Accretion states and thermonuclear bursts in neutron star X-ray binaries
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Neutron stars in low-mass X-ray binaries accrete mass at very different rates, from less than 1% of the Eddington rate in the weakest atoll sources to near or above the Eddington rate in the so-called Z sources. We present a study of the luminosity, spectral and timing properties of two Z sources, GX 17+2 and GX 340+0, across their different states. We also perform a detailed comparison between these properties and those of a large sample of atoll sources. We find intrinsic differences in the transition between the normal and flaring branches in both Z sources. Namely, GX 17+2 shows stronger variability in that state than GX 340+0. On the other hand, on the horizontal branch GX 340+0 is more strongly variable than GX 17+2. Atoll sources in hard states can show harder spectra and stronger variability than Z sources, yet the ranges in spectral hardness and fractional rms variability amplitude largely overlap in the two types of source. We finally point out that the normal-to-flaring branch vertex shows a similar luminosity in GX 17+2 and GX 340+0, which argues against a systematic difference in mass accretion rate between these two types of Z source.
Figure 6.1: Top panel: Z coordinate, $S_Z$, versus 2-50 keV luminosity for GX 17+2 (left) and GX 340+0 (right). The color scale shows the 1-100 Hz fractional rms amplitude of the variability. The $S_Z$ ranges that correspond to different states are indicated with horizontal dashed lines. Note the $S_Z$-luminosity correlations on the FB and HB and the $S_Z$-luminosity anticorrelation on the NB. Each point corresponds to 256 s of data. Middle panel: Hardness-luminosity diagrams of GX 17+2 (left) and GX 340+0 (right), in 256 s steps. The different branches or states are indicated and the color scale shows the fractional rms amplitude of the 1–100 Hz variability. Bottom panel: Hardness-luminosity diagrams, where grey points show all the 256 s segments analyzed in this work. Those segments where the HBO fundamental was detected are overplotted with green filled points. Red points and blue open circles show the observations where we detect the NBO/FBO and upper kHz QPO, respectively.
6.1 Introduction

Accretion onto compact objects is one of the most efficient ways of converting rest-mass energy into radiation and gives rise to one of the most powerful classes of object in our Galaxy, the low-mass X-ray binaries (LMXBs). These are neutron stars (NSs) or black holes that accrete matter from a low-mass star through an accretion disk. Of the two main types of NS-LMXB (Hasinger & van der Klis 1989), Z sources feature higher (near-Eddington) X-ray luminosities than atoll sources. Z sources show, on average, softer spectra than atolls, and conversely atoll sources can show stronger variability. The X-ray spectral and variability properties are correlated in both source types, and define different accretion (spectral & timing) states. In Z sources these different accretion states result in three distinct paths in color-color and hardness-intensity diagrams: the horizontal branch (HB), the normal branch (NB) and the flaring branch (FB). Together, these branches show two characteristic shapes (Fig. 6.1): a “Z” in the Cyg-like sources (after Cyg X-2) and a “ν” in the Sco-like sources (after Sco X-1).

Z sources show a number of variability components: kHz quasi-periodic oscillations (kHz QPOs; mostly observed in the HB and upper NB), horizontal branch oscillations (HBOs; seen in the HB and NB and often accompanied by harmonics), normal branch and flaring branch oscillations (NBOs/FBOs; seen in the NB and FB, at frequencies lower than the HBO when both are present), low-frequency noise (LFN; peaked or broad and present on the HB and NB) and very-low-frequency noise (VLFN; red noise, strongest on the FB). See van der Klis (2006) for a review. Even though the six well-identified Z sources have been actively accreting since their discovery, a remarkable exception was found recently by Homan et al. (2007): a transient source that was in outburst for about one year and a half and showed virtually all canonical Z source behavior at the highest luminosities.

Revnivtsev & Gilfanov (2006) describe the X-ray spectrum of Z sources as the sum of accretion disk and boundary layer emission, whereas Church et al. (2006) propose a model consisting of blackbody radiation from the NS surface together with Comptonized emission from an accretion disk corona. Earlier models were proposed by Psaltis et al. (1995) and Done et al. (2002), specifically for the X-ray emission of Z sources. The frequency of the HBO is known to correlate with the position along the HB (e.g. Jonker et al. 2000). By studying the X-ray timing behavior of the Sco-like Z source GX 17+2, Homan et al. (2002) found that the frequencies of the HBO and upper kHz QPO correlate below $\nu_u \approx 1000$ Hz and anticorrelate above that value.

Lack of systematic study has prevented a complete understanding of the pre-
cise relation between luminosity and accretion states in LMXBs. By studying this relation in atoll sources, Linares & van der Klis (2009) showed that luminosity and hardness are positively correlated among different sources when they feature the same variability frequencies, and proposed an explanation that involves different inner disk temperatures across sources for the same inner disk radius. This luminosity-hardness correlation contradicts the widespread idea that harder sources are less luminous. In the present work we take the following step towards a complete understanding of the luminosity-state relation by extending our study to two Z sources, which accrete near the Eddington limit. We analyze in an homogeneous way the full RXTE dataset of GX 17+2 and GX 340+0, each representing one of the two Z sub-classes described above and each covering all three Z branches well), and measure their luminosity, spectral and timing properties. We then compare the results found for Z and atoll sources.

### 6.2 Observations and Data Analysis

We included in our analysis all pointed Rossi X-ray Timing Explorer (RXTE) observations of the two well sampled Z sources GX 17+2 and GX 340+0 that were publicly available in March 2009. These were taken over nearly twelve years. The total amount of data analyzed herein, after the filters explained below were applied, was ~620 ksec and ~470 ksec for GX 17+2 and GX 340+0, respectively.

We extracted background and deadtime corrected count rate (intensity) from Standard 2 data (16 s time resolution) of the Proportional Counter Array (PCA) in four energy bands covering the 2–16 keV range. We filtered out type I X-ray bursts and instrumental spikes from the resulting lightcurves, and following the recommended screening criteria we excluded data taken when the sources were close to the Earth (<10°) or off-axis (>0.01°). The background was estimated with pcabackest (V. 3.6) and the bright source model. We calculated colors (hardness ratios) in order to measure the slope and evolution of the energy spectrum in a model independent way. The soft (SC) and hard (HC) colors were defined as the ratios of count rates in the following bands (in keVs): SC=[3.5–6]/[2–3.5]; HC=[9.7–16]/[6–9.7]. We then normalized colors and intensity to the Crab values closest in time (and within the same gain epoch, van Straaten et al. 2003; Kuulkers et al. 1994). Finally, we averaged the colors and intensity in each of the 256 s data segments used for the timing analysis (see below). With the resulting colors and intensity we constructed color-color (CD) and hardness-intensity diagrams. Following previous work (Hertz et al. 1992; Kuulkers et al. 1994; Homan et al. 2002), we measured the
position on the Z track by projecting each data point onto a spline subtended along the track. This “Z-coordinate”, $S_Z$, gives a one-dimensional measure of the spectral state, that we define in accordance to previous work as $S_Z \equiv 1$ in the HB-NB vertex and $S_Z \equiv 2$ in the NB-FB vertex.

We selected Event and Single Bit modes with time resolution of 250 µs or better and covering all energy channels below~100 (i.e. between 2 and ~40 keV, except for data of GX 17+2 from proposals 20053-03 and 92042-01, in which this energy range was not available and we used instead the full PCA range). We performed Fourier transforms on 256 s data segments, with a uniform time resolution of 250 µs and without previous background or deadtime corrections. The Poissonian noise was subtracted from the resulting power spectra following Zhang et al. (1995) and Klein-Wolt (2004), and the powers were rms-normalized (van der Klis 1995b) using the average observation-averaged background rate in the corresponding energy band.

We calculated the fractional rms amplitude of the variability in each power spectrum, in two frequency bands: 0.01–1 Hz ($r_L$), and 1–100 Hz ($r_H$). We searched for kHz QPOs in the 300–1300 Hz range of the average power spectrum of all observations (which typically last a few hours) and fitted a single or double Lorentzian model to those observations that showed one or two kHz QPOs in order to measure the characteristic frequency $\nu$ of the upper ($\nu_u$) and lower ($\nu_l$) kHz QPO. We attempted to fit the kHz QPOs in shorter (256 s) steps, but given their moderate amplitude, on these timescales the kHz QPOs were mostly ill-constrained or undetected. We searched for HBOs and LFN in the observations of the HB and fitted them with a model consisting of a power law (to fit the VLFN, although it is weak in those parts of the CD), a broad (zero-centered) Lorentzian to fit the LFN and one Lorentzian that fitted the HBO. The characteristic frequency of the zero-centered Lorentzian gives a measure of the cutoff or break frequency of the LFN ($\nu_{LFN}$). After an initial search with all parameters left free, we fixed the quality factor of the HBO to 4, as this gave a good approximation to the coherence of the feature and improved the overall stability of the fits. Whenever the HBO was detected in an averaged observation, we used the best-fit parameter values as initial guess to fit all individual (256s long) power spectra within the same observation, leaving all parameters free. Even though the LFN, being broader and weaker than the HBO, is not well constrained in the resulting “time-resolved” power spectra, this technique allowed us to measure the frequency of the HBO ($\nu_{HBO}$).

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1We use the “numax” representation (Belloni et al. 2002), where if $\nu_0$ is the Lorentzian’s centroid frequency and $\Delta$ its HWHM (half width at half maximum), $\nu_{max} = \sqrt{\nu_0^2 + \Delta^2}$ gives the characteristic frequency of the feature (near the centroid if it is narrow and near the half-width if it is wide). The quality factor $Q = \nu_0 / 2\Delta$ is used as a measure of the coherence of the variability feature.
on timescales much shorter than the typical duration of an observation ($\nu_{\text{HBO}}$ is known to vary on timescales of minutes, e.g. Jonker et al. 2000). We used in this search the frequency range below 50 Hz in order to characterize the timing state of the sources in the HB (the HBO has been identified at slightly higher frequencies in the upper NB; e.g. Homan et al. 2002, but it is weaker in that range and it therefore becomes ill-constrained in the time-resolved fits). We searched the 0.01–20 Hz power spectra of all observations in the FB and NB for NBOs/FBOs, and when these components were present we fitted a power law plus Lorentzian model and obtained thereby the characteristic frequency of the NBO/FBO ($\nu_{\text{FBO}}$). In order to compare the Z source timing properties with those of atoll sources, we study the evolution of $r_L$, $h$ and $\nu_u$ (which were also measured in atoll sources, Linares & van der Klis 2009) along the three branches of the Z track. We also look in detail at the behavior of the HBO and LFN, which can be directly compared to the flat-topped noise of atoll sources.

Hard X-ray components from Z sources have been detected in the hardest part of the HB, but contrary to atoll sources they carry less than ~8% of the 0.1-200 keV flux (Di Salvo et al. 2000; di Salvo et al. 2004). We extracted and inspected High Energy X-ray Timing Experiment (HEXTE) background and deadtime corrected 20-200 keV spectra of both sources and detected no significant emission above 50 keV (with one single exception in GX 17+2; see Migliari et al. 2007). We therefore exclude the HEXTE data from the remaining spectral analysis. We extracted one PCU2 spectrum for each of the 256 s intervals used for the timing analysis (see above), and corrected for dead time using the average rates during the observation. We grouped the energy channels of the resulting spectra to have a minimum of 20 counts per energy bin, created one response matrix per observation with pcarsp (V. 10.1) and subtracted the background spectrum accumulated in each 256 s interval. We finally fitted the energy spectra with XSPEC (Arnaud 1996, Version 11.3.2), using an absorbed disk-blackbody plus broken power law model. In the FB of GX 340+0 the broken power law component was not required so we used instead a simple absorbed disk-blackbody model. We note that we perform these spectral fits with the goal of estimating the luminosity, and not to study in detail the spectral decomposition of the two studied sources (see Psaltis et al. 1995; Done et al. 2002; Church et al. 2006; Revnivtsev & Gilfanov 2006, for a different approach). The column density was held fixed during the fits at the values reported by Christian & Swank (1997) from 0.5–20 keV spectral fits to EXOSAT spectra (1.9×$10^{22}$ cm$^{-2}$ and 6.0×$10^{22}$ cm$^{-2}$ for GX 17+2 and GX 340+0, respectively). We finally obtained the luminosity from the 2–50 keV unabsorbed flux, using the distance estimates obtained by Galloway
et al. (2008b) for GX 17+2 (9.8±0.4 kpc; from analysis of photospheric radius expansion type-I X-ray bursts) and by Christian & Swank (1997) for GX 340+0 (11±3 kpc; from measurements of the absorbing column density as no type-I bursts have been observed from this source thus far). The errors on these distances translate into a ~50% systematic uncertainty on the luminosity of GX 340+0, and a ~10% systematic uncertainty on the luminosity of GX 17+2.

Figure 6.2: Observation-averaged measurements of the fractional rms amplitude in the 1–100 Hz frequency range versus $S_Z$. Along the HB, GX 340+0 is more strongly variable than GX 17+2, although the variability amplitude decays until both sources reach a similar value on the NB. Note the increase in variability amplitude in the NB-FB vertex of GX 17+2.

6.3 Results

We show in Figure 6.1 (lowest two panels) the location in the hardness-luminosity diagram of those power spectra where we detect upper kHz QPOs (blue circles), HBOs (green points) and NBO/FBOs (red points). The HBO and upper kHz QPO are present throughout the HB. We detect upper kHz QPOs in 19 and 4 observations of GX 17+2 and GX 340+0, respectively. In some of these observations (ten in GX 17+2 and one in GX 340+0) only
one kHz QPO was detected, which therefore remained unidentified at first instance. However, like in the case of atoll sources (Linares & van der Klis 2009), upper and lower kHz QPOs trace clearly distinct tracks in hardness-frequency diagrams (where hardness refers to HC), which allowed us to identify them in all cases. The middle panels of Figure 6.1 show the changes in the strength of the 1–100 Hz variability (in the fractional rms amplitude, $r_H$) as the sources move along the Z track. In the upper panels we plot the Z coordinate, $S_Z$ versus the 2-50 keV luminosity, showing that these two are correlated on the FB and HB but anticorrelated on the NB (Fig. 6.1, top). Looking at the middle and upper panels a systematic behavior is evident in both the HB and the FB, where $r_H$ decreases (drastically on the HB) when the sources move along the Z track in the sense of increasing $S_Z$. We note that, contrary to $r_H$, the 0.01–1 Hz variability amplitude ($r_L$) increases in the FB of GX 17+2 with increasing $S_Z$. This is because the VLFN, which dominates the variability below $\sim$1 Hz, becomes stronger there (e.g. Homan et al. 2002).

The evolution of $r_H$ along the Z track of both Z sources is shown in Figure 6.2. On the HB and upper NB ($S_Z \lesssim 1.5$), GX 340+0 features always higher $r_H$ (stronger variability) than GX 17+2. As noted above, $r_H$ decreases drastically along the HB with increasing $S_Z$ in both sources, starting from different values ($\sim$13% at $S_Z \approx 0.4$ in GX 340+0; $\sim$9% at $S_Z \approx -0.2$ in GX 17+2). At the HB-NB vertex ($S_Z \approx 1$) a sudden transition occurs in the two sources, and the variability amplitude levels off between 2 and 4%. We also find that, in GX 17+2, $r_H$ is higher on the NB-FB vertex ($S_Z \approx 2$) than in its immediate surroundings, reaching values of more than 5% (Fig. 6.1, middle left panel, and Fig. 6.2). This increase in variability amplitude is due to the appearance of a strong NBO/FBO component (see Homan et al. 2002, and Fig. 6.1). Surprisingly, this is not the case in GX 340+0, which shows instead its strongest NBOs/FBOs on the NB, and a FB much shorter than that of GX 17+2 (Fig. 6.1).

In Figure 6.3 we show the time-resolved measurements (256 s steps) of $\nu_{HBO}$, versus both HC (left panels) and luminosity (right panels). Also shown are the $\nu_{HBO}$ values obtained from observation-averaged power spectra (black empty circles). The frequencies obtained with these two methods are consistent. The short timescale measurements show some scatter and “sub-structure”, i.e., tracks not visible in the observation-averaged measurements, which could be due to intrinsic deviations from the main track combined with observational windowing or to small systematic errors in the hardness or luminosity measurements at different epochs.

The color-luminosity diagrams of atoll and Z sources are shown in Figure 6.4, which displays both soft (SC) and hard (HC) colors versus the 2–50 keV
Figure 6.3: Grey filled points show the time-resolved (256 s) measurements of the HBO frequency ($\nu_{HBO}$) versus hardness (left) and luminosity (right). The observation-averaged frequencies are shown with black circles. $\nu_{HBO}$ and hardness are anticorrelated in both sources, as is the case for atoll sources. $\nu_{HBO}$ and luminosity are correlated in GX 340+0 but not in GX 17+2, which shows a more vertical HB in the hardness-luminosity diagram (hence a narrower luminosity range on that branch; see Fig. 6.1).

luminosity. The narrow range in luminosities of the Z sources is readily visible, between 0.8 and 2 times the Eddington luminosity ($L_{Edd}$; we use throughout this work a value of $2.5 \times 10^{38}$ erg s$^{-1}$). This is in contrast with the much wider range (more than two orders of magnitude) in luminosity spanned by atoll sources. Z sources span a range of HC similar to that of atoll sources in soft and intermediate states (Linares & van der Klis 2009), with the exception of the lower NB and the FB of GX 340+0, which are softer than soft states of atoll sources (HC between 0.45 and 0.3, in Crab units; see Fig. 6.4). GX 340+0 features the highest values of the SC, reaching values of $\sim 2.1$ times that of Crab (which correspond to the HB-NB vertex). SC and luminosity are correlated in both Z sources, as is the case for soft and hard states of atoll sources.

In Figure 6.5 we plot the fractional rms amplitude of the variability in the
high and low frequency bands ($r_H$ and $r_L$, respectively; see Sec. 6.2) versus the luminosity and spectral hardness. In the left panels it is readily visible that the hardness and variability amplitudes occupy overlapping ranges in atoll and Z sources. The lower NB and FB of GX 340+0, however, stand out in the rms-HC diagrams (due to their afore mentioned softer spectra) and show opposite trends in the $r_H$-HC and $r_L$-HC relations. Namely, in those states the HC is correlated with $r_H$ but anticorrelated with $r_L$. Atoll sources in hard states feature substantially harder spectra and stronger variability. In the right panels of Figure 6.5 one can see that the fractional rms of Z sources shows the same range as intermediate and soft states of atoll sources (i.e., 0.5-15%), even though their luminosities can differ by more than one order of magnitude.

The characteristic frequencies of the HBO, LFN and upper kHz QPO are plotted versus the spectral hardness and luminosity in Figure 6.6. For a given HC, the frequencies of GX 17+2 are somewhat lower than those of GX 340+0 and in both studied sources all three frequencies are anticorrelated with the spectral hardness (Fig. 6.6, top right). We show for comparison the values of the break and upper kHz QPO frequencies measured in atoll sources (Linares & van der Klis 2009). The $\nu_{\nu}$-HC track of GX 17+2 lies between those of the atoll sources 4U 0614+09 and 4U 1636–536, and the $\nu_{\nu}$-HC track of GX 340+0 is below that of 4U 0614+09. Now looking at the bottom right panel of Figure 6.6, the path subtended by the break frequency of atoll sources in the frequency hardness plane lies between those of $\nu_{HBO}$ and $\nu_{LFN}$ in the Z sources. As already noted by Ford et al. (2000), the same kHz QPO frequencies occur in Z sources, which accrete near the Eddington limit, and in atoll sources, at luminosities two orders of magnitude lower (Fig. 6.5, bottom left). A similar phenomenon is visible in the top left panel of Fig. 6.6: the LFN of Z sources and the flat top noise of atoll sources span the same break frequency range, whereas the luminosities at which these frequencies are observed differ by more than two orders of magnitude.

### 6.4 Discussion

Atoll sources show a broad range of spectral hardness and luminosity, as witnessed by Figure 6.4. For a fixed value of their variability frequencies, Linares & van der Klis (2009) showed that luminosity and spectral hardness are positively correlated across different sources. This can be explained with an inner disk temperature varying across sources for a given inner disk radius, which would make luminosities higher and increase the spectral hardness as the disk gets hotter. We find that Z sources do not follow this luminosity-hardness cor-
Figure 6.4: Hardness-luminosity planes, showing the sample of nine atoll sources studied by Linares & van der Klis (2009) (grey circles) and the two Z sources studied in this work: GX 17+2 (black squares) and GX 340+0 (grey triangles). Soft (upper panel) and hard (lower panel) colors are plotted versus luminosity. Each point corresponds to one observation. Note the narrow range in luminosities of the two Z sources compared to that of atolls. A general soft color-luminosity correlation is apparent in both types of source, with a relatively large scatter partly due to the different absorption towards the sources.

relation, as they are much more luminous than atoll sources (up to two orders of magnitude) but show the same, or even a lower, spectral hardness when comparing observations with the same variability frequencies (see Figure 6.6). If we take the common working hypothesis that characteristic variability frequencies are set by the inner disk radius, then it is clear that the scenario proposed to explain the luminosity-hardness correlation does not apply to Z sources. At near-Eddington luminosities radiation pressure may change the
Figure 6.5: Fractional rms amplitude of the variability in the high (1–100 Hz, bottom panels) and low (0.01–1 Hz, top panels) frequency ranges, versus the 6–16 keV spectral hardness (left panels) and 2–50 keV luminosity (right panels). GX 340+0 and GX 17+2 are compared to the atoll sources studied by Linares & van der Klis (2009).

disk structure and emergent spectrum (e.g. because the inner disk is puffed up; e.g. Frank et al. 2002), and that could yield a luminosity-hardness relation different from that proposed for the less luminous atoll sources by Linares & van der Klis (2009). Alternatively, the higher soft photon flux in Z sources could affect the radiative properties of the Comptonizing medium. Therefore, a comparison between their energy spectra must be made with care. Extending this luminosity-state study to the bright atoll sources can bridge the \( \sim 0.5–0.8 L_{\text{Edd}} \) luminosity gap between “classical” atoll sources and Z sources, and potentially give new insights in the accretion disk behavior at different luminosities.

The HB of Z sources shows clear similarities with intermediate states of atoll sources (van der Klis 2006, and references therein): broadband noise and kHz QPOs that increase in frequency as the 6–16 keV spectrum softens (HC decreases), variability amplitude that decays in both cases when HC decreases, and the same range of frequencies and HC. There are also a number
of interesting differences: \( S_Z \) and luminosity are strongly correlated along the HB of Z sources, whereas the luminosity-\( S_a \) relation is more erratic in atolls (Linares & van der Klis 2009). The luminosities of the HB are of course higher than those of atolls in intermediate states, whereas the variability amplitude spans a similar range. The HB shows typically higher values of the SC than atoll-intermediate states, which is most likely connected to the higher X-ray luminosity (SC and luminosity are positively correlated in both hard and soft states of atoll sources).

It is worth noting that, while we use distance estimates that make no assumption on the luminosity of the different states (Sec. 6.2), we find that the NB-FB vertex of both Z sources shows a similar luminosity of \( \sim 0.8 L_{Edd} \). This supports the earlier suggestion that some states of Z sources occur always at the same luminosity, but improvements on the distance estimates and analysis
of a larger sample of sources are needed to confirm this. Homan et al. (2007) suggested that Cyg-like Z-source behavior is associated with a higher mass accretion rate than Sco-like behavior, based on the evolution of the intensity of the NB-FB vertex in the transient Z source XTE J1701–407. Unless the distance to GX 340+0 is severely underestimated, the results presented here do not support that hypothesis, which requires a difference of a factor ~1.5 in the measured luminosities of the NB-FB vertex. The upper FB of GX 17+2 shows luminosities higher than those of GX 340+0, even when considering the distance uncertainties in both systems.