A comparison between the spectral and long term timing properties of GX 3+1, GX 5-1 and GX 13+1

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Using GX 3+1 as an example of a bright Atoll, GX 5-1 as an example of a Z source, and GX 13+1 as a peculiar hybrid, we take a look at the spectral and long-term time evolution differences in these three neutron star Low-Mass X-ray Binaries representing different subtypes. We utilize a recently developed spectral model based on mixed thermal and bulk motion Comptonization of soft seed photons from the accretion disc and the neutron star surface. The hard X-ray tails exhibited by GX 5-1 and GX 13+1 are attributed to efficient bulk motion Comptonization, which is not present in GX 3+1 due to too low or too high a local accretion rate. Accreting well below the Eddington limit also enables GX 3+1 to exhibit amplitude modulation presumably due to changes in the accretion output from the companion star, visible in the *RXTE*/ASM light curve on a time scale of ∼6 years.

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1. Introduction

GX 3+1 is a persistently bright Atoll-type neutron star Low-Mass X-ray Binary (NS LMXB) that has long been known to show flux variations of a factor of $\sim$2–3 on time scales of several years (Makishima et al., 1983; Asai et al., 1993; Kotze & Charles, 2010). Kuulkers & van der Klis (2000) found one X-ray burst that shows evidence for radius expansion of the neutron star photosphere during a thermonuclear runaway, suggesting temporary super-Eddington emission. The binary companion and orbital period remain undetected.
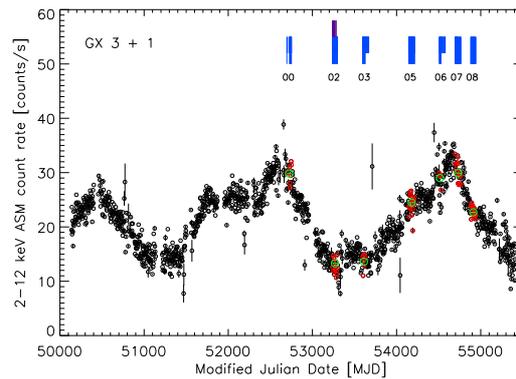

Figure 1: The *RXTE*/ASM light curve of GX 3+1 from 1996 February to 2010 August. The points corresponding to near-simultaneous *INTEGRAL* observations (long blue lines) are shown in red, and the green circles represent the weighted averages (per *INTEGRAL* observing interval) of the red data points. The *INTEGRAL* observations span from 2003 March to 2009 April. Interval 02 also has near-simultaneous observations by RXTE (purple lines).

GX 13+1 was classified as an Atoll source by Hasinger & van der Klis (1989), as its X-ray colour-colour diagram and power spectrum placed it in the banana state. This is at odds with other studies grouping it together with the more luminous NS LMXBs (Parsignault & Grindlay, 1978; Ponman, 1982; Schulz et al., 1989), and, given the theory that the dichotomy in NS LMXBs is due to their companions (van Paradijs & Lewin, 1986), observations suggesting that the secondary is a K giant (Garcia et al., 1992; Bandyopadhyay et al., 1999), including those supporting a ~ 25 d orbital period (Bandyopadhyay et al., 2002; Corbet, 2003). GX 13+1 also displays radio emission (Grindlay & Seaquist, 1986), a ~ 60 Hz Quasi-periodic oscillation (QPO) (Homan et al., 1998), and a transient hard tail (Paizis et al., 2006), which are otherwise associated with Z sources, as well as iron K absorption features similar to those in apparently superluminal black hole X-ray binaries (Ueda et al., 2001; Sidoli et al., 2002). In any case, type I X-ray bursts indicate it to be a neutron star source (Fleischman, 1985; Matsuba et al., 1995).

The Z source GX 5-1 is the second brightest persistent X-ray source after Sco X-1. QPOs have been detected in the X-ray light curves at various frequencies (e.g. van der Klis et al. 1985; Wijnands et al. 1999), and extensively studied since. Naylor et al. (1991) identified several candidate infrared counterparts, one of which was confirmed by Bandyopadhyay et al. (2003), but the type of the mass donor and the orbital period are yet to be established. GX 5-1 has a hard tail above
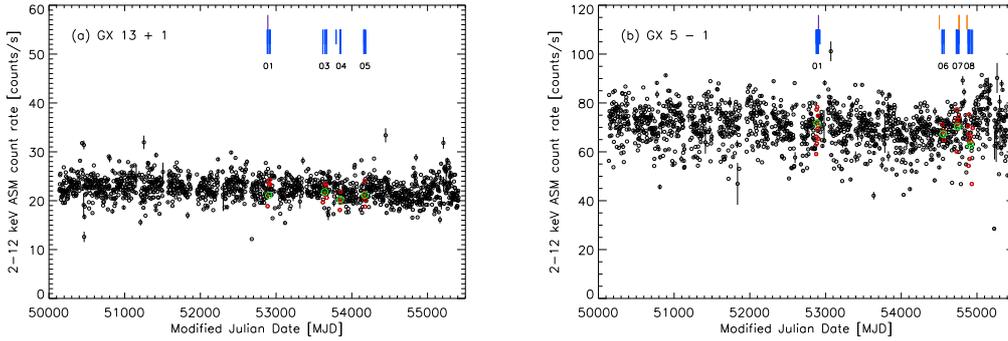
Figure 2: **(a)** The *RXTE*/ASM light curve of GX 13+1 from 1996 February to 2010 August. **(b)** The *RXTE*/ASM light curve of GX 5-1 from 1996 February to 2010 August. Note that the y-scale here is twice that of Figs. 1 and 2(a).

20 keV (Paizis et al., 2005), the study of which has been complicated by contamination from the nearby (40') black hole candidate GRS 1758-258 (Asai et al., 1994).

2. Observations, data reduction and modeling

Our *INTEGRAL* data sample was selected from Science Windows (ScWs) with offsets $< 4°$ and more than 1000 s of JEM-X1 or JEM-X2 and IBIS/ISGRI data. The sources have been observed by *INTEGRAL* recurrently within intervals of $\sim$70 days twice a year. For each source, we picked a few of these intervals that had relatively good coverage (Figs. 1 & 2). Most of the data is from GX 3+1, as it has the best *INTEGRAL* coverage and the most complex long-term *RXTE* All-Sky Monitor (ASM) light curve (Fig. 1). The data were reduced with the Off-line Science Analysis (OSA) version 8 software. We have also analyzed *RXTE* PCA and HEXTE spectra which were available for our *INTEGRAL* observing intervals.

For modeling the spectra with XSPEC 12, we used the COMPTB model recently introduced by Farinelli et al. (2008), and employed to study *BeppoSAX* spectra of Cyg X-2 in Farinelli et al. (2009), and several NS LMXBs in Mainardi et al. (2010). COMPTB combines the thermal and bulk motion Comptonization of a seed photon spectrum to create a unified physical model that seeks to explain the spectral evolution of NS LMXBs. In this scenario, thermal Comptonization operates on soft accretion disc blackbody seed photons in the hot plasma of the outer Transition Layer (TL) between the accretion disc and the NS, while photons from the NS surface and inner part of the TL may experience both thermal and bulk motion Comptonization in a free-fall region which may form in the inner TL, depending on the accretion rate and resulting radiation pressure (Fig. 3 shows a schematic of the model).

The *INTEGRAL* and *RXTE* spectra were fitted with three model variations of increasing complexity: (1) a single COMPTB with thermal Comptonization only (Fig. 4); (2) two COMPTB components, one of which thermally Comptonized and the other reduced to a blackbody (Fig. 5(a)); (3) two COMPTB components, one of which only thermally and the other thermally as well as bulk motion Comptonized (Fig. 5(b)). The absorbing hydrogen columns (model tbabs) were set to values from literature.
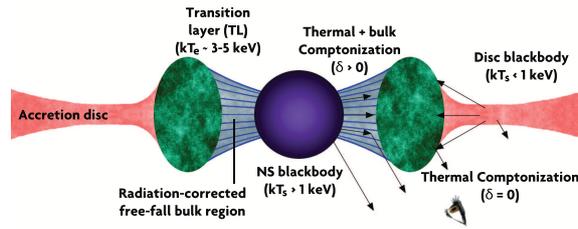
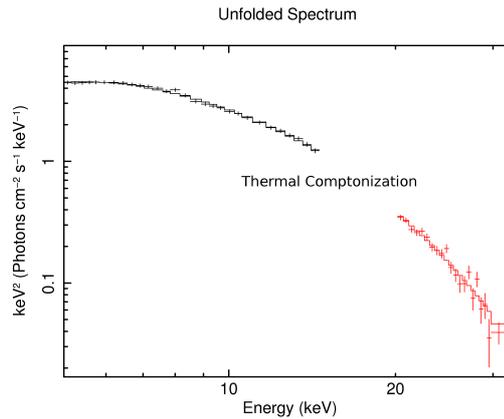**Figure 3:** Schematic of the accretion/emission model used in this work.

Figure 4: *INTEGRAL* JEM-X1 (black) and IBIS/ISGRI (red) spectrum of the Atoll source GX 3+1 from interval 07 (see Fig. 1) with the best-fit model of thermal Comptonization of $kT_s \lesssim 1$ keV blackbody photons from a $kT_e \sim 3$–4 keV electron plasma. Three of the seven interval-averaged GX 3+1 spectra were best fit with this single-component version. The other four spectra favored a second component (see Fig. 5).

3. Results and discussion

In terms of the accretion scenario used in this study, the hard X-ray tails exhibited by GX 5-1 and GX 13+1 (as well as other Z sources) can be explained by efficient bulk motion Comptonization in a freefall region near the NS surface, i.e. the inner TL. The hard emission is observed while the sources are in the Horizontal Branch (e.g. Paizis et al. 2005), corresponding to a certain range of local accretion rates. When the rate is increased, radiation pressure stops the bulk motion, suppressing the hard emission in the Normal and Flaring branches. This may be the case permanently in the bright Atoll sources such as GX 3+1, or possibly the local accretion rate is too low for bulk motion Comptonization to produce observable hard emission.

Changes in the matter transfer rate from the companion due to a Solar-like magnetic cycle have been suggested as the origin of the long-term modulation in GX 3+1 and other persistent Atoll sources (Kotze & Charles, 2010). Z sources could be less affected due to the output from the donor exceeding the Eddington limit for accretion onto the NS; the local accretion/emission rate remains near the Eddington limit and the surplus matter gets ejected. The cycle of the evolved companions could also be too long or too weak to be observed.
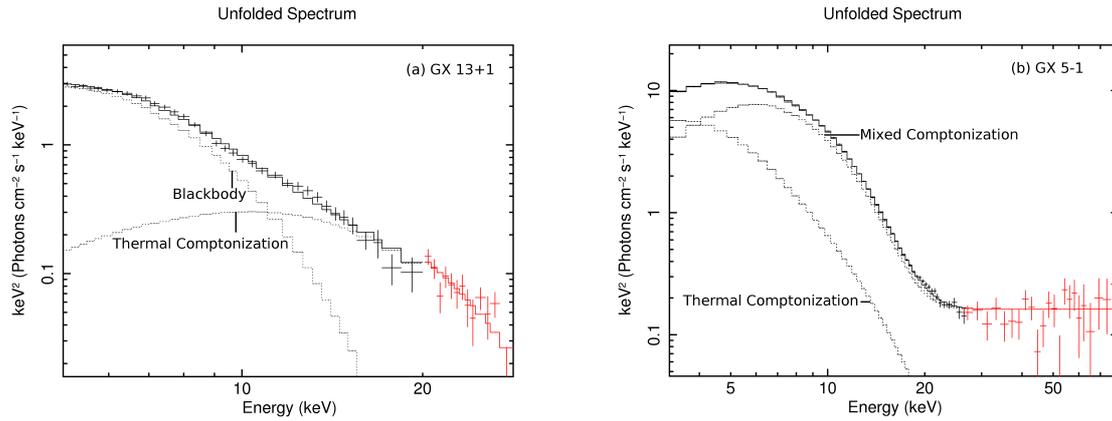
Figure 5: **(a)** *INTEGRAL* JEM-X1 (black) and IBIS/ISGRI (red) spectrum of the Atoll source GX 13+1 from interval 01 (see Fig. 2(a)) with the best-fit thermal Comptonization + blackbody model. This model version was favored by three out of four of the GX 13+1 spectra: thermal Comptonization of soft photons dominates, while a harder (> 1 keV) blackbody-like component is also discernible. The spectrum from interval 04 was harder, supporting bulk motion Comptonization (the model of Fig. 5(b)). **(b)** *RXTE* PCA (black) + HEXTE (red) spectrum for the Z source GX 5-1 from interval 01 (see Fig. 2(b)) with the best-fit thermal Comptonization + mixed (thermal and bulk) Comptonization model. The spectrum from this interval showed an unambiguous hard tail which required bulk motion Comptonization to fit it, while the other three GX 5-1 intervals could be adequately fit also with the simpler model versions.

4. Future work

We have studied the few available Swift spectra of GX 5-1, and are presently looking at Chandra grating spectra, as a means of establishing the low-energy parameters such as the seed photon temperatures. This will allow the Comptonization parameters to be better constrained.

5. Acknowledgements

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