged per observation. We refer to Appendix A.1 for a detailed description. The soft color (SC) gives a model independent (but $n_H$ dependent) measurement of the average spectral slope in the 2.0–6.0 keV range. The hard color (HC) gives a model independent (and $n_H$ independent, for the relatively low absorption to the sources in our sample) measurement of the spectral index in the 6.0–16.0 keV energy range. We refer to the HC herein as “spectral hardness” or “hardness”. We constructed color-color diagrams (CDs) to study the spectral evolution of each source and following previous work (Hertz et al. 1992; Kuulkers et al. 1994; Homan et al. 2002) we measured the position along the atoll tracks displayed on the CDs with the parameter $S_a$. To do so we projected every data point onto a spline drawn along the atoll track and defined a hard vertex ($S_a=1$) and a soft vertex ($S_a=2$), so that soft and hard states have $S_a > 2$ and $S_a < 1$, respectively (see Fig. 5.1 for the precise location of the vertices). By means of this method we can characterize the spectral state or position in the CD with a single parameter and compare it among the sample of sources.

We performed simultaneous fits of background and deadtime corrected PCA and HEXTE energy spectra (Appendix A.1 and A.2 for details of extraction) of each observation using XSPEC (Arnaud 1996, Version 11.3.2). We included the 3–25 keV range from the PCA spectra and the 20–200 keV range from the HEXTE spectra (to avoid in both instruments the lowest and highest energy channels, which are ill-calibrated and background-dominated, respectively). We included a multiplicative constant in the model and allowed it to vary when fitting the HEXTE spectra to account for the relative error in the effective areas of PCA and HEXTE. We obtain thereby fluxes referred to the PCA. In all cases we fix the equivalent hydrogen column density to the values reported in the literature (listed in Table A.1), as the energy range of the PCA is not well suited for constraining the absorption. Following a similar approach to that of Lin et al. (2007) we use a spectral model consisting of two thermal components (bb and diskbb) and a power law. The hard states of 1608 and 1705 did not require two thermal components so we use a simple diskbb + power law model to fit their spectra. From the best fit model we obtained the unabsorbed flux in the 2–200 keV energy band and calculated the
luminosity using the most reliable and up to date distance measurements (see Table A.1 and references therein). Given the large uncertainties that would be introduced by extrapolating the spectral model below the PCA energy band, our 2–200 keV luminosity is the most robust estimate of the bolometric luminosity that can be obtained from RXTE data. We tried a more physical model for the hard X-ray emission (comptt, which describes Comptonization of soft photons in a hot plasma) and verified that the fluxes thereby obtained are consistent within the errors with those of our adopted model. We stress that we perform these spectral fits with only the aim of estimating the luminosity and not to study details of spectral formation in our sources. For details of the spectral decompositions in atoll sources we refer to the recent works of Done et al. (2007); Lin et al. (2007). We finally stress that given the systematic uncertainty on the distance measurements (typically ~15% for those derived from type I X-ray bursts; see Table A.1 and references therein) the typical fractional systematic uncertainty on the luminosity is ~30%.

5.2.3 Timing analysis

We performed Fourier transforms on 256 s-long data segments using high time resolution PCA light curves including all energies below ~35 keV. We thereby access variability frequencies in the range ~4 mHz–4 kHz. We rms-normalized the resulting power spectra and subtracted the Poisson noise contribution (see App. A.1 for details). After inspecting by eye all the power spectra, we measured the following parameters from the power spectra (as discussed further below) in order to characterize the timing state of the sources in each observation: i) break frequency of the flat-topped noise, ii) frequency of the upper kHz QPO, iii) slope of the very low frequency noise and iv) fractional rms amplitude of the variability integrated in two frequency bands: 0.01–1 Hz and 1–100 Hz.

In those observations where flat-topped broadband noise is present we fitted a broken power law model to the power spectrum in order to measure the cutoff or break frequency, \( \nu_b \), of the flat-topped noise, fixing the pre-break slope to zero (see Fig. 5.2 for an overview). We added one or two Lorentzians to the fit model to account for other variability components often present at frequencies higher than \( \nu_b \) (\( L_h \) and \( L_{\text{low}} \), where L stands for Lorentzian, “h” for hump and “low” for low-frequency; see van Straaten et al. 2002, 2005 for details). When fitting the flat-topped noise we used a variable frequency range to accommodate the changes in \( \nu_b \), including only the relevant ~1 to ~2 decades in frequency around the break. Table A.2 shows the number of observations of each source where we were able to measure \( \nu_b \) using this method.

We searched for kHz QPOs in the 300–1300 Hz frequency range of all obser-
5.3 Results

observations taken when the sources were in soft or transitional states (banana or island states) and we used a simple or double Lorentzian fit function to obtain their frequency. kHz QPOs are known to change their frequency on timescales much shorter than the typical time span of one RXTE observation (e.g. Berger et al. 1996; Ford et al. 1997; Paltani et al. 2004). Therefore this method yields an average value of the QPO frequency during the observation, which is suited to our goal of characterizing the timing state of the source. In the observations where we detected two kHz QPOs we readily identified the higher frequency component with the upper kHz QPO and the lower frequency component with the lower kHz QPO. Based on the relation between their frequencies (\( \nu_u \) and \( \nu_l \) for the upper and lower kHz QPO, respectively) and the spectral hardness (as traced by the HC; see Sec. 5.2.2 and Fig. 5.3) we were able to identify the large majority of the kHz QPOs detected as single peaks. The number of \( \nu_u \) measurements obtained from twin and single kHz QPO detections is shown in Table A.2.

We searched all the observations taken in the soft state for red noise at the lowest frequencies (often called very low frequency noise, VLFN). We fitted a simple power law in the 0.01–1 Hz frequency range and obtained thereby the VLFN index (slope of the best fit power law). The fit results are somewhat sensitive to the presence of variability components at the high end of the frequency range spanned by the VLFN (i.e. between 0.1 and 1 Hz; see e.g. Reerink 2005). Only in five observations we detected simultaneously VLFN and flat-topped noise, which in those cases had \( \nu_b \geq 30 \) Hz, i.e., near the maximum observed break frequency. To get a model independent measure of the variability present in all the states we calculated the fractional rms amplitude of the variability in two frequency bands: 0.01–1 Hz (\( r_L \)), and 1–100 Hz (\( r_H \)). We constructed rms-rms diagrams using \( r_H \) and \( r_L \) and, in direct analogy with CDs (Sec. 5.2.2), we measured the position along the resulting tracks projecting each point onto a spline. Using these various measurements we characterized the timing state of each of the sources for each observation. This characterization is robust: it uses variability components that can be unambiguously identified (flat-topped noise, upper kHz QPO and red noise) and model independent measurements of the strength of the variability (\( r_L \) and \( r_H \)).

5.3 Results

Based on our systematic analysis of luminosity, spectral and timing properties of atoll sources and on the results that will be presented in this Section, we divide the accretion states of atoll sources into three main classes: soft states,
hard states and intermediate states. These three classes are named after the average slope of the hard X-ray spectrum (Sec. 5.2.2) but, as shown by previous work (Hasinger & van der Klis 1989; van Straaten et al. 2000) and detailed hereafter, they also differentiate the timing state of the sources. However, as explained in Secs. 5.3.2 and 5.3.3, the relation between spectral/timing states and luminosity is not one-to-one. Soft states ($S_a > 2$) and hard states ($S_a < 1$) are frequently called in the literature “banana” states and “extreme island” states, respectively. Intermediate states were originally named “island” states due to their patchiness in CDs, which (as already noted by Hasinger & van der Klis 1989) was partly due to observational windowing. The transient sources in our sample show rapid (within a few days) state transitions during which their spectral and timing properties are like those of the persistent sources in the intermediate state. Together with the typical RXTE sampling (daily observations in the best case but more sparse in most cases), this results in sparsely populated intermediate state branches in the transient systems. On the contrary, some of the persistent sources are in intermediate states most of the time, which results in densely populated intermediate state branches (Sec. 5.3.2). We refer alternatively to these states ($1 < S_a < 2$) as transitional or intermediate state.

5.3.1 Variability and spectra

A summary of our correlated spectral and timing analysis is presented in Figure 5.1, which shows color-color diagrams (CDs) of all the studied sources. The observations where we detect flat-topped broadband noise, an upper kHz QPO or VLFN in the power spectrum are highlighted in each CD in green, blue and red, respectively. One can readily see the regions of the CD where each of these variability components is present. Namely, flat-topped noise (green) appears in hard and intermediate (extreme island and island) states, kHz QPOs (blue) are present in intermediate and soft states (only in soft states with relatively low SC, in the region of the CD called “lower-left banana”) and the VLFN (red) dominates the power spectra of most soft state observations. Table A.2 shows the total number of detections of these three variability components in each source, as well as the observed range of variability frequencies. In all nine sources we measure values of the VLFN index between $\sim 0.8$ and $\sim 3$, and find no correlation with luminosity, SC or HC, so we do not consider this quantity further in this analysis.

By comparing the results of our timing and spectral analysis we find a frequency-hardness anticorrelation within individual sources. The break frequency of the flat-topped noise, $\nu_b$, anticorrelates with the HC over nearly three orders of magnitude in frequency (Figure 5.2; Figure 5.4, top right).
The frequencies of both the upper and lower kHz QPOs, $\nu_u$ and $\nu_l$, also anticorrelate with the HC (Fig. 5.3 and bottom right panel of Fig. 5.4). Of course, $\nu_u$ and $\nu_l$ follow different tracks in a frequency-hardness diagram (as shown by Fig. 5.3), which in practically all cases allows us to identify the upper kHz QPO in those observations where the lower kHz QPO is not detected (Sec. 5.2.3). The steepness of the $\nu_u$-HC tracks increases at the highest HC values ($\sim$1.1; i.e. when the sources reach the hard or extreme island state). For the kHz QPOs we find instead a steepening of the $\nu_u$-HC and $\nu_l$-HC anticorrelations when the sources reach the soft state (Fig. 5.3, which also shows a steepening of the $\nu_u$-HC relation towards the hard state in some of the sources). We also find that the highest ($\nu_u$) and the lowest ($\nu_l$) characteristic frequencies of the rapid X-ray variability are correlated with each other, as witnessed by previous work based mostly on averages of several observations (van Straaten et al. 2005; Linares et al. 2005; Altamirano et al. 2005) and as expected if both frequencies are anticorrelated with the spectral hardness. The overall strength of the variability, measured by its fractional rms amplitude, decreases gradually within each source as the spectral hardness decreases. This can be clearly seen in Figure 5.5, which displays the integrated 1–100 Hz rms fractional variability for each point of the CD. When looking at the full sample, however, we find that different values of the fractional rms amplitude occur at the same spectral hardness (e.g. between 10% and 25% for HC $\approx$0.9).

5.3.2 Luminosity and spectra

Active atoll sources feature broadband (2–200 keV) luminosities in the range 0.1–50% $L_{Edd}$ ($3 \times 10^{35}$–$1 \times 10^{38}$ erg s$^{-1}$). Figure 5.6 shows hardness-luminosity diagrams (HLDs) for all nine sources. The two transient systems, 1608 and Aql, show a similar luminosity range during their outbursts, with maximum$^2$ luminosities of $\sim$20% $L_{Edd}$ and $\sim$30% $L_{Edd}$, respectively, and cover almost the entire luminosity range of the full sample of sources (luminosity ranges are shown in Table A.2). The HC is independent of the interstellar absorption and traces clearly the changes in spectral state. Three systems (1608, Aql and 1705) show a bimodal distribution in HC, i.e., they are most of the time in the soft state or in the hard state. The luminosity of 1705 varies by more than an order of magnitude (between $\sim$1% and $\sim$40% $L_{Edd}$), which adds to the similarities between 1705 and the two transient systems. Two systems (0614 and 1728) are anchored in the intermediate state, and they maintain roughly

$^2$As witnessed by previous work based on deeper observations (Campana et al. 1998b; Jonker et al. 2003; Linares et al. 2008a), the luminosity of the transients drops to $\sim 10^{35}$–$10^{34}$ erg s$^{-1}$ after such episodes of intense accretion, and decays to $10^{33}$–$10^{32}$ erg s$^{-1}$ in quiescence (van Paradijs et al. 1987; Wijnands et al. 2004; Cackett et al. 2006).
constant luminosities that differ by one order of magnitude (~0.8% and ~8% $L_{\text{Edd}}$ for 0614 and 1728, respectively). Figure 5.6 also shows that 1636 moves (in a quasi-regular cycle, see Belloni et al. 2007 and references therein) along two branches in the HLD: an intermediate state branch produced by changes in its spectral hardness and a soft state branch mainly due to luminosity changes. The remaining three systems (1820, 1735 and GX 3+1) are predominantly in soft states, although 1820 has visited the intermediate and hard states on a few occasions (Bloser et al. 2000; Altamirano et al. 2005). We note that the soft state branches clearly defined in at least five of the nine sources (Fig. 5.6), while relatively constant in HC in a given source, span a wide range in spectral hardness across sources, with HC values between ~0.5 and ~0.8. On the other hand the hard state branches, traced out clearly by 1608, Aql and 1705, have a similar value of HC=1.1±0.1. Our work also shows that hard states can be as luminous as ~15% $L_{\text{Edd}}$ and hence the term “low-hard state”, often used in the literature and inspired by the relatively low count rates observed in the soft X-ray band during hard states, can be misleading. It is also worth noting that the intermediate state forms a nearly vertical track in all the studied systems, indicating that the broadband luminosity remains approximately constant when the sources transit between the soft and the hard state, or vice versa. However, the SC increases in the intermediate states when going from soft to hard states, with the exception of only 0614. Figure 5.6 also shows that the intermediate state luminosity (i.e., the location of the vertical track) in different systems differs by more than one order of magnitude, from ~0.5 to ~14% $L_{\text{Edd}}$ (a much wider range than was previously thought; e.g. Maccarone 2003). The reported distance uncertainties for the two systems at the high and low end of this luminosity range are ~15% (Table A.1) and can not account for the large dispersion in intermediate state luminosity. This implies that the wide range in intermediate state luminosity of different sources is most likely produced by an intrinsic parameter that differs between sources, as already suggested by Ford et al. (2000) (See Sec. 5.4.3).

In Figure 5.7 we show the broadband luminosity of each source throughout its CD. In the case of 1608, Aql X-1 and 1705, the most luminous hard states present luminosities as high as or higher than the least luminous soft states. The two transients, 1608 and Aql, feature underluminous regions in the bottom-left part of the soft state branch (i.e. in the lower left banana) compared to the rest of that branch. As explained in Section 5.2, we determine the spectral state with a single parameter, $S_a$, which measures the position along the atoll track (from $S_a<1$ in hard to $S_a>2$ in soft states; Fig. 5.1) and allows a direct comparison between sources. Figure 5.9 shows the relation between the broadband luminosity and $S_a$. A correlation between $S_a$ and luminosity is
visible in soft and hard states (except in the soft state of 1728 and GX 3+1). During intermediate or transitional states, however, \( S_a \) and luminosity are in general not correlated (see also Galloway et al. 2008b). Interestingly, even though these two parameters are widely used in the literature as tracers of \( \dot{M} \), this lack of correlation implies that in intermediate states \( \dot{M} \) is not simply related to both \( S_a \) and luminosity (further discussion in Sec. 5.4.1).

5.3.3 Luminosity and variability

As explained in Section 5.3.4, detailed analysis of individual outbursts of the transient atoll sources reveals correlations on timescales shorter than about one week between broadband luminosity and break frequency. In order to search the full sample for longer timescale correlations, we split our measurements into consecutive seven days intervals (when available). We found no strong correlation between frequencies and luminosity in the resulting intervals. We repeated the same procedure using continuous series of observations (defined as having gaps between observations of less than two days), and again found no obvious \( \nu \)-L correlations.

The rms-rms diagrams displayed in Figure 5.8 show the evolution of the power spectrum as its characteristic frequencies change. We can distinguish two branches: i) a “steady” branch where \( r_L \) is low and approximately constant (\( r_L \lesssim 5\% \)) while \( r_H \) increases from a few percent to \( \sim 10-15\% \) and ii) a “variable” branch where \( r_H \) has reached a high (\( \sim 20-25\% \)) and roughly constant value while \( r_L \) increases. The steady branch corresponds to high characteristic variability frequencies and soft spectra whereas the variable branch corresponds to low frequencies and hard states. As can be clearly seen from the color scale in Figure 5.8, and in direct analogy with the spectral states shown in the CDs (Fig. 5.7), the same timing states can occur at very different luminosities. The relations between the characteristic variability frequencies, \( \nu_u \) and \( \nu_b \), and the fractional amplitude of the variability are shown in Figure 5.10. In general these two measures of the X-ray variability are anticorrelated, in agreement with the well known power decay towards high frequencies (and soft states). We find, however, that this anticorrelation breaks down for 1820, 1735 and 1636 at the highest upper kHz QPO frequencies (Fig. 5.10, bottom panels; see also Sec. 5.4.3). The case of 1820 is of particular interest as it features a correlation between \( \nu_u \) and both \( r_L \) and \( r_H \) when \( \nu \gtrsim 1000\text{Hz} \), where all other sources (with the possible exception of 1735) show an anticorrelation. This increase of variability amplitude when \( \nu_u \) reaches its highest values is due to the appearance in 1820 and 1735 of a strong “peaked noise” component at a few tens of Hz. This component is reminiscent of the flaring branch oscillation observed in Z sources and it arises in the two highest luminosity sources.
within our sample, which suggests a link between the soft states of the highest luminosity atoll sources and Z sources.

In Figure 5.4 (left) we show the values of $\nu_b$ and $\nu_u$ plotted versus the luminosity. Clearly, in the whole dataset variability frequencies and luminosity are not correlated, neither within a single source nor across different sources. Three sources, 1608, Aql X-1 and 1705, present a similar feature in the $\nu_b$-luminosity diagram (Fig. 5.4, top left): when $\nu_b < 1$ Hz their maximum luminosity is correlated with $\nu_b$ (showing up as a lower-right envelope in their $\nu_b$-luminosity diagrams). This constitutes another similarity between 1705 and the two transient systems (Sec. 5.3.2). Summarizing, although spectral hardness and variability frequencies are in one-to-one correspondence within each individual source, the same hardness-frequency pairs can occur at luminosities that differ up to one (for a given source) or two (across different sources) orders of magnitude (Fig. 5.4; Sec. 5.3.1). We stress that similar shifts between sources are observed in a frequency-[2–50 keV]-luminosity diagram and in a frequency-[2–200 keV]-luminosity diagram (Ford et al. 2000; this work). We therefore conclude that it is not just the energy radiated in the hard X-ray band (50–200 keV) that “decouples” the variability frequencies and luminosity (Sec. 5.4.3).

Even though the mutual relations between spectral hardness, variability frequencies and luminosity appear complex when considering the ensemble of systems and states, we have discovered a very systematic aspect to these relations that was not yet known. In Figure 5.4 (right) the frequency-hardness tracks subtended by different sources are offset from one another. Looking now at the left panels of Figure 5.4 one can see that the frequency-luminosity tracks are also offset, and in the same order as in the right panels. These systematic differences between sources lead to a strikingly simple relation between luminosity and spectral hardness at a given timing state, in the form of a positive luminosity-hardness correlation across different sources. We select observations with $\nu_u \sim 1000$ Hz and show their luminosity versus spectral hardness in Figure 5.11. The luminosity-hardness relation of all observations with $\nu_b \sim 30$ Hz is also shown. In both cases luminosity and hardness are clearly correlated over nearly two orders of magnitude in luminosity. The frequencies thereby selected are in the high end of both $\nu_b$ and $\nu_u$ ranges and correspond to $1.8 \leq S_n \leq 2.2$, i.e., to the “lower-left banana”. A similar luminosity-hardness correlation is present when selecting lower variability frequencies, somewhat less strong but still significant. We show this by plotting in Figure 5.11 luminosity versus hardness for those observations with $\nu_u \sim 500$ Hz and those with $\nu_b \sim 1$ Hz. This correlation is therefore strongest in soft, thermal dominated states where variability timescales are short, but occurs in all states where
variability frequencies can be measured.

5.3.4 Time evolution

To illustrate how the broadband luminosity, the spectral properties and the variability change during the course of an outburst, we show in Figures 5.12 and 5.13 a detailed view of these quantities along two outbursts of the two transient systems studied herein (1608 and Aql X-1). Figure 5.12 (left) shows the luminosity, colors, characteristic frequencies and fractional rms variability of the 2002 outburst of 1608. The source started in the hard state as can be seen from the values of the HC, then transited to the soft state while it was not being observed by RXTE and started a smooth luminosity decline. Around MJD 52540 a series of five state transitions started that lasted about 20 days, until the source went back to quiescence. The break frequency during the initial hard state tracks the luminosity changes (the corresponding track in the frequency-luminosity plane can be seen in blue in the upper part of Figure 5.12). All the observed transitions in this outburst occur at a similar luminosity of \( \sim 0.4-0.5 \, L_{\text{Edd}} \). In the 2005 outburst (Fig. 5.12, right) instead all transitions occur at higher luminosity, the two soft-to-hard transitions (S\( \rightarrow \)H) occur around 1% \( L_{\text{Edd}} \) and the H\( \rightarrow \)S ones at a still higher luminosity of \( \sim 3\% \, L_{\text{Edd}} \). It is also interesting to note that the H\( \rightarrow \)S transition is anticipated by an increase of the break frequency (as well as of the SC and luminosity). The flat-topped noise disappears when HC reaches its minimum and the source reaches the soft state. After the source transits back to the hard state (within about four days), the break frequency decreases continuously for about twenty days, i.e., on a similar timescale to that observed after BH state transitions (Kalemci et al. 2004). Aql X-1 behaved in the same way during its 1999 and 2000 outbursts (Fig. 5.13). In both outbursts the initial H\( \rightarrow \)S transitions are preceded by an increase in luminosity, SC and break frequency. The luminosity of these transitions (around \( \sim 10\% \, L_{\text{Edd}} \) or above) is higher than the luminosity of the S\( \rightarrow \)H transition (between \( \sim 1 \) and \( \sim 3\% \, L_{\text{Edd}} \); see also Maccarone & Coppi 2003; Tudose et al. 2009) that occurs later on in the outburst, in a way analogous to BH transients (Homan & Belloni 2005).

5.4 Discussion

5.4.1 Luminosity and mass accretion rate

We present in Figure 5.14 a sketched summary of the luminosity and variability evolution along each of the three states of atoll sources: soft, hard and
intermediate. It also shows the luminosities at which these states are observed along the full sample of sources (Fig. 5.6). The two transients (1608 and Aql X-1) and 1705 are the only systems that fully sample the hard state, which as pointed out by Barret & Olive (2002) and Muno et al. (2002c) results in a “Z”-shaped track on the CD. However, these three atoll sources can be clearly distinguished from Z sources by their lower luminosity, harder average spectra and stronger variability (van Straaten et al. 2003), which shows that (as already pointed out by Hasinger & van der Klis 1989) CD morphology per se is not sufficient to classify an LMXB. As explained in Sec. 5.3.2, 1608, Aql X-1 and 1705 show two distinct and populated branches in the HLD and SaLD, corresponding to hard and soft states, and a less densely populated intermediate state branch. This suggests that the transitional state is unstable, that each of these two branches corresponds to a stable configuration of the accretion flow and that the movements along each branch are produced by changes in the \( \dot{M} \) of such stable configurations (Done et al. 2007). However, 1636, 0614 and 1728 show intermediate states that are instead densely populated, which indicates that the inner accretion flow in the intermediate state is not intrinsically unstable in these systems. The fact that the three systems with the longest orbital periods show the largest long term luminosity changes (Table A.2) supports the picture that large disks are colder in the outer parts and tend to be unstable (Lasota 2001). Some atoll sources are mostly in soft states (1820, 1735 and GX 3+1 in our sample; Figs. 5.6 and 5.9, lower panels; Table A.2), which could be due to a sustained high mass transfer rate that has maintained the accretion disk hot and bright during more than a decade of RXTE observations.

The approximately constant luminosities that we observe during state transitions imply that such transitions involve mainly a redistribution of the flux at different energies, so that the total radiated energy does not change by large amounts in intermediate or transitional states. If \( \dot{M} \) increases during the hard to soft transition (as e.g. the burst properties of 1636 suggest, van der Klis et al. 1990) the net efficiency in converting \( \dot{M} \) into 2–200 keV radiation must decrease in order to keep a constant luminosity. This would imply, however, that hard states are more radiatively efficient than soft states, in clear contradiction with the high efficiency usually attributed to soft (a.k.a “thermal” or “disk-dominated”) states. An alternative is that two accretion flows operate simultaneously and only the mass accretion rate through the disk, \( \dot{M}_d \), increases during the H→S transition while the mass accretion rate in the corona, \( \dot{M}_c \), decreases accordingly so as to keep a constant total \( \dot{M} \) (Esin et al. 1997; Meyer-Hofmeister et al. 2005; Done et al. 2007, see also 5.4.3.2). Several mechanisms have been proposed to produce the switch between hard and soft
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states, from a disk-instability induced transition (Mineshige 1996), disk evaporation into a corona (Meyer-Hofmeister et al. 2005), the ejection of the corona into a transient jet (suppressing the steady jet, Fender et al. 2004b) or the onset of an ADAF (Narayan & Yi 1995). The mechanism responsible for such state transitions must account for i) approximately constant luminosities in a single transition, a narrow range of luminosities in a given source at different epochs and a wide range of luminosities across sources (Secs. 5.3.2, 5.3.4 and Table A.2), ii) densely populated intermediate states in non-transients and sparsely populated intermediate states in transients (with the same timing and spectral properties; Sec. 5.3) and iii) variability frequencies that increase when going from the hard to the soft state (Fig. 5.4, right, Sec. 5.3.1). Our work also shows that a successful model for the accretion flow in the hard state must be able to explain luminosities as high as 15% $L_{\text{Edd}}$ (as in 1705 or 1820), and that disk dominated (soft) states can have luminosities as low as 1% $L_{\text{Edd}}$ (as is the case of 0614 or 1608, Fig. 5.9). As noted in Section 5.3.2, distance uncertainties do not affect these conclusions. Clearly, soft states of atoll sources are not necessarily more luminous than hard states. Hard and soft states show overlapping ranges in luminosity, both in a given source and across sources. Hence the terms “low-hard state” and “high-soft state” are misleading and should be abandoned.

5.4.2 Comptonization and variability frequencies

It is widely agreed that the hard X-ray flux in LMXBs is produced by Compton up-scattering of soft thermal photons within a population of hot electrons. The location and geometry of the comptonizing medium is a matter of debate (corona, ADAF, base of the jet, boundary layer...). Our work gives an important constraint to model the behavior of this comptonizing medium in atoll sources: the fraction of comptonized flux is anticorrelated with the variability frequencies. This is true not only for QPOs but also for broadband (flat-topped) noise. In other words, the harder the energy spectrum, the longer the variability timescales (see Fig. 5.4, right). A similar phenomenon has been seen in some BH systems (Vignarca et al. 2003; Titarchuk & Fiorito 2004; Titarchuk & Shaposhnikov 2008), indicating that this constitutes a basic property of accretion flows around compact objects.

Linares et al. (2007) showed that NS-LMXBs can have variability frequencies lower than BH systems, contrary to the common belief that characteristic variability timescales of LMXBs scale linearly with the mass of the accreting compact object. In this work we show that the main tracer of such frequencies is the spectral hardness. It is interesting to note in this respect that the accreting millisecond pulsar Linares et al. (2007) studied, IGR J00291+5934,
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featured an X-ray spectrum harder than any of the sources studied herein (HC > 1.2 Crab). In terms of the hardness-frequency anticorrelation presented in this work (Sec. 5.3.1), this can explain the anomalously low frequencies observed in this object (\(\nu_b \approx 0.02\) Hz). We also stress that, if the X-ray luminosity tracks \(\dot{M}\), the observed break frequencies are not correlated with \(\dot{M}\) (Fig. 5.4, left). Therefore, if the characteristic frequency of the BH system Cyg X-1 used to infer AGN masses (Uttley & McHardy 2005; Axelsson et al. 2005) changes due to the same process as the characteristic frequencies of atoll sources, then it is imperative to identify and understand this process before using variability frequencies to measure the mass of super massive BHs.

If the variability frequencies are set by the orbital frequency at the inner edge of the disk, this relation between hardness and frequencies is consistent with a scenario in which the disk recedes when the sources transit from the soft to the hard state, leaving an optically thin inner accretion flow (Narayan & Yi 1995; Done et al. 2007). In this framework the inner accretion flow (or “corona”) must yield a higher flux in hard X-rays (more Compton upscattered photons) when the disk is truncated far out. Therefore a larger fraction of the soft seed photons produced in the disk and/or NS surface must be intercepted by the corona before reaching the observer, which poses strong constraints on the geometry of the flow (Maitra et al. 2009). Our results on the frequencies and luminosities during state transitions (Fig. 5.4, Table A.2) imply that, if the “receding disk” scenario applies, the same change in inner disk radius should occur at luminosities between \(\sim 0.5\) and \(\sim 15\% \, L_{\text{Edd}}\).

5.4.3 Decoupling variability and luminosity

Our work shows that, even when including the hard X-ray band (up to 200 keV), the same kHz QPO frequencies can be present in a given source at luminosities that differ by a factor of \(\sim 2\) (see 0614, 1820, 1728 and 1636 in lower left panel of Fig. 5.4) or a factor of \(\sim 8\) in the case of 1608. This is a consequence of the parallel track phenomenon in individual sources operating throughout the present work (see Sec. 5.1). Considering the full sample of atoll sources, one can readily see that the same kHz QPO frequencies are observed over a range of two orders of magnitude in luminosity. This is often known as the parallel track phenomenon across sources in reference to the tracks in a frequency-luminosity diagram displayed by different sources (Ford et al. 2000). We stress that different NS masses and accreted material compositions will change \(L_{\text{Edd}}\) by a factor of \(\sim 3.5\) at most (for a NS mass between 1 and 2 \(M_\odot\)), much less than the two orders of magnitude range in luminosities actually observed. As a consequence of the spectral hardening that occurs when upper kHz QPO frequencies decrease (Fig. 5.4, lower right) such tracks become vertical when
Figure 5.1: Color-color diagrams of the nine atoll sources studied. Green points mark observations where we measure the break frequency of the flat-topped broadband noise, small blue open circles mark our detections of upper kHz QPOs, red points show those observations where VLFN is present and grey points the cases where none of these phenomena were present. There were only five instances where flat-topped noise and VLFN occurred in the same power spectrum (Sec. 5.2.3). Observations combining either VLFN or flat-topped noise with upper kHz QPO show up as blue circles with red or green interior, respectively. The hard ($S_1$) and soft ($S_2$) vertices are marked with a large black open circle on the upper and lower part of the atoll track, respectively (Sec. 5.2.2).

considering the broadband luminosity instead of the soft X-ray intensity or the 2–50 keV luminosity (as in Ford et al. 2000). At $\nu_u > 1000$ Hz, however, a “bending” of the tracks towards high luminosities is apparent in some of the sources (Fig. 5.4, lower left; the same sources stand out in Fig. 5.10, see Sec. 5.3.3). In summary, when considering all observations taken over more than ten years, there is no correlation between luminosity and kHz QPO frequency in any of the sources.
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Figure 5.2: Overview of flat-topped noise present in hard and intermediate states (Sec. 5.2.3). Representative power spectra are shown together with their fit functions, with break frequencies spanning more than two decades. It should be noted that the break frequency of each individual system varies over a similar range (see Fig. 5.4).

We showed in Section 5.3.3 that the luminosity observed at a given timing state (or variability frequency) in different sources is correlated with the spectral hardness above 6 keV (see Fig. 5.11). This constitutes a new ingredient to model accretion flows in LMXBs. The fact that luminosity and spectral hardness are correlated at a given variability frequency also offers a potential tool to estimate the distance to systems that show no photospheric expansion bursts by only measuring one frequency ($\nu_a$ or $\nu_b$), together with spectral hardness and flux. van Paradijs & van der Klis (1994) found an anti-correlation between spectral hardness and luminosity in a sample of LMXBs using the HEAO-1 A4 catalogue. The fact that they average over different states and use a different hardness energy band (13–80 keV) prevents a direct comparison between these results. In the following we discuss several mechanisms to decouple X-ray variability from luminosity, both in a single source and across sources, and for the latter case speculate on how the observed luminosity-hardness correlation may or may not be explained by such mechanisms. In the rest of this Section we adopt the hypothesis that the variability frequencies trace the radius of the inner edge of the disk ($R_{\text{in}}$), and in particular that the frequency of the upper kHz QPO reflects the orbital frequency at $R_{\text{in}}$. 

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Figure 5.3: kHz QPO frequencies versus spectral hardness. Black dots represent upper kHz QPOs and grey triangles lower kHz QPOs. Squares show initially unidentified (single) kHz QPOs. We can identify most of these as upper or lower kHz QPO based on the distinct tracks clearly visible in this Figure (see also Sec. 5.3.1). In this and the following Figures each point represents one observation. Fragments of these kHz QPO frequency-hardness diagrams were reported for 1608 (Méndez et al. 1999) and 1636 (Di Salvo et al. 2003; Belloni et al. 2007).

5.4.3.1 Relative change in mass accretion rate

van der Klis (2001) proposed a mechanism to decouple variability frequencies from luminosity that involves a single variable ($\dot{M}_d$ in the simplest version) and its value averaged over a certain timescale ($<\dot{M}_d>$). In this model, the observed shifts in kHz QPO frequencies are caused by changes in $\dot{M}_d$, which in turn change the inner radius of the disk and the orbital frequencies therein (as in e.g. Miller et al. 1998; Lamb & Miller 2003). However, the frequencies are not simply set by the instantaneous value of $\dot{M}_d$ but depend on $\dot{M}_d/<\dot{M}_d>$, and therefore on how much $\dot{M}$ differs from its average. The luminosity is
assumed to vary in response to both the instantaneous and the time-averaged $\dot{M}_d$. In this way the same frequencies can occur at luminosities different by a factor of up to 10 in one source and up to two orders of magnitude across sources. The physical mechanism used to maintain the same $R_{in}$ over such a wide range in luminosity in this model is a balance between mass accretion $\dot{M}_d$ “pushing” the inner disk inwards and radiation force “pushing” it outwards (as proposed by Miller et al. 1998). Luminosity and $\dot{M}_d$ would balance out so

Figure 5.4: Top right: Break frequency versus spectral hardness for the eight sources where flat-topped noise is present. Bottom right: upper kHz QPO frequency versus spectral hardness for the seven sources that show upper kHz QPOs. The frequency-hardness anticorrelation is visible in both cases, and “saturates” towards soft and hard states (Secs. 5.3.1 and 5.4.2 for details). Top left: Break frequency versus luminosity for the eight sources where flat-topped noise is present. Bottom left: upper kHz QPO frequency versus luminosity for the seven sources that show upper kHz QPOs (see also Ford et al. 2000). Note that the same range in break frequency (more than two orders of magnitude) is observed at very different luminosities, both in a single source (spanning $\sim$1 order of magnitude in 1608, Aql X-1 and 1705) and across sources (spanning $\sim$2 orders of magnitude). See Secs. 5.3.3 and 5.4.3 for details.
as to keep $R_{in}$ within a certain range.

Figure 5.5: “Color-color-color” diagrams of the nine atoll sources studied. The color scale shows the 1–100 Hz fractional rms amplitude of the variability. Hard states are more variable, but hardness does not determine rms.

In this context, we propose that our luminosity-hardness correlation at a given kHz QPO frequency (Sec. 5.3.3) could reflect an underlying correlation between total luminosity and disk temperature. For a fixed inner disk radius, and upper kHz QPO frequency, a hotter disk would produce more luminosity and its high energy tail would increase the observed spectral hardness. As an example, increasing the disk-blackbody temperature by a factor of two in the best-fit spectral model of one of the observations near 1% $L_{Edd}$ (while keeping the inner disk radius and remaining parameters fixed) leads to an increase of a similar factor in the spectral hardness (as defined in Sec. 5.2.2, i.e., in the 6–16 keV band). The steep ($T^4$) dependence of luminosity on black body temperature can reconcile the observed large range of luminosities with a sensible range of inner disk temperatures. NS mass difference between sources
could slightly affect the luminosity-hardness correlation, but by much less than the range covered by the data. Finally, we note that this interpretation would also explain why the luminosity-hardness correlation is strongest at the highest variability frequencies: in soft states the disk contributes more to the total spectrum, and changes in its temperature can therefore affect more strongly the spectral hardness.

![Hardness-Luminosity diagrams of the nine atoll sources studied. The luminosity range is indicated in Eddington units (lower axis) and erg s\(^{-1}\) (upper axis). Hard and soft state branches are approximately horizontal while intermediate states trace out vertical tracks.]

**Figure 5.6:** Hardness-Luminosity diagrams of the nine atoll sources studied. The luminosity range is indicated in Eddington units (lower axis) and erg s\(^{-1}\) (upper axis). Hard and soft state branches are approximately horizontal while intermediate states trace out vertical tracks.

### 5.4.3.2 Two flows, bolometric corrections, jets and anisotropy

If \(\dot{M}_d\) is in one-to-one correspondence with the variability frequencies, one of the proposed ways to explain the different luminosities at which such frequencies are observed is by means of an additional accretion flow that varies the total \(\dot{M}\) for a given \(\dot{M}_d\) (e.g. Wijnands et al. 1996; Ford et al. 2000, see also...
Sec. 5.4.3.1). However, if changes in the mass accretion rate of such spherical inflow (or “corona”; $M_c$) are responsible for the variability-luminosity decoupling one expects a comparable decrease in the fractional amplitude of the kHz QPOs towards high luminosities, in disagreement with observations (Méndez et al. 2001).

Emission outside the RXTE 2–200 keV band can constitute another sink of energy and a way to decouple X-ray luminosity from variability frequencies (as noted e.g. by van der Klis 1995a). For instance, Thompson et al. (2008) point out that in some particular states about 30% of the bolometric luminosity can reside in the soft X-ray band, below the PCA energy range. Radiation of a variable fraction of the bolometric luminosity in the soft X-rays and UV band may therefore account for the frequency-luminosity decoupling in a given source, but expected bolometric correction factors being a factor 2 or 3 at most (Migliari & Fender 2006; in’t Zand et al. 2007), it can hardly account for the more than two orders of magnitude difference in 2–200 keV luminosity between different sources in the same accretion (spectral/timing) state.

Based on the interaction between the jet and surrounding medium Gallo et al. (2005); Heinz et al. (2007) argue that the time-averaged jet power in some X-ray binaries is comparable to their X-ray luminosities. Although such estimates are still subject to large uncertainties, mechanical energy leaving the system in the form of a jet and at a variable rate gives another potential mechanism to decouple the radiated energy from the mass accretion rate through the disk and from the variability frequencies (Méndez et al. 1999). When considering a sample of sources, however, we see that the difference in jet power should be as high as two orders of magnitude in order to explain the observed frequency-luminosity relation. Moreover, if the low X-ray luminosity systems have large jet power this would be in contradiction with their low radio luminosities (Migliari & Fender 2006).

For a number of reasons, accretion flows in LMXBs are expected to radiate anisotropically. The emission of a flat accretion disk will have a $\cos i$ angular dependence, based purely on the change in projected area (where $i$ represents the angle between the line of sight and the perpendicular to the disk). Beloborodov (1999) proposed a scenario in which Thomson scattering in an outflowing disk atmosphere collimates most of the soft X-ray emission along the disk axis. Jets are known to exist and emit in the radio, IR and perhaps X-ray band in hard states of LMXBs (Fender 2006; Russell et al. 2007; Falcke et al. 2004). Their emission is strongly beamed if they move away from the compact object at relativistic speeds. We refer hereinafter to the apparent luminosity (calculated from the measured flux and assuming anisotropy) as simply “luminosity”, and to the total (integrated over all solid angles) energy
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Figure 5.7: “Color-color-color” diagrams of the nine atoll sources studied. The color scale shows the 2–200 keV luminosity, in Eddington units and logarithmic scale. The luminosity ranges from $2.5 \times 10^{35}$ erg s$^{-1}$ (0.1% $L_{\text{Edd}}$) to $1.3 \times 10^{38}$ erg s$^{-1}$ (50% $L_{\text{Edd}}$). In a given source hard states are on average less luminous, but HC does not determine luminosity, and hard states in some sources (e.g. 1820, 1705) can be more luminous than soft states in other sources (e.g. 0614, 1608).

per unit time that escapes the system in the form of radiation as “radiated power”. In all the cases mentioned above the (apparent) luminosity will depend on the inclination angle $i$ so that systems with the same radiated power, when seen at low inclination will appear more luminous than those seen at high inclination. This provides a plausible mechanism to decouple variability frequencies and luminosity: if $\dot{M}_d$ sets both variability frequencies and radiated power (e.g. because $\dot{M}_d$ sets $R_{in}$, and this sets variability frequencies), then systems with the same radiated power and variability frequencies will show large differences in luminosity when viewed at different inclinations. As an

$^3$We assume in this context that the disk is in the plane of the orbit and the jet axis is perpendicular to the disk, so that the inclination of the system is unambiguously defined.
example, applying the formula for the (de)boosting factor of a continuous jet given by (Fender 2006), assuming a jet velocity of 0.8c and a radiated power of 5% $L_{Edd}$ we estimate that the observed luminosity at an inclination between 0 and 80 degrees would be between 3 and 45% $L_{Edd}$. Two words of caution are necessary here: i) this formula gives a rough estimate and the problem obviously deserves detailed modelling (see e.g. Maitra et al. 2009) and ii) this scenario predicts that high inclination systems should be systematically underluminous for a given state, which so far has not been observed.

Figure 5.8: RMS-RMS diagrams of the nine atoll sources studied. The color scale shows the 2–200 keV luminosity, in Eddington units and logarithmic scale. The luminosity ranges from $2.5 \times 10^{35}$ erg s$^{-1}$ (0.1% $L_{Edd}$) to $1.3 \times 10^{38}$ erg s$^{-1}$ (50% $L_{Edd}$). See Section 5.3.3 for details.
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Figure 5.9: Color coordinate representing the position along the atoll track, $S_a$, versus luminosity (in the same units as Fig. 5.7). The $S_a$ ranges corresponding to soft, hard and intermediate states are separated by the double dashed lines and indicated on the right-hand axis. Luminosity and $S_a$ are in general anticorrelated in soft and hard states, but not in intermediate states.

5.5 Summary and conclusions

We have performed a systematic analysis of the luminosity, variability and spectral properties of a large sample of atoll sources in order to study how accretion flows around weakly magnetic neutron stars relate to the different observed accretion states, and how these relate to luminosity. In the following we summarize the main results and conclusions that arise from this work.

- State transitions and intermediate states are one and the same state: they share the same spectral and timing properties as well as luminosity range. The only difference is how populated these states are: some persistent sources have spent most of the last decade in the intermediate
state, whereas transient sources (which have the longest orbital periods; Table A.1) are predominantly in hard or soft states and show rapid transitions between them. We conclude that the inner accretion flow is not necessarily unstable during state transitions. It is most likely an “external” parameter (perhaps disk size) that determines how long a source stays in the intermediate state.

- The luminosity during a given state transition in a given transient is approximately constant, yet the intermediate state luminosity spans more than one order of magnitude when considering the full sample.

- Hard states are not necessarily low: they can show luminosities as high as 15% $L_{\text{Edd}}$. Similarly, high luminosities are not a defining property of soft states: they can feature luminosities down to 1% $L_{\text{Edd}}$.

- Variability frequencies are anticorrelated with spectral hardness in each of the studied sources. Our results show this frequency-hardness anti-correlation for the upper kHz QPO and break frequencies present in the power spectra of atoll sources. Similar results have been found in BH systems, suggesting that this is a common property of accretion flows around compact objects.

- By considering a fixed timing state we have discovered a correlation between luminosity and spectral hardness across different sources, which therefore links luminosity with spectral and timing properties. This constitutes a new ingredient for accretion flow models, which so far face trouble in explaining the very different luminosities at which similar accretion states take place. We argue that strongly beamed X-ray emission and different viewing angles could explain the difference in luminosity for a given value of the variability frequencies. We also propose a new explanation for the luminosity-frequency decoupling that involves different inner disk temperatures for a fixed inner disk radius.

**Acknowledgments:**
The research presented here used NASA’s *HEASARC* and observations obtained thanks to a number of *RXTE* proposers. It is a pleasure to thank P. Casella, J. P. Lasota, D. Maitra, M. Méndez, S. Migliari, R. Rothschild, S. Suchy, P. Uttley and R. Wijnands for uncountable and useful discussions during several stages of this work.
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Figure 5.10: Break (top) and upper kHz QPO (bottom) frequencies versus the fractional rms amplitude of the variability in the low (left) and high (right) frequency bands. Note the $\nu_u$-$r_L$ and $\nu_u$-$r_H$ positive correlations in 1820 on top of the obvious general anticorrelation between frequencies and rms.

Figure 5.11: Luminosity-hardness correlation across sources for a given timing state (Secs. 5.3.3 and 5.4.3). Left: Observations with upper kHz QPO frequency near 1000 Hz and 500 Hz. Right: Observations with break frequency near 30 Hz and 1 Hz.
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Figure 5.12: 2002 and 2005 outbursts of 4U 1608 showing the time evolution of the luminosity, colors, variability frequencies and 1–100 Hz rms variability. Hardness- and break frequency-luminosity diagrams are also shown in the upper panels. Arrows indicate the state transitions (Sec. 5.3.4).

Figure 5.13: 1999 and 2000 outbursts of Aql X-1 showing the time evolution of the luminosity, colors, variability frequencies and 1–100 Hz rms variability. Hardness- and break frequency-luminosity diagrams are also shown in the upper panels. Arrows indicate the state transitions (Sec. 5.3.4).
Figure 5.14: Summary of the atoll tracks in the color-color (CD; left) and hardness-luminosity (HLD; right) diagrams (SC: soft color; HC: hard color; L: 2–200 keV luminosity; see Section 5.2.2 for details). Soft, intermediate and hard states are shown in black, dark grey and light grey, respectively. The ranges spanned by the break frequency and the upper kHz QPO frequency in different states of individual sources are displayed on the CD (left). The luminosity ranges spanned by each state in the full sample of sources are displayed on the HLD (right). Both the upper kHz QPO and break frequencies are anticorrelated with the spectral hardness in each source (see Sec. 5.3.1 and Fig. 5.4). For a fixed value of these frequencies, luminosity and hardness are correlated across different sources (Sec. 5.3.3 and Fig. 5.11).