

A Comparison of the Variability of the Symbiotic X-ray Binaries GX 1+4, 4U 1954+31, and 4U 1700+24 from Swift/BAT and RXTE/ASM Observations

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ABSTRACT

We present an analysis of the X-ray variability of three symbiotic X-ray binaries, GX 1+4, 4U 1700+24, and 4U 1954+31, using observations made with the Swift Burst Alert Telescope (BAT) and the Rossi X-ray Timing Explorer (RXTE) All-Sky Monitor (ASM). Observations of 4U 1954+31 with the Swift BAT show modulation at a period near 5 hours. Models to explain this modulation are discussed including the presence of an exceptionally slow X-ray pulsar in the system and accretion instabilities. We conclude that the most likely interpretation is that 4U 1954+31 contains one of the slowest known X-ray pulsars. Unlike 4U 1954+31, neither GX 1+4 nor 4U 1700+24 show any evidence for modulation on a timescale of hours. An analysis of the RXTE ASM light curves of GX 1+4, 4U 1700+24, and 4U 1954+31 does not show the presence of periodic modulation in any source, although there is considerable variability on long timescales for all three sources. There is no modulation in GX 1+4 on either the optical 1161 day orbital period or a previously reported 304 day X-ray period. For 4U 1700+24 we do not confirm the 404 day period previously proposed for this source from a shorter duration ASM light curve.

Subject headings: stars: individual (GX 1+4, 4U 1954+31, 4U 1700+24) — stars: neutron — — binaries (symbiotic) — X-rays: binaries

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1. Introduction

A symbiotic binary is a system which contains a hot object accreting from an M giant companion (e.g. Iben & Tutukov 1996) either from the wind of the M star or via Roche lobe overflow. In most symbiotic stars the accreting object is a white dwarf, and these systems can be modest X-ray emitters (e.g. Mürset et al. 1997). In far fewer systems is the accreting object thought to be a neutron star. There are presently only five sources for which there is strong evidence that they are “symbiotic X-ray binaries” with a neutron star component. This paper discusses three of these sources: GX 1+4, 4U 1954+31, and 4U 1700+24. GX 1+4 has been known as a symbiotic source containing an X-ray pulsar for some time (e.g. Davidsen et al. 1977). 4U 1700+24 was suspected to be a symbiotic source and this is now confirmed and 4U 1954+31, which was initially thought to be a high-mass X-ray binary, has also recently been found to have an M giant counterpart (Masetti et al. 2006). In addition to these sources, Sct X-1 and IGR J16194-2810 have also recently been suggested to be symbiotic X-ray binaries (Kaplan et al. 2007, Masetti et al. 2007b).

We present an analysis of the X-ray variability of GX 1+4, 4U 1954+31, and 4U 1700+24 using long term observations made with the Swift Burst Alert Telescope (BAT) and the Rossi X-ray Timing Explorer (RXTE) All Sky Monitor (ASM). Sct X-1 and IGR J16194-2810 are not considered here as BAT light curves are not available for these sources and an ASM light curve is not available for IGR J16194-2810. These observations enable a study of variability on timescales from hours to years. The BAT observations show the presence of a strong modulation with period of about 5 hours in 4U 1954+31 first reported by Corbet et al. (2006). We consider possible mechanisms that could cause this modulation. We find no evidence for orbital modulation in any of these three systems.

2. Previous Observations of Symbiotic X-ray Binaries

We summarize here previous observations of symbiotic X-ray binaries with emphasis on variability and previously claimed periodicities in GX 1+4, 4U 1954+31, and 4U 1700+24. Source parameters are listed in Table 1.

2.1. GX 1+4

Pulsations with a period of ~ 120 s from GX 1+4 were discovered by Lewin, Ricker, & McClintock (1971). The optical counterpart was identified as the bright infrared source V2116 Oph (Glass & Feast 1973) and GX 1+4 was classified as a symbiotic X-ray binary

containing an M giant mass donor by Davidsen, Malina, & Bowyer (1977), making it the first such object to be identified. The long term X-ray light curve shows extensive variability, and the pulsar shows both spin-up and spin-down (e.g. Chakrabarty et al. 1997). Chakrabarty & Roche (1997) presented extensive optical, infrared, and X-ray observations of GX 1+4 and concluded that the binary period must be greater than 100 days, and was most likely greater than 260 days, based on the assumption that the M giant does not overflow its Roche lobe. Cutler, Dennis, & Dolan (1986) proposed an orbital period of approximately 304 days based on variations in the pulse period measured with the high-energy X-ray spectrometer on OSO-8, and Pereira, Braga, & Jablonski (1999) claimed confirmation for this from BATSE pulse period measurements with a refined period of 303.8 ± 1.1 days. However, using infrared radial velocity measurements of the M giant, Hinkle et al. (2006) excluded the 304 day period and instead found an orbital period of 1161 ± 12 days and a system eccentricity of 0.10 ± 0.02 . GX 1+4 is thus a very variable source with well studied pulsations. Its classification as a symbiotic X-ray binary is firm - the pulsations, the change in their period, and the high luminosity clearly show that the system contains a neutron star.

2.2. 4U 1954+31 (3A 1954+319)

Pointed observations of 4U 1954+31 were first obtained with EXOSAT (Cook, Warwick, & Watson 1984) and Ginga (Tweedy, Warwick, & Remillard 1989). In both sets of observations flaring behavior on timescales of minutes was reported. Cook et al. (1984) found that the X-ray spectrum could be fitted with either a power-law or a thermal bremsstrahlung model. Tweedy et al. (1989) reported that a more complicated model was required such as the typical X-ray pulsar spectrum of a power-law with high energy cutoff. However, even with this model Tweedy et al. (1989) found evidence for the presence of an additional soft component. Because of the variability and the power law spectrum both Cook et al. (1984) and Tweedy et al. (1989) concluded that 4U 1954+31 was likely to be a high-mass X-ray binary (HMXB). However, Masetti et al. (2006) obtained a precise position from Chandra observations which enabled the optical counterpart to be identified as an M giant. 4U 1954+31 is thus a symbiotic system rather than an HMXB. Masetti et al. (2007a) give a summary of a variety of X-ray observations of 4U 1954+31. No orbital period has been proposed for this system and, apart from the 5 hour period discussed in this paper, no pulsations had previously been reported.

2.3. 4U 1700+24 (2A 1704+241)

4U 1700+24 was proposed to be a symbiotic X-ray binary by Garcia et al. (1983) on the basis of a positional association with the M giant star HD 154791 obtained from observations with the Einstein Observatory Imaging Proportional Counter (IPC). A position obtained with the ROSAT High Resolution Imager by Morgan & Garcia (2001) was apparently inconsistent with HD 154791. However, subsequent observations with the Chandra High Resolution Camera Imager by Masetti et al. (2006) gave a position consistent with that of HD 154791 and inconsistent with that reported by Morgan & Garcia (2001). The Masetti et al. (2006) position appears to firmly identify 4U 1700+24 as a symbiotic system.

Garcia et al. (1983) reported the presence of 900s quasi-periodic modulation from their IPC observations. Morgan & Garcia (2001) also claimed to detect modulation near a period of 900s in ROSAT observations, but with a different frequency from that reported previously. Masetti et al. (2002) report on ASCA, BeppoSAX, ROSAT, and RXTE Proportional Counter Array (PCA) observations of 4U 1700+24. They found erratic “shot noise” variability on timescales of tens to thousands of seconds but did not confirm the modulation on the 900s timescale reported by Garcia et al. (1983) and Morgan & Garcia (2001).

Masetti et al. (2002) reported a tentative periodicity of ~ 400 days from RXTE ASM observations obtained between 1996 and 2001. Galloway, Sokoloski, & Kenyon (2002) also analyzed RXTE ASM observations obtained between January 1996 and April 2002 and claimed to confirm this modulation at a refined period of 404 ± 20 days. Galloway et al. (2002) reported optical radial velocity measurements which showed marginally significant modulation at a period of 404 ± 3 days. Galloway et al. (2002) suggested that the modulation could be caused by either orbital motion or pulsational modulation of the red giant.

In summary, there is strong evidence that 4U 1700+24 is a symbiotic X-ray source. It is highly variable in the X-ray band, there is possible evidence of modulation on a ~ 400 day timescale, but there is no convincing evidence of pulsations.

2.4. Scutum X-1 and IGR J16194-2810

Sct X-1 has been observed by many instruments since its discovery in a rocket flight by Hill et al. (1974). Kaplan et al. (2007) recently derived a corrected position for Sct X-1 that showed it to be associated with a late type giant or supergiant optical counterpart. Pulsations at a period of 111 s were first detected in Ginga observations (Makino 1988; Koyama et al. 1991) and Kaplan et al. (2007) showed from observations with Ginga, RXTE, and XMM-Newton that the pulsar has exhibited spin-down over a period of 17 years.

IGR J16194-2810 is another recent candidate symbiotic X-ray binary. The source was reported in the 2nd IBIS survey (Bird et al. 2006) and associated with the ROSAT source 1RXS J161933.6-280736 by Stephen et al. (2006). Masetti et al. (2007b) used a position obtained with the Swift X-ray Telescope to identify an M2 III optical counterpart. Masetti et al. reported erratic X-ray variability on timescales of hundreds to thousands of seconds, but no pulsations were found.

3. Observations

3.1. Swift BAT

The Swift BAT is described in detail by Barthelmy et al. (2005) and the data reduction process is described by Markwardt et al. (2005). The BAT is a very wide field of view (1.4 sr half-coded) hard X-ray telescope that utilizes a 2.7 m² coded-aperture mask and a 0.52 m² CdZnTe detector array divided into 32,768 detectors each with an area of 0.16 cm². The pointing direction of the BAT is determined by observations using the narrow-field XRT and UVOT instruments also on board Swift which are primarily used to study gamma-ray bursts and their afterglows. BAT observations of X-ray sources are thus generally obtained in a serendipitous and unpredictable fashion. Typically the BAT observes 50% to 80% of the sky each day. The data considered here consists of individual “snapshots”, i.e. times spent observing the same position without a break. These have exposure times ranging between 150 to 2678 s with means of 891 s (GX 1+4), 987 s (4U 1954+31) and 979 s (4U 1700+24).

From these snapshots light curves are constructed in 4 energy bands: 14 to 25 (“A”), 25 to 50 (“B”), 50 to 100 (“C”), and 100 to 195 (“D”) keV. For the entire energy range the Crab produces approximately 0.045 counts s⁻¹ per fully illuminated detector for an equivalent on-axis source (hereafter abbreviated to counts s⁻¹). In each energy band the Crab produces 0.019, 0.018, 0.0077, and 0.0012 counts s⁻¹ respectively. The BAT light curves used here cover the periods MJD 53,373 to 53,818 (GX 1+4), 53,350 to 53,815 (4U 1954+31), and 53,352 to 53,818 (4U 1700+24).

3.2. RXTE ASM

The RXTE ASM (Levine et al. 1996) consists of three similar Scanning Shadow Cameras which perform sets of 90 second pointed observations (“dwells”) so as to cover ~80% of the sky every ~90 minutes. Light curves are available in three energy bands: 1.5 to 3.0 keV (“A”), 3.0 to 5 keV (“B”), and 5 to 12 keV (“C”). The Crab produces approximately 75.5

counts s^{-1} in the ASM over the entire energy range and 26.8 (A), 23.3 (B), and 25.4 (C) counts s^{-1} in each energy band. Observations of blank field regions away from the Galactic center suggest that background subtraction may produce a systematic uncertainty of about 0.1 counts s^{-1} (Remillard & Levine 1997). The ASM light curves used in our analysis span the period from MJD 50,087 to 54,195 except for the light curve of GX 1+4 which starts on MJD 50,088.

4. Analysis and Results

The RXTE ASM light curves cover a longer duration than the Swift BAT light curves and so are better suited for searches for orbital modulation on the long time scales as is expected for symbiotic X-ray binaries. The BAT light curves are generally more sensitive than the ASM light curves, particularly for highly-absorbed sources, and so have advantages in studying variability on shorter timescales. We use power spectra of the light curves to search for periodic modulation and in all cases the calculation of power spectra employed the “semi-weighting” scheme discussed in Corbet et al. (2007a, b).

4.1. GX 1+4

The ASM and BAT light curves of GX 1+4 are shown in Fig. 1 and the mean count rates are given in Table 1. There is considerable variability seen with both instruments. During the interval covered simultaneously by both instruments the BAT light curve shows dramatic flaring while the modulation in the ASM light curve appears to be smaller. The power spectrum of the ASM light curve is shown in Fig. 2. Although there are a number of peaks in the power spectrum at low frequencies, none exactly coincide with either the 1160 day period proposed by Hinkle et al. (2006) or the 304 day period reported by Cutler et al. (1986). Although the largest peak in the power spectrum is at 270 days, which is similar length to the Cutler et al. 304 day period the peak does not overlap with this period. The peak at 270 days is also far from the dominant feature of the power spectrum and appears to be part of the general low frequency noise present in the power spectrum. At higher frequencies there is a peak around the orbital period of RXTE at $\sim 15.0185 \text{ day}^{-1}$ and a smaller peak close to 1 day^{-1} which is likely related to aliasing of the strong low frequency noise with a one day sampling pattern (see Farrell, O’Neill & Sood 2005, Wen et al. 2006). In Fig. 3 we show the ASM light curve of GX 1+4 folded on the Hinkle et al. (2006) orbital period. The folded light curve does not show obvious periodic modulation. In particular, there is neither a flux enhancement at periastron passage nor flux reduction at the phase of

predicted eclipse (Hinkle et al. 2006).

The BAT power spectrum of GX1+4 is shown Fig. 4. No features due to source variability are detected and the only peak visible is due to the orbital period of the Swift satellite.

4.2. 4U 1954+31

The light curves of 4U 1954+31 obtained with the RXTE ASM and Swift BAT instruments are shown in Figs. 5 and 6 and the mean count rates are given in Table 1. The ASM light curve shows the presence of several outbursts, the most recent of which was also observed with the BAT. However, some differences are seen in the structure within the flare (6). We first searched for long period variations by calculating the power spectrum of the RXTE ASM light curve as this has the longer duration. The resulting power spectrum is shown in Fig. 7. At low frequencies there is no obvious orbital period, but substantial noise is present related to the outbursts that can be seen in the light curve.

We next utilized the more sensitive BAT observations to investigate higher frequency variability. The power spectrum of the entire BAT light curve is shown in Fig. 4 with linear frequency scaling to emphasize the high frequency portion of the spectrum. Excluding the low frequency noise, the dominant feature is a set of peaks around the orbital period of the Swift satellite at $\sim 14.96 \text{ days}^{-1}$. However, in addition to this peak a number of other peaks can be seen. Investigation of these peaks shows that they are all related to a modulation at a period of approximately 5.09 hours (4.72 day^{-1}) and aliases with the orbital period of the Swift satellite. Present are the first and second harmonics of this ~ 5 hour period and beats between this period and Swift's orbital period. The Fourier modulation amplitude at 5 hours is approximately $6.5 \times 10^{-4} \text{ counts s}^{-1}$.

The peak in the power spectrum near 5 hours shows a complex structure (Fig. 8). When power spectra are calculated from subsets of the BAT light curve (Fig. 9) it is seen that during the course of the BAT observations the period changed from approximately 5.19 to 5.02 hours in a nearly monotonic fashion (Fig. 10). We estimate the period decrease rate to be $-2.6 \pm 0.2 \times 10^{-5} \text{ day day}^{-1}$, equivalent to a timescale of 22 ± 2 years (see also Mattana et al. 2006). We corrected the BAT light curves for the period change and folded them on the pulse period (Fig. 11). The 14 to 25 keV and 25 to 50 keV folded data show similar morphology, whereas the 50 to 100 keV profile appears to show a maximum at a slightly earlier phase.

Because of the detection of the 5 hour period in the BAT light curve we examined the

ASM power spectrum in more detail for the possible presence of this period. The ASM power spectrum is plotted with linear frequency scaling in Fig. 12. A low amplitude peak is seen near 4.72 days^{-1} . We then divided the ASM power light curve into sections to investigate the time dependence of this peak. Fig. 13 shows the ASM power spectrum in the 4.2 to 5.1 day^{-1} range. When split in this way, there is only a possible detection of modulation in a single section of the light curve that was obtained between MJD 51,397 and 52,052.

We next corrected the ASM light curves in the time range MJD 53,350 to 53,650 for the period changes detected in the BAT light curve, and folded the energy separated data (Fig. 14). The folded 1.5 - 3 keV and 3 - 5 keV bands do not exhibit any obvious modulation. The folded 5 - 12 keV ASM light curve suggests a possible modulation which peaks at the same phase as the folded BAT light curves.

4.3. 4U 1700+24

The ASM and BAT light curves of 4U 1700+24 are shown in Fig. 15 and the mean count rates are given in Table 1. The ASM light curve shows considerable variability with at least two prominent outbursts. The power spectrum of the ASM light curve is shown in Fig. 16 where the dashed line indicates the 404 day period proposed by Masetti et al. (2002) and Galloway et al. (2002). This does not coincide with any significant peak in the power spectrum. The BAT light curve of 4U 1700+24 shows that it was in a low luminosity state during this time. The power spectrum of the BAT light curve (Fig. 4) does not show the presence of any periodicities from the source at higher frequencies.

5. Discussion

5.1. Lack of Orbital Flux Modulation

None of the three symbiotic X-ray binaries shows modulation on long timescales which could be interpreted as the orbital period of the system. There is no modulation at the 1161 day orbital period of GX 1+4 and the previously proposed modulation period of 404 days in 4U 1700+24 is also found not to be a persistent feature of the X-ray light curve. The long term light curves of all three of these systems appear to be dominated by irregular flaring type behavior. The cause of these flares may be variability in the stellar wind of the M giant as almost all red giants are optically photometrically variable on time scales of hundreds to thousands of days (e.g. Percy et al. 2001). If the mass loss rate in the wind varies in conjunction with the photometric variations then this could produce a modulation of the

accretion rate onto the neutron star. For GX 1+4 a modest eccentricity of 0.10 ± 0.02 was reported by Hinkle et al. (2006) and any accretion rate modulation caused by the motion in this eccentric orbit is apparently much less than that caused by other mechanisms.

5.2. The 5 hour period in 4U 1954+31

Masetti et al. (2006) determined the optical counterpart of 4U 1954+31 to be an M 4-5 giant which would imply a long orbital period in order for the star not to overflow its Roche lobe. For comparison, Chakrabarty & Roche (1997) derive a constraint of $P_{orb} > 100$ days for GX 1+4 where the donor is an M5 III star. The 5 hour period thus cannot be the orbital period of a compact object about the M star. The large change in the 5 hour period also makes it implausible that it is caused by orbital modulation which also rules out triple star models. We note that the period change is too large for the period to come from the rotation period of an accreting white dwarf because of the large moment of inertia of these objects. We therefore consider other possible models that could explain the 5 hour modulation.

5.2.1. Neutron Star Rotation Period

The 5 hour period in 4U 1954+31 is somewhat reminiscent of the 2.7 hour period seen in the high-mass X-ray binary 2S 0114+650. This period was discovered by Finley, Belloni, & Cassinelli (1992) and was proposed to be a neutron star rotation period. Apparent confirmation of this interpretation comes from the continued presence of the 2.7 hour modulation in the ASM light curve (Corbet, Finley, & Peele 1999; Farrell, Sood, & O’Neill 2006) which implies the modulation is rather coherent. An indirect argument for the modulations on periods of hours in both 4U 1954+31 and 2S 0114+650 being neutron star pulsation periods is that no other periodicity has been found in these systems that could be neutron star pulsation periods. A long period of 1.6 hours has also been reported for IGR J16358-4726 (Kouveliotou et al. 2003, Patel et al. 2004). However, for IGR J16358-4726 it is not clear whether this period is a neutron star rotation period or an orbital period. A 5 hour neutron star rotation period for 4U 1954+31 would make it one of the longest known with only the 6.67 period from the point source in the supernova remnant RCW 103 exceeding this value (DeLuca et al. 2006).

If the periodicity in 4U 1954+31 does indeed represent the rotation period of a neutron star, then the rapid spin-up requires an X-ray luminosity of approximately 5×10^{35} ergs s^{-1} (e.g. Mason 1977, Joss & Rappaport, 1984). For comparison, in an earlier outburst of

4U 1954+31 Masetti et al. (2007) derive luminosities of $\sim 2 \times 10^{35}$ ergs s^{-1} , *not* corrected for absorption from RXTE and BeppoSAX observations obtained on MJD 50796 and 50937 respectively. Masetti et al. (2007) also found the absorption to be complex and variable.

The observed period change timescale is very short at only a few decades. For a 5 hour period material corotating in a Keplerian orbit about the neutron star would be at a radius of $\sim 10^{11}$ cm. In contrast, the magnetospheric radius, at which the magnetic field would dominate over the ram pressure, would be located at $\sim 10^9 (L_X/10^{35} \text{ ergs } s^{-1})^{-2/7} (B/10^{12} \text{ G})^{4/7}$ cm. The 5 hour period is thus apparently much longer than the equilibrium spin period. This appears to be similar to the case of GX 1+4 where the corotation radius is estimated to be 3×10^9 cm and the magnetospheric radius is estimated to be significantly smaller at $\sim 3 \times 10^8$ cm for a magnetic field of 10^{12} G (Chakrabarty & Roche 1997). Despite this, GX 1+4 has primarily exhibited long-term spin-down, with occasional spin-up behavior seen in the brightest states (e.g. Chakrabarty et al. 1997, Ferrigno et al. 2007). In order to explain the spin-down in GX 1+4 without the need for an unusually strong magnetic field, it has been proposed (e.g. Makishima et al. 1988, Chakrabarty et al. 1997, Nelson et al. 1997) that a counter-rotating accretion disk may sometimes form. Alternatively, Parna et al. (2007) consider a spin-down mechanism related to the fallback of material expelled when a neutron star is in the propeller regime.

The possible detection of the 5 hr period in 4U 1954+31 with the ASM was at a similar period to that seen at the start of the outburst observed with the BAT. This suggests that 4U 1954+31, like GX 1+4, may also exhibit spin-down between outbursts. However, additional observations are needed to determine whether this is indeed the case.

5.2.2. *Accretion Instability*

The 5 hour modulation might alternatively be caused by some type of instability in the accretion flow onto the neutron star. The 5 hour timescale is similar to that of the 3.96 hour quasi-periodic flares observed on one occasion from the Be/neutron star binary EXO 2030+375 (Parmar et al. 1989). As this modulation was only detected once for a brief period we have no information on whether such a modulation might exhibit long term period changes such as shown by 4U 1954+31. Therefore, although this model cannot yet be definitely excluded, its transient appearance in only one other source may make it a less likely explanation.

5.2.3. *Variations in the Mass Donor*

The interpretation of the 2.7 hr period in 2S 0114+650 as a neutron star rotation period has been questioned by Koenigsberger et al. (2006) who propose that the period comes from tidal interactions which drive oscillations in the B supergiant primary. However, an explanation of the 5 hr period in 4U 1954+31 as a pulsation in the mass donor appears problematic as the fundamental pulsation periods of M giants are very long and there is little evidence for pulsations on periods less than 10 days (Percy et al. 2001, Koen et al. 2002). We therefore exclude this model as a possible explanation of the 5 hour periodicity.

5.3. Summary of Models

The persistence of the 5 hour period over an extended length of time, the change in period consistent with accretion torque, and lack of any other periodicity in the light curve that could be a pulse period, all suggest that the 5 hr period is a neutron star rotation period. However, an EXO 2030+375 type instability is not yet completely ruled out.

6. Conclusion

The three symbiotic X-ray binaries considered here show considerable X-ray variability on long time scales, dominated by the presence of slow flares. In none of the systems does the long term X-ray flux show detectable orbital modulation and there is no evidence for modulation at any of the previously reported periods. Any accretion rate variation caused by modulation in an eccentric orbit appears to be much less than the non-periodic flares.

In contrast, on shorter timescales, two of the three sources, GX 1+4 and 4U 1954+31, exhibit periodic modulation that appears to come from a neutron star rotation period. This, together with the pulsations shown by Sct X-1, suggests that further observations of 4U 1700+24, preferably during an outburst, might also reveal a pulsation period in this source. Additional observations of 4U 1954+31 should help to better constrain the nature of the 5 hour modulation by showing whether this is a persistent feature of the light curve and, if so, how the period changes in response to varying flux levels.

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Table 1. Symbiotic X-ray Binaries

System	P_{spin}	P_{orb} (days)	Optical Counterpart	Spectral Type	Distance (kpc)	Mean ASM Count Rate	Mean BAT Count Rate
GX 1+4	120 s (C97)	1161 (H06)	V2116 Oph (GF73)	M5 III (CR97)	3-6 (CR97)	1.1	1.4×10^{-3}
4U 1954+31	5 hr (C07)	?	U1200+13816030 (M06)	M4 III (M06)	1.7 (M06)	0.7	1.1×10^{-3}
4U 1700+24	[900s? (MG01)]	[404? (G02)]	HD 154791/V934 Her (M06)	M2 III (M02)	0.42 (M02)	0.4	9×10^{-5}
Sct X-1	111 - 113s (K07)	?		- late K/early M I-III	≥ 4 (K07)	0.2	-
IGR J16194-2810	?	?	U0600.20227091 (M07)	M2 III (M07)	≤ 3.7 (M07)	-	-

Note. — (i) References: C07 - this work, C97 - Chakrabarty et al. (1997), CR97 - Chakrabarty & Roche (1997), G02 - Galloway et al. (2002), GF73 - Glass & Feast (1973), H06 - Hinkle et al. (2006), K07 - Kaplan et al. (2007), M02 - Masetti et al. (2002), M06 - Masetti et al. (2006), M07 - Masetti et al. (2007b), MG01 - Morgan & Garcia (2001) References are not exhaustive and additional references can generally be found within those given. (ii) Parameters in square brackets are considered to be questionable.

Figure Captions

Fig. 1.— BAT and ASM light curves of GX 1+4 in ten day averages. The full energy ranges are used for each instrument.

Fig. 2.— Power spectrum of the ASM light curve of GX 1+4. The 1161 day orbital period found by Hinkle et al. (2006) is marked by the dashed red line (left) and the 304 day period of Cutler et al. (1986) is marked by the dashed blue line (right).

Fig. 3.— The ASM light curve of GX 1+4 folded on the 1160 day period from Hinkle et al. (2006). Phase 0 corresponds to periastron passage and the dashed line indicates the phase when an eclipse of the neutron star could take place.

Fig. 4.— Power spectra of BAT light curves. Lower panel: GX 1+4, middle panel: 4U 1954+31, upper panel: 4U 1700+24.

Fig. 5.— BAT and ASM light curves of 4U 1954+31 in ten day averages. The full energy ranges are used for each instrument.

Fig. 6.— Detail of BAT and ASM light curves of 4U 1954+31 in three day averages. The full energy ranges are used for each instrument.

Fig. 7.— Power spectrum of the ASM light curve of 4U 1954+31.

Fig. 8.— Detail of the power spectrum of the BAT light curve of 4U 1954+31 around the 5 hour period.

Fig. 9.— Power spectra of BAT observations of 4U 1954+31. Each power spectrum is obtained from observations covering 25 days, and each data set is offset by 25 days from the next. Time increases from the bottom panel to the top.

Fig. 10.— Measurements of the period of 4U 1954+31 during outburst.

Fig. 11.— BAT light curves of 4U 1954+31 folded on the 5 hour period corrected for period changes. Panel (A): 14 to 25 keV, panel (B): 25 to 50 keV, panel (C): 50 to 100 keV, panel (D): 100 to 195 keV.

Fig. 12.— Detail of the high frequency portion of the power spectrum of the ASM light curve of 4U 1954+31. The 5 hour period found in the BAT observations is marked by the dashed line.

Fig. 13.— Power spectra of the ASM light curve of 4U 1954+31 around the 5 hour period.

Each power spectrum is taken from a 655 day long stretch of data and the time ranges covered are (a) MJD 50,087 - 50,742; (b) 50,742 - 51,397; (c) 51,397 - 52,052; (d) 52,052 - 52,707; (e) 52,707 - 53,362; and (f) 53,362 - 54,017.

Fig. 14.— ASM light curves of 4U 1954+31 from the time range covered by BAT observations folded on the 5 hour period corrected for period changes in the same was as for Fig. 11. Panel (A): 1.5 to 3 keV, panel (B): 3 to 5 keV, panel (C): 5 to 12 keV.

Fig. 15.— BAT and ASM light curves of 4U 1700+24 in ten day averages. The full energy ranges are used for each instrument.

Fig. 16.— Power spectrum of the ASM light curve of 4U 1700+24. The dashed red line marks the 404 day period previously reported for this source by Masetti et al. (2002).































