SOFT LAGS IN NEUTRON STAR kHz QUASI-PERIODIC OSCILLATIONS: EVIDENCE FOR REVERBERATION?

Didier Barret
Université de Toulouse, UPS-OMP, IRAP, F-31400 Toulouse, France; didier.barret@irap.omp.eu
CNRS, Institut de Recherche en Astrophysique et Planétologie, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France

Received 2013 February 27; accepted 2013 April 19; published 2013 May 17

ABSTRACT

High frequency soft reverberation lags have now been detected from stellar mass and supermassive black holes. Their interpretation involves reflection of a hard source of photons onto an accretion disk, producing a delayed reflected emission, with a time lag consistent with the light travel time between the irradiating source and the disk. Independently of the location of the clock, the kHz quasi-periodic oscillation (QPO) emission is thought to arise from the neutron star boundary layer. Here, we search for the signature of reverberation of the kHz QPO emission, by measuring the soft lags and the lag energy spectrum of the lower kHz QPOs from 4U1608-522. Soft lags, ranging from \( \sim 15 \) to \( \sim 40 \) \( \mu s \), between the 3–8 keV and 8–30 keV modulated emissions are detected between 565 and 890 Hz. The soft lags are not constant with frequency and show a smooth decrease between 680 Hz and 890 Hz. The broad band X-ray spectrum is modeled as the sum of a disk and a thermal Comptonized component, plus a broad iron line, expected from reflection. The spectral parameters follow a smooth relationship with the QPO frequency, in particular the fitted inner disk radius decreases steadily with frequency. Both the bump around the iron line in the lag energy spectrum and the consistency between the lag changes and the inferred changes of the inner disk radius, from either spectral fitting or the QPO frequency, suggest that the soft lags may indeed involve reverberation of the hard pulsating QPO source on the disk.

Key words: accretion, accretion disks – galaxies: active – stars: neutron – X-rays: binaries – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Kilohertz quasi-periodic brightness oscillations (kHz QPOs at frequency above \( \sim 300 \) Hz) have been observed with the Rossi X-ray Timing Explorer (RXTE; Bradt et al. 1993) from about 30 neutron star low-mass X-ray binary systems (see van der Klis 2000 for a review). Those signals have triggered much excitement because their frequencies match the orbital frequencies of matter orbiting very close to the neutron star, and hence may be related to strong field general relativity effects. Most of the analysis performed so far on kHz QPOs has focused on their frequency, rms amplitude, quality factor, relation to continuum spectral parameters, and variability at lower frequency, but very little is known about their energy-related to continuum spectral parameters, and variability at lower frequency, but very little is known about their energy-

variations. Independently of the mechanism setting up the frequency, it is generally agreed that the QPO modulated emission arises from the boundary layer between the neutron star surface and the accretion disk (Gilfanov et al. 2003; Abramowicz et al. 2007). The strongest evidence comes from Fourier frequency resolved spectroscopy showing that the QPO energy spectrum resembles the energy spectrum of the boundary layer. The QPO spectrum is significantly harder than the average continuum emission, and certainly the disk emission, also detected in the energy spectrum (Gilfanov et al. 2003).

In this paper, we investigate whether the soft lags detected in kHz QPOs can be interpreted in the framework of the reverberation lags recently detected in AGNs and stellar mass black holes. For this purpose, we measure the lags and the spectral parameters of the continuum emission as a function of the lower kHz QPO frequency. We limit the present analysis to the highest quality RXTE data of 4U1608-522, showing strong kHz QPOs between 565 and 890 Hz, as to maximize the sensitivity to lag detections (basically the same data used in Barret et al. 2005). We note that our work extends on de Avellar et al. (2013), who did not use data above 800 Hz for 4U1608-522 and did not combine the lag measurements with the spectral analysis of the continuum emission. In the next section, we describe the technique used and the main results.

...
To measure the time lags, we have first extracted events in two adjacent energy bands: 3–8 keV and 8–30 keV, using high time resolution science event data. The cross spectrum of the soft and hard band time series gives the phase difference between the two energy bands (Nowak et al. 1999). This phase difference is converted back into a frequency-dependent time lag: \( \tau (\nu) = \Delta \phi / 2 \pi \nu \). In this paper, a positive lag means that the soft band lags behind the hard band.¹ We have computed power density and cross spectra over segments of a fixed duration \( T \) and have averaged \( M \) of those to produce an individual cross spectrum (CP). The lower kHz QPO frequency (\( \nu_{l,i} \)) can vary by tens of Hz over the typical duration of the observation (~3000 s). The analysis presented below applies only to the lower kHz QPO of 4U1608-522, and is not suited for the upper kHz QPO, which is much harder to detect (mostly because of its larger width). As to maximize the lag detection sensitivity, we bin each individual CP over adjacent frequencies, sampling the QPO profile. This implies knowing the QPO centroid frequency and its width (\( \bar{\nu}_{l,i} \), FWHM) in each CP. In order to do this, we first reconstructed the time evolution of the QPO frequency, extracting Fourier Power Density Spectrum (PDS) using events in a 3–30 keV reference band. The reference energy band chosen maximizes the signal-to-noise ratio of the QPO detection, and therefore enables a better determination of the QPO frequency than in the soft and hard bands. \( \bar{\nu}_{l,i} \) was obtained with a maximum likelihood technique (Barret & Vaughan 2012). We also shifted-and-added all the PDS to the mean QPO frequency to obtain the mean QPO width (\( \bar{\nu} \)) over contiguous segments of data. Here we have assumed \( \bar{\nu}_{l,i} = \bar{\nu} \) and averaged the CP over a frequency bandwidth of twice \( \bar{\nu} \). As a final product of the analysis, for each observation, we have frequency-dependent time lags integrated over segments of \( M \times T \) second duration and frequency bandwidth \( 2\bar{\nu} \). Hereafter, we have assumed \( T = 4 \) s, which provides adequate frequency resolution to sample to the QPO profile, whose width varies from ~3.5 to ~10 Hz in the data considered here.

In the second segment of the 1996 March 3 observation (ObsID 10072-05-01-00), the lower kHz QPO can be significantly detected in the soft and hard X-ray bands on timescales as short as 32 s, as a combination of a large source count rate (the five detector units of the proportional counter array were operating) and high coherence. In Figure 1, we show the soft lags between the 3–8 keV and 8–30 keV bands, measured on 32 and 128 s, respectively (i.e., \( M = 8 \) and 32). As can be seen, increasing \( M \) yields fully consistent results, while the scatter on the lags and associated error bars have been reduced. Note that the lag is consistent with being constant in both cases, around a mean value of ~23 \( \mu s \). Such a value is fully consistent with previous measurements (Vaughan et al. 1998).

### 2.1. Frequency-dependent Time Lags

Across its full frequency span, the QPO cannot be detected on timescale as short as 32 s in the two adjacent bands. For this reason, we have adopted 128 s integration time for the lag measurements (i.e., averaging \( M = 32 \) intervals of 4 s). In Table 1 we list the observations considered in this paper, together with the mean lag measured. We split the data in ObsIDs first, but also within an ObsIDs in the contiguous segments of data provided by the science event files. In deriving the mean soft lag, we considered only segments of 128 s, in which the QPO is detected above ~4.5\( \sigma \) (excess power) in both the soft and hard energy bands (this corresponds to a cut of \( R \geq 1.5 \), where \( R \) is the ratio between the Lorentzian normalization and its 1\( \sigma \) error; see Boutelier et al. 2010 for a discussion). For a given integration time, the QPO significance depends on the source count rate and frequency; the latter parameter defining the QPO rms amplitude and width (Barret et al. 2005). In the data set considered, the significance of the QPO goes down at both ends of the frequency range, more dramatically at the lower end where the source count rate was the lowest. Nevertheless, adopting the cuts above, enables to detect the lags between ~565 and ~890 Hz. In Figure 2, we show the soft lags measured on 128 s as a function of the QPO frequency. The lags have also been binned into ten adjacent frequency bins. A clear trend is now obvious in the data, in particular above 680 Hz where the soft lags smoothly decrease with frequency.

### 2.2. The Energy Spectrum of the Lags

We now examine how the lags vary with energy. In each energy bin, using the same procedure as described above, the lag is computed between the light curve in that bin and the light curve in the reference energy band (3–30 keV), where the signal to noise ratio of the QPO detection is highest. The light curve in the energy bin considered is subtracted from the reference light curve to ensure that Poisson noise remains uncorrelated (Uttley et al. 2011). For each segment of 128 s, and hence for each QPO frequency \( \nu_i \), for each energy bin we thus have a measurement of the lag, as the average of \( M = 32 \) values. A mean lag-energy spectrum can be computed by averaging all the measurements weighted by their errors, within a continuous science event file duration, and even within one ObsID, provided that the channel energy boundaries do not change. Two examples of such lag spectra are shown in Figure 3 for the first twoObsIDs which provide better statistics (10072-05-01-00 and 30062-02-01-000). Note that unfortunately the data were not recorded in the same spectral mode.
in the two ObsIDs: 64, 32 channels. Although of limited significance, for the first ObsID where the source count rate is highest, it is interesting to note the lag spectrum is fairly steep below 4 keV, and seems to flatten around 5–8 keV, where the weak and broad Iron line is significantly present in the energy spectrum (see below) before steepening again. There is also a dip in the lag spectrum just around 6.4 keV. This could be due to the presence of a constant and narrow iron line component (e.g., the core of the broad line), produced at larger distances from the neutron star or over a wider range of radii than its red wing. The same features are, however, not so clear in the other segment of data shown in Figure 3 (right panel), although the data were recorded with a poorer spectral resolution, which could easily hide the structure seen at higher spectral resolution.

2.3. Time-averaged Continuum Emission Spectrum

In order to place the results described above into context, it is worth looking at the time-averaged energy spectrum to see how it changes with respect to the QPO frequency. One of the most extensive spectral analysis of the RXTE data, presented in Gierliński & Done (2002), sampled the full set of spectral states of the source (it did not include any timing information, though). When grouping data based on spectral colors (as to improve the statistics), they showed that across the Z-shaped color-color diagram all X-ray spectra could be represented as the sum of a disk blackbody component plus a Comptonized component and a weak reflection component from an ionized disk. Both the reflection and its self consistently evaluated iron line emission were statistically detected in all the spectra. In this paper, we have extracted Standard 2 spectra for all the time intervals of Table 1. We combined the data from all Proportional Counter Units and used the latest calibration data available in heasoft 6.12, adding a systematic uncertainly of 0.25% to the data. We froze the column density to $1.5 \times 10^{22}$ cm$^{-2}$ (Penninx et al. 1989). Although there is more than one possible decomposition of the X-ray spectrum of 4U1608-522, (e.g., Lin et al. 2007; Takahashi et al. 2011), we assumed the widely used spectral model of Gierliński & Done (2002; see also, e.g., Barret et al. 2000; Barret 2001; Di Salvo & Stella 2002; Tarana et al. 2008; Cackett et al. 2010 for a discussion of models). However, with the reduced statistical quality of our data compared to Gierliński & Done (2002), we were unable to obtain stable fits when adding the self-evaluated reflection of the Comptonized emission (this is largely a consequence of having two curvy components and a broad iron line profile within the relatively limited bandpass.
of the Proportional Counter Array; PCA). We also used the Comptonization model (Titarchuk 1994) instead of the nthcomp model (Zycki et al. 1999). We checked, however, that both models provide consistent fits. The addition of a diskline component improved the fit significantly in all segments of data, as previously found (Gilfanov et al. 2003; Gierliński & Done 2002). Unfortunately, the data do not allow us to constrain the inner disk radius of the diskline model, which we froze to 10R_g (for a disk inclination of 45°). Different values (e.g., 6R_g) would fit the data as well. The normalization (N_{DBB}) of the diskbb component was converted into an inner disk radius (R_in), following Gierliński & Done (2002):

\[
R_{in} = 0.61 N_{DBB}^{1/2} \left( \frac{2.7}{\eta} \right) \left( \frac{D}{3.6 \text{ kpc}} \right) \left( \frac{f_{col}}{1.8} \right) \left( \frac{0.5}{\cos i} \right)^{1/2} \text{ km},
\]

where D is the source distance, i is the disk inclination angle, f_{col} is the ratio of the color to effective temperature (Shimura & Takahara 1995), and \eta is the correction factor for the inner torque-free boundary condition (\eta = 2.7 for R_{in} = 6R_g) (Gierliński et al. 1999).

The best-fit spectral parameters are listed in Table 2 and plotted in Figure 4 against the lower kHz QPO frequency. As can be seen, all spectral parameters show a smooth behavior with frequency, suggesting that our spectral decomposition is robust. From Table 2, the significance of the line can be inferred from looking at the \chi^2 with and without the line. In our observations, the \Delta \chi^2 varies between ~15 up to ~60 for 2 additional degrees of freedom (and a total of degrees of freedom around 40), making the diskline component highly significant.

3. SUMMARY OF THE RESULTS

As advocated, for instance, by Uttley et al. (2011), frequency and energy-dependent time lags give additional information compared to time average energy and power density spectra, providing new and independent constraints on models for the emission mechanisms and the location at which they take place in the system. Our main results can be summarized as follows.

1. The soft lags between the 3–8 and 8–30 keV QPO photons vary with frequency, dropping at both end of the frequency range investigated (from 565 to 890 Hz). In particular, the lags decrease smoothly from about 40 \mu s to 15 \mu s, while the frequency varies from 680 Hz to 890 Hz. Our results are consistent with the values reported by de Avellar et al. (2013) below 800 Hz. The same curvy shape in the lag-frequency plot seems to be present in the data of 4U1636-536 (see the top panel of Figure 3 in de Avellar et al. 2013), suggesting that this may be a common feature of lags from lower kHz QPOs. It should be stressed, however, that this is not the intrinsic lags that is measured, due to the fact primary direct and delayed emissions are likely to contribute to the emission in both energy bands (the so-called lag dilution, e.g., Zoghbi & Fabian 2011). With this caveat in mind, it is still worth trying to relate the change in the lags with frequency with proxies of the disk location, such as the kHz QPO frequencies or the inner disk radii inferred from the spectral fitting of the continuum emission.

2. When the lower kHz QPO frequency varies from ~600 to ~900 Hz, the upper kHz QPO frequency varies from ~900 to ~1070 Hz. For a neutron star of 1.4–2.0 M_\odot, assuming that either frequency is an orbital frequency at the inner edge of the disk, this implies a change of the inner disk radius of ~6.2–7.0 km (or ~3.5R_g for a 1.4 M_\odot canonical neutron star) or 2.2–2.4 km, or equivalently a light travel time difference of 23–21 or 7–8 \mu s. These values are not very different from the span of the soft lags measured. Interestingly, considering only the decreasing part of the lag-frequency variation of Figure 1
Figure 4. Variation of the best-fit spectral parameters as a function of the lower kHz QPO frequency. Left (from top to bottom): the iron line equivalent width (in keV), the inner disk radius (in km), computed from Equation (1) (with canonical parameters), and the inner disk temperature (in keV). Right (from top to bottom): the optical depth, the electron temperature (in keV), and the seed photon temperature (in keV). Errors on the fitted parameters are given at the 1σ level. The error bar on the frequency is determined by the spread of QPO frequency over the continuous science event file. As can be seen, all best-fit spectral parameters, but the seed photon temperature (at the highest frequencies), show a smooth behavior with frequency.

(A color version of this figure is available in the online journal.)

Table 2
Best-fit Spectral Parameters Listed by ObsID and Event Files. Numbered n, within an ObsID

| ObsID   | n | $kT_{in}$ | $N_{DBB}$ | $kT_{هد}$ | $kT_e$ | $\tau$ | $E$   | $E_{EqW}$ | $L_x$ | $\chi^2$ |
|---------|---|----------|----------|----------|-------|-------|------|-----------|------|---------|
| 10072-05-01-00 | 1 | 0.68±0.07 | 1580.00±179.41 | 0.97±0.08 | 2.66±0.02 | 5.43±0.13 | 7.27±0.14 | 85.46±22.85 | 9.01±0.01 | 29.54 (44) | 58.74 (46) |
| 10072-05-01-00 | 2 | 0.73±0.07 | 1200.28±566.12 | 1.03±0.08 | 2.66±0.03 | 5.43±0.13 | 7.32±0.18 | 76.34±19.62 | 8.66±0.01 | 30.46 (44) | 53.11 (46) |
| 10072-05-01-00 | 3 | 0.71±0.08 | 1285.93±533.07 | 1.02±0.10 | 2.69±0.04 | 5.43±0.15 | 7.38±0.14 | 84.20±21.75 | 8.80±0.01 | 31.46 (44) | 46.62 (46) |
| 30062-02-01-000 | 0.70±0.04 | 1347.54±520.20 | 1.21±0.06 | 3.04±0.13 | 4.29±0.26 | 7.31±0.16 | 104.11±16.14 | 5.97±0.01 | 31.71 (37) | 61.23 (39) |
| 30062-02-01-000 | 0.73±0.04 | 1153.56±527.17 | 1.23±0.06 | 2.92±0.11 | 4.36±0.28 | 6.99±0.17 | 73.91±22.86 | 6.25±0.01 | 22.23 (37) | 38.50 (39) |

Notes: The parameters are the normalization of the disk blackbody component $kT_{in}$, the normalization $N_{DBB}$ of the disk blackbody component, the seed photon temperature $kT_{هد}$, the electron temperature $kT_e$, the optical depth of the Comptonization cloud $\tau$, the line energy of the disk blackbody component, its equivalent width, the 2–20 keV X-ray luminosity ($L_x$), the reduced $\chi^2$, with and without the diskline component. All errors are quoted at the 1σ level.

(between 680 and 900 Hz), the relative change of the lags by ~25 μs would be very comparable to the light travel time difference, associated with the relative change of the orbital radius inferred from the lower kHz QPO frequency change (~4.7 km or ~16 μs).

3. The spectral analysis of the continuum emission is consistent with a picture in which the disk gets closer to the neutron star, while the QPO frequency increases. The relative change of the inner disk radius inferred from fitting the disk component is again broadly consistent with the span...
of the lags measured. It is also consistent with the relative radius change assuming that the lower kHz QPO is an orbital frequency. The distance to the source is not very well known, ranging from 3.6 kpc (Nakamura et al. 1989), as used by Gierliński & Done (2002) in Equation (1), to a more recent value of 5.8+3.9 kpc ( Güver et al. 2010) from type I burst analysis (see also Suleimanov et al. 2011). Assuming, for instance, a distance of 4.4 kpc or 5.0 kpc in Equation (1), for a neutron star of 1.4 \( M_\odot \) or 2.0 \( M_\odot \), respectively, would provide a perfect match between the inferred inner disk radius variations from spectral fitting and the orbital radius changes assuming the lower kHz QPO is providing the orbital frequency (see Figure 5). On the other hand, this would not work if one assumed that the upper kHz QPO is providing an orbital frequency, because the change in radii associated with the change of frequency would be too limited (\( \sim 2 \) km as opposed to \( \sim 6\text{–}7 \) km). We note that the debate on which one of the two kHz QPO frequencies is an orbital frequency is not yet settled (Osherovich & Titarchuk 1999; Sanna et al. 2012), although most models predict that it is the upper QPO that provides an orbital frequency (e.g., Miller et al. 1998; van der Klis 2000). As discussed by Lamb & Miller (2001), it is also possible that the observed upper kHz QPO frequency is significantly lower than an orbital frequency, which may then span a wider frequency range and reach higher frequencies, so that the associated change of radius would be actually larger than observed. In absolute units (km), to make it consistent with the inner disk radius changes inferred from spectral fitting (Figure 4), one would need to tune some of the parameters in Equation (1) so that \( R_{\text{in}} \) drops by some 20% or so. This does not seem unfeasible given the uncertainties on the four parameters of Equation (1) (e.g., the source distance). As a side note, interpreting the drop of the quality factor of the lower kHz QPO, assumed to be orbital, as a signature of the innermost stable circular orbit would then be more natural

Figure 5. Same as Figure 4 but the inner disk radius inferred from spectral fitting is computed from Equation (1) for a distance of 5 kpc. The solid line represents the orbital radius derived from the orbital frequency (assumed to be provided by the lower kHz QPO) around a neutron star mass of 2 \( M_\odot \). The Spearman correlation coefficient is \( -0.69 \), corresponding to a null hypothesis probability of \( \sim 5 \times 10^{-4} \). The source distance is 5.8+3.9 kpc according to Güver et al. (2010).

(A color version of this figure is available in the online journal.)

4. Evidence for reflection comes from the presence of a broad ionized Iron line, significantly detected in all spectra, although weak, as pointed out by Gierliński & Done (2002). This is a necessary ingredient for the reverberation scenario. The presence of several components (from the disk, the Comptonization cloud and the reflection) in the PCA bandpass, together with its limited spectral resolution, do not enable us to extract the parameters of the reflection component (e.g., ionization state of the reflector). There is a trend for the equivalent width of the line to decrease with frequency that needs to be understood.

5. Understanding the lag energy spectrum would require detailed simulations of the transfer function of the irradiated disk, but looking at Figure 2, it is quite striking that they may already contain some very valuable information. This is particularly true in the highest count rate observations (recorded with the highest spectral resolution), which show both a soft excess and a broad bump around the broad iron line, present in the averaged energy X-ray spectrum. It is thus tempting to interpret the soft excess as thermal reprocessing of the hard X-ray photons onto the disk, and the bump around the broad iron line as the signature of delayed reflection. Further support for this interpretation comes from looking at the energy spectrum of the lag 2. The mean lag around 15 keV is \( -20 \mu s \) while the lag around 5–7 keV is about 10 \( \mu s \). The total lag of 30 \( \mu s \) corresponds to a distance of \( \sim 4R_g \) for a 1.4 \( M_\odot \) neutron star. For a neutron star of 10 km or 5\( R_g \) radius, this would put the inner disk radius at \( \sim 9R_g \); a value that would fit the data with the diskline model and that is typically inferred from fitting the broad iron line of neutron stars (Cackett et al. 2010). More detailed modeling is still required to test the reverberation scenario.

4. CONCLUSIONS

To conclude, although alternative explanations for the soft lags have been proposed, for instance, as being due to an intrinsic spectral softening of the emission along the QPO cycle (Kaaret et al. 1999), or due to temperature oscillations in the corona driving with some delays the temperature oscillations of the soft photon source (Lee et al. 2001; de Avellar et al. 2013), the recent detection of soft lags in a variety of compact objects, from stellar mass black holes to AGNs, and the evidence accumulated above suggest that the lags measured involves reverberation of the hard pulsating source located in the boundary layer and interacting with the accretion disk. It is worth noting that for a similar geometry, down scattering of hard X-rays (from the accretion column) in a cool medium (the accretion disk) was proposed to explain the \( \sim 100 \mu s \) soft lags observed in the pulsed emission of millisecond pulsars (e.g., Falanga & Titarchuk 2007). In our data, the distance between the irradiating hard source and the
reflector varies in a way that can be tracked by the frequency of kHz QPOs.

Our results clearly illustrate the power of lag measurements to probe the innermost regions of the accretion flows onto compact objects. Even if the surfaces and faster variability timescales of neutron stars make them more complex to analyze than black holes, kHz QPO sources offer stable and coherent clocks that allow us to measure time lags comparable to the light crossing time of a few $R_g$ (the light crossing time at $1R_g$ is about 7 μs for a canonical neutron star), just as for AGNs. Interpreting the detailed shape of the lag energy spectra, and determining intrinsic lag values will require modeling the transfer function of the response of the accretion disk to the irradiating source, which is beyond the scope of this paper. Putting a yardstick on a neutron star accretion disk will then be within reach.

The joint timing and spectral analysis presented here should also be extended to other sources for which kHz QPOs were detected cleanly with the RXTE PCA (such as 4U1636-536, de Avellar et al. 2013). The discovery of patterns similar to what we have found for 4U1608-522 (e.g., broad bump around the iron line in the energy spectrum of the lags) would add support to the reverberation scenario. It would also prepare the ground for breakthrough observations to be performed by the next generation of timing missions, such as LOFT (Feroci et al. 2011), whose combination of large effective area and improved spectral resolution will uncover exquisite details about the soft lags for both the lower and upper kHz QPOs, providing errors on the lags twenty time smaller and enabling truly iron line reverberation studies. This holds great potential to constrain the neutron star mass and to understand the underlying physics of the QPO emission and its propagation in the strong field region around the neutron star.

It is my pleasure to thank Phil Uttley for very stimulating discussions that triggered the analysis presented here. Great thanks also to Cole Miller, Jean-Pierre Lasota, Ed Cackett, Jon Miller, Chris Done, and Jean-Francois Olive for useful discussions along the preparation of this paper. The author thanks an anonymous referee whose comments helped to clarify some of the statements made in the paper.

REFERENCES

Abramowicz, M. A., Horak, J., & Kluzniak, W. 2007, A&A, 57, 1
Barret, D. 2001, AdSpR, 28, 307
Barret, D., Kluzniak, W., Olive, J. F., Paltani, S., & Skinner, G. K. 2005, MNRAS, 357, 1288
Barret, D., Olive, J. F., Boirin, L., et al. 2000, ApJ, 533, 329
Barret, D., Olive, J.-F., & Miller, M. C. 2006, MNRAS, 370, 1140
Barret, D., & Vaughan, S. 2012, ApJ, 746, 131

Boutelier, M., Barret, D., Lin, Y., & Torok, G. 2010, MNRAS, 401, 1290
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Cackett, E. M., Fabian, A. C., Zoghbi, A., et al. 2013, ApJL, 764, L9
Cackett, E. M., Miller, J. M., Ballantyne, D. R., et al. 2010, ApJ, 720, 205
de Avellar, M. G., Méndez, M., Sanna, A., & Horvath, J. E. 2011, in Proc. Fast X-ray Timing and Spectroscopy at Extreme Count Rates (HTRS 2011), 2011 February 7–11, Champéry, Switzerland, http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=122, id.52
de Avellar, M. G. B., Méndez, M., Sanna, A., & Horvath, J. E. 2013, MNRAS, submitted (arXiv:1302.6464)
De Marco, B., Ponti, G., Capili, M., et al. 2013, MNRAS, 431, 2441
Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, Natur, 467, 1081
Di Salvo, T., & Stella, L. 2002, arXiv:astro-ph/0207219
Emmanoulopoulos, D., McHardy, I. M., & Papadakis, I. E. 2011, MNRAS, 416, L94
Fabian, A. C., Kara, E., Walton, D. J., et al. 2013, MNRAS, 429, 2917
Falanga, M., & Titarchuk, L. 2007, ApJ, 661, 1084
Feroci, M., Stella, L., van der Klis, M., et al. 2011, ExA, 34, 415
Gierliński, M., & Done, C. 2002, MNRAS, 337, 1373
Gierliński, M., Zdziarski, A. A., Poutanen, J., et al. 1999, MNRAS, 309, 496
Gilfanov, M., Revnivtsev, M., & Molkov, S. 2003, A&A, 410, 217
Güver, T., Özel, F., Cabrera-Lavers, A., & Wroblewski, P. 2010, ApJ, 712, 964
Kaaret, P., Piraino, S., Ford, E. C., & Santangelo, A. 1999, ApJL, 514, L31
Kara, E., Fabian, A. C., Cackett, E. M., Minniti, G., & Uttley, P. 2013a, MNRAS, 430, 1408
Kara, E., Fabian, A. C., Cackett, E. M., et al. 2013b, MNRAS, 428, 2795
Lamb, F. K., & Miller, M. C. 2001, ApJ, 554, 1210
Lee, H. C., Misra, R., & Tsam, R. E. 2001, ApJL, 549, L229
Lin, D., Remillard, R. A., & Homan, J. 2007, ApJ, 667, 1073
Markwardt, C. B., Lee, H. C., & Swank, J. H. 2000, in Proc. of Rossi2000: Astrophysics with the Rossi X-ray Timing Explorer, 5
Miller, J. M. 2007, ARA&A, 45, 441
Miller, M. C., Lamb, F. K., & Psaltis, D. 1998, ApJ, 508, 791
Nakamura, N., Dotani, T., Inoue, H., et al. 1989, PASJ, 41, 617
Nowak, M. A., Vaughan, B. A., Wilms, J., Dove, J. B., & Begelman, M. C. 1999, ApJ, 510, 874
Osherovich, V., & Titarchuk, L. 1999, ApJL, 522, L113
Penninx, W., Damen, E., van Paradijs, J., Tan, J., & Lewin, W. H. G. 1989, A&A, 208, 146
Reynolds, C. S. 2013, in Proc. of The ISSI-Bern Workshop “The Physics of Accretion onto Black Holes”, in press (arXiv:1302.3260)
Sanna, A., Méndez, M., Belloni, T., & Altamirano, D. 2012, MNRAS, 424, 2936
Scaringi, S., Koerding, E., Groot, P. J., et al. 2013, MNRAS, 431, 2535
Shimura, T., & Takahashi, F. 1995, ApJ, 455, 780
Suleimanov, V., Poutanen, J., & Werner, K. 2011, A&A, 527, A139
Takahashi, H., Sakurai, S., & Makishima, K. 2011, ApJ, 738, 62
Tanana, A., Bazzano, A., & Ubertini, P. 2008, ApJ, 688, 1295
Titarchuk, L. 1994, ApJ, 434, 570
Uttley, P., Wilkinson, T., Cassatella, P., et al. 2011, MNRAS, 414, L60
van der Klis, M. 2000, ARA&A, 38, 717
Vaughan, B. A., van der Klis, M., Méndez, M., et al. 1998, ApJL, 509, L145
Zoghbi, A., & Fabian, A. C. 2011, MNRAS, 418, 2642
Zoghbi, A., Fabian, A. C., Reynolds, C. S., & Cackett, E. M. 2012, MNRAS, 422, 129
Zoghbi, A., Reynolds, C., Cackett, E. M., et al. 2013, ApJ, 767, 121
Zycki, P. T., Done, C., & Smith, D. A. 1999, MNRAS, 309, 561