Swift/BAT and RXTE Observations of the Peculiar X-ray Binary 4U 2206+54 - Disappearance of the 9.6 Day Modulation

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ABSTRACT

Observations of the high-mass X-ray binary 4U 2206+54 with the Swift Burst Alert Telescope (BAT) do not show modulation at the previously reported period of 9.6 days found from observations made with the Rossi X-ray Timing Explorer (RXTE) All-Sky Monitor (ASM). Instead, the strongest peak in the power spectrum of the BAT light curve occurs at a period of 19.25 ± 0.08 days, twice the period found with the RXTE ASM. The maximum of the folded BAT light curve is also delayed compared to the maximum of the folded ASM light curve. The most recent ASM data folded on twice the 9.6 day period show similar morphology to the folded BAT light curve. This suggests that the apparent period doubling is a recent secular change rather than an energy-dependent effect. The 9.6 day period is thus not a permanent strong feature of the light curve. We suggest that the orbital period of 4U 2206+54 may be twice the previously proposed value.

Subject headings: stars: individual (4U 2206+54) — stars: neutron — X-rays: stars

1. Introduction

The Uhuru X-ray source 4U 2206+54 (Giacconi et al. 1972) was identified with the optical counterpart BD +53\textdegree 2790 by Steiner et al. (1984). Optical photometry and the presence of a double peaked H\alpha line in the spectrum led Steiner et al. (1984) to conclude that BD +53\textdegree 2790 is a Be star. However, it has been argued that the optical properties,
in particular the behavior of the Hα emission line, show that this star is actually a very peculiar active O type star (Negueruela & Reig 2001, Ribó et al. 2006, Blay et al. 2006).

Saraswat & Apparao (1992) reported the detection of X-ray pulsations from 4U 2206+54 with a period of 392s from EXOSAT observations. However, Corbet & Peele (2001) argued that the period search technique used by Saraswat & Apparao (1992) was inappropriate in searching for coherent variability. Corbet & Peele (2001) reanalyzed the same EXOSAT data set and did not find any evidence for pulsations. In addition, Corbet & Peele (2001) and Negueruela & Reig (2001) analyzed Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) observations of 4U 2206+54 made in 1997 and again failed to find any pulsations. The X-ray spectrum can be well fitted with a “standard” high-mass X-ray binary spectrum (White, Swank, & Holt 1983) of a power law modified by a high-energy cut off (e.g. Corbet & Peele 2001; Masetti et al. 2004). The lack of an iron line in the spectrum (Negueruela & Reig 2001; Masetti et al. 2004) makes it similar to high-mass X-ray binaries containing Be stars rather than supergiant donors which often have significant emission near 6.4 keV (e.g. Nagase 1989). Despite the lack of pulsations, evidence for the presence of a neutron star in 4U 2206+54 has been claimed to come from X-ray spectroscopy. Masetti et al. (2004) analyzed a BeppoSAX observation of 4U 2206+54 made in 1998 and found tentative evidence for the presence of a cyclotron resonance absorption feature. Torrejón et al. (2004) analyzed the same data set together with RXTE observations made in 1997 and 2001 and also found possible evidence for the presence of a cyclotron absorption feature around 30 keV. Blay et al. (2005) also report the presence of an absorption feature near 32 keV in spectra obtained with INTEGRAL.

From an analysis of approximately 5.5 years of observations of 4U 2206+54 with the RXTE All-Sky Monitor (ASM) Corbet & Peele (2001) found modulation at a period of 9.568 ± 0.004 days. If this modulation is due to orbital variability then this would be one of the shortest orbital periods known for a Be type system (Raguzova & Popov 2005). Corbet & Peele (2001) looked for differences between “odd” and “even” outbursts that would indicate that the underlying period was actually twice this value but did not find any evidence for this. Ribó et al. (2006) analyzed additional RXTE ASM data and derived a refined period of 9.5591 ± 0.0007 days. Overall, the X-ray light curve of 4U 2206+54 differs from the majority of Be/neutron star systems in that the source does not display either periodic Type I outbursts that occur near periastron passage separated by quiescent intervals or less frequent but larger Type II events which are not modulated on the orbital period (e.g. Charles & Coe 2003). Instead, although 4U 2206+54 is very variable, particularly on shorter timescales, it is essentially persistent on long timescales.

In summary, although initial results suggested that 4U 2206+54 was a member of the
common Be/neutron star binary class of objects, further observations have called this into question. Optical spectroscopy has cast doubt on the Be star classification, and the lack of pulsations means that the nature of the presumed accreting compact object in the system is not yet securely determined. Because of the lack of pulsations from 4U 2206+54 Corbet & Peele (2001) considered alternative models for 4U 2206+54 in which the accreting object might be a white dwarf, black hole, or the magnetosphere of a neutron star rather than the surface of a neutron star.

In this paper we present an analysis of observations of 4U 2206+54 made with the Burst Alert Telescope (BAT) on board the Swift satellite. These data do not show modulation on the 9.6 day period but, unexpectedly, show a maximum in the power spectrum at twice this period. We update the ASM results and compare the folded BAT and ASM light curves and show that recent ASM data show similar behavior to that found with the BAT. We find that the phase of the BAT maxima in the light curve does not exactly coincide with either the “odd” or “even” outbursts on the 9.6 day period. We also present light curves of 4U 2206+54 obtained with the RXTE Proportional Counter Array (PCA) and High Energy Timing Experiment (HEXTE) in 2001 which cover orbital phases around the maximum in the folded BAT light curve. We make a comparison of 4U 2206+54 with other systems with somewhat similar properties. While there is some similarity with GRO J2058+42, the overall properties of 4U 2206+54 so far appear to be unique.

2. Observations

2.1. Swift BAT

The BAT is described in detail by Barthelmy et al. (2005) and data reduction is described by Markwardt et al. (2005). In brief, 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 controlled by observations using the narrow-field XRT and UVOT instruments also onboard 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. The BAT sky survey is therefore non-uniform and the signal to noise level of each observation of a source depends on the location of the source within the BAT field of view. Typically the BAT observes 50% to 80% of the sky each day. The data considered here consists of individual “snapshots” which have exposure times ranging between 150 to 2660 s with a mean of 1000 s. From these snapshots light curves are constructed in 4 energy bands: 14 to 24 (“A”), 24 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, equivalent to approximately 311, 295, 126, and 19.7 counts s\(^{-1}\) for the entire array after accounting for the 50% obscuration by the mask. The light curve used in our analysis spans the interval from MJD 53,352 to 53,633 (2004-12-13 to 2005-09-20). The fractional live time (uncorrected for partial coding) on 4U 2206+54 is 15%, that is the average exposure per day is approximately 3.6 hours. The mean efficiency due to partial coding during the observations is 58%.

2.2. RXTE ASM

The RXTE ASM (Levine et al. 1996) consists of three similar Scanning Shadow Cameras which perform sets of 90 second pointed observations ("dwell") 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 observations presented here cover the period from MJD 50,087 to 53,866 (1996-01-05 to 2006-05-11).

2.3. RXTE PCA and HEXTE

In addition to the ASM, RXTE carries two coaligned pointed instruments - the PCA and HEXTE. The PCA is described in detail by Jahoda et al. (1996). This instrument is sensitive to X-rays with energies between 2 - 60 keV and has a total effective area of ∼6500 cm\(^2\). The Crab produces 13,000 counts s\(^{-1}\) for the entire PCA across the complete energy band. Full specifications of HEXTE are given by Rothschild et al. (1998). This instrument has a ∼1600 cm\(^2\) collecting area and covers the energy range 15 - 250 keV.

Observations of 4U 2206+54 were obtained with the PCA and HEXTE between MJD 52193 to 52201 (2001-10-11 to 2001-10-19). These observations were designed to sample four phases of the assumed 9.6 day period. Spectral results from these observations are reported by Torrejón et al. (2004). For our analysis we use the “standard products” light curves
provided by the RXTE Guest Observer Facility¹ (Boyd et al. 2001). Although not intended for detailed analysis, these RXTE standard products are sufficient to provide the general light curve structure and are only used for that purpose in this paper. PCA light curves from the “Standard 2” mode are background subtracted using the appropriate model for each gain epoch and have a time resolution of 16s. In this paper we employ the 2 - 9 keV light curve. Background subtracted HEXTE light curves have a time resolution of 16s and are available for the energy ranges 15 - 30 keV, 30 - 60 keV, and 60 - 250 keV.

3. Analysis and Results

3.1. Weighting Data Points in Power Spectra

Due to various factors such as source location in the detector field of view, exposure duration, and non-uniform sky coverage, the light curves from both the BAT and ASM show considerable variability in the statistical quality of individual data points. When searching for periodic modulation it is common to calculate power spectra. Two common ways to calculate the power spectrum of a data set with non-uniform error bars are to either weight the contribution of a data point to the power spectrum (e.g. Scargle 1989) or to use uniform weighting. The use of weighting is briefly discussed for RXTE ASM data in Corbet (2003) where a weighting factor of \( y_i/\sigma_i^2 \) (“simple weighting”) was used where \( y_i \) is the value of a data point and \( \sigma_i \) is its associated error. Whether weighted or unweighted power spectra was preferred was argued by Corbet (2003) to depend on the relative size of the error bars compared to overall variability. If the scatter in data values is large compared to error bar size then weighting by error bars can be inappropriate. In addition, it was noted by Corbet (2003) that periodic or quasi-periodic changes in data quality, such as caused by the precession period of RXTE’s orbit, may introduce spurious signals in the power spectrum if weighting is used. The effects of periodicities in data quality in ASM light curves are also noted by Wen et al. (2006).

For the Swift BAT we investigated the difference between “weighted” and “unweighted” power spectra for a number of high-mass X-ray binaries with already well determined orbital and superorbital periods that covered a range of count rates. As a quality parameter we used the ratio of the height of the peak in the power spectrum compared to the mean noise level. We then calculated the relative peak heights measured in this way for weighted and unweighted power spectra and this ratio is plotted against count rate in Fig. 1. We find

¹http://heasarc.gsfc.nasa.gov/docs/xte/recipes/stdprod_guide.html
that, as predicted, the benefits of weighting are strongly dependent on source brightness, with weighting very beneficial for faint sources, but detrimental for bright sources. The count rate of 4U 2206+54 lies in the transition region between weighting being detrimental to beneficial. We next investigated an alternative weighting scheme ("modified weighting") which incorporates the variance due to source variability. The contribution of each data point to the power spectrum is calculated as:

\[
\frac{y_i}{((f \sigma_i)^2 + V_S)}
\]

where \(V_S\), the estimated variance due to source variability, is estimated by calculating the difference between the observed variance and the mean square of the error bar sizes. i.e.:

\[
V_S = \frac{\sum_{i=1}^{N}(\bar{y} - y_i)^2}{(N - 1)} - \frac{\sum_{i=1}^{N}(f \sigma_i)^2}{N}
\]

The factor \(f\) is a correction to nominal error on each point, it is derived from observations of sources expected to be constant such as supernova remnants and galaxy clusters and is set so that the \(\chi^2\) value for constant count rate becomes 1. For the BAT the correction factor adopted was 1.2. For cases where the calculated value of \(V_S\) was found to be less than zero it was set equal to zero. A comparison of peak detection significance using this modified weighted scheme is also shown in Fig. 1. We note that the modified weighting is comparable to simple weighting for the weakest sources and is essentially equivalent to unweighted power spectra for the brightest sources. For sources with count rates comparable to 4U 2206+54 (IGR J19140+0951 and IGR J17252-3616) we find that modified weighting results in period detections which are more significant than if either simple weighting or no weighting is used. The modified weighting scheme was found to be at least as good as, and often superior to, both unweighted and simply weighted power spectra for all except the very faintest sources. We therefore employ this modified weighting for all power spectra in this paper.

### 3.2. BAT and ASM

The light curves of 4U 2206+54 obtained with the BAT and ASM are shown in Figs. 2 and 3. 4U 2206+54 is seen to be very variable as reported in Corbet & Peele (2001). However, there is no long term trend in the source brightness, and there are no obvious exceptionally bright or faint states that the source remains in for any extended period of time.

The weighted mean count rate from 4U 2206+54 for the entire BAT energy range is 3.3 \(\times\) \(10^{-4}\) \(\pm\) 1 \(\times\) \(10^{-6}\) (statistical) counts s\(^{-1}\) which corresponds to 7.3 mCrab. In the four
energy bands the weighted mean count rates and their statistical errors are A: $1.61 \times 10^{-4} \pm 5 \times 10^{-6}$ counts s$^{-1}$ (8.5 mCrab), B: $1.22 \times 10^{-4} \pm 5 \times 10^{-6}$ counts s$^{-1}$ (6.7 mCrab), C: $4.3 \times 10^{-5} \pm 3 \times 10^{-6}$ counts s$^{-1}$ (5 mCrab), and D: $7 \times 10^{-7} \pm 2 \times 10^{-6}$ counts s$^{-1}$ (< 2 mCrab).

The weighted mean ASM count rate from 4U 2206+54 is $0.365 \pm 0.004$ (statistical) counts s$^{-1}$, equivalent to 4.9 mCrab. In each ASM energy band the weighted mean count rates and statistical errors are $0.050 \pm 0.002$ (A), $0.079 \pm 0.002$ (B) and $0.178 \pm 0.003$ (C) counts s$^{-1}$, corresponding to 1.9, 3.4, and 7.0 mCrab respectively.

In a light curve averaged over intervals of one day the mean significance with which 4U 2206+54 was detected in the BAT is 2.5σ. For the ASM the mean significance with which 4U 2206+54 was detected is 1.4σ for the total light curve, and 1.14σ for just the interval coinciding with the BAT observations. The BAT thus detects 4U 2206+54 at a higher average significance than does the ASM. However, due to the differences in the way ASM and BAT observations are obtained the ASM provides more uniform coverage than does the BAT.

We searched for periodic modulation from 4U 2206+54 by first calculating the power spectrum of the BAT light curve for the entire 14 - 195 keV energy range and this is shown in the lower panel of Fig. 4. No signal is present at the previously reported 9.6 day period, instead the strongest peak is at a period of 19.28 days at a level of 19 times the mean value of the power spectrum and $\sim$6 times the local power level. This period coincides to better than 1% with twice the 9.6 day period. We will use the term “2P” hereafter to refer to the period of twice the originally proposed orbital period near 9.6 days, i.e. 19.118 days.

We next calculated the power spectrum of each BAT energy band separately and the results for bands A and B are also shown in Fig. 4. Band A shows multiple peaks in the power spectrum including one near 19.28 days. and the power spectrum of Band B has its strongest peak at 19.28 days at a level of 19 times the mean power, and $\sim$7 times the local power. Apart from the peak at 19.28 days, there are less strong peaks in the B band power spectrum than in the lower energy A band power spectrum. For neither spectrum do any of the peaks appear to be related to each other as harmonics or aliases. The BAT power spectra thus demonstrate the considerable variability on a variety of timescales commented on in previous work (Section 1). However, the clear discrepancy from previous work is the lack of significant modulation at 9.6 days.

We divided the B band light curve into two halves and examined the power spectra of these separately. In both cases we see peaks near 19 days and no significant peak near 9.6 days. Results are not shown in Figure 4 for bands C and D due to the low count rates in
these bands.

We next calculated the power spectrum of the RXTE ASM to search for modulation at a period of twice the previously reported value. Although the modified weighting described in Section 1 was employed with an error bar modification factor, $f$, of 1.27 this procedure gave an estimated source variance, $V_s$, of zero and hence was equivalent to simple weighting. The resulting power spectrum (Fig. 5) shows a low amplitude structured peak containing 2P with strongest power at 19.27 days.

We next folded both the ASM and BAT data on 2P using simple weighting and the results are shown in Fig. 6. The ASM and BAT A and B band data all show clear modulations. However, as expected from the power spectra, the ASM light curve shows two nearly equal peaks, whereas the BAT A and B bands shows only a single broad peak. We note that the peaks in the folded BAT light curves do not appear to coincide in phase with either peak in the ASM folded light curve. In these folded light curves we also note the possible presence of a brief flux increase in the folded BAT 14 - 24 keV light curve near a phase of 0.75 (for a period of 2P). Although possible corresponding features may also exist in the folded ASM light curves and the 24 - 50 keV BAT light curve, when the BAT light curve is divided into two halves we find that this is not a persistent feature of the light curve. The folded ASM overlap light curve also does not show any significant feature near a phase of 0.75.

To further quantify periodic modulation we next fitted sine waves to the non-folded ASM (1.5 - 12 keV) and BAT (24 - 50 keV) light curves. In these fits data points were weighted by their individual errors. From the ASM dwell data we obtain a period of 9.5592 ± 0.0010 d. This is consistent with the value of 9.5591 ± 0.0007 d obtained by Ribó et al. (2006). The epoch of maximum flux was found to be MJD 53567.74 ± 0.23. From the BAT data we obtained a period of $2P = 19.25 ± 0.08$ d, equivalent to $P = 9.625 ± 0.04$ d. The periods derived from the ASM and BAT are thus consistent (when the factor of 2 period difference is allowed for) to within 0.6%, equivalent to a 1.6$\sigma$ difference. To quantify any phase difference we next fixed the BAT period at twice the ASM derived value and allowed just the phase and amplitude of the sine wave to float. We find that the zero crossing phases of the sine fits to the ASM and BAT light curves are consistent within the errors. Since the period found with the BAT is twice the length of that derived from the ASM, the maximum of the BAT curve thus occurs later than the corresponding maximum in the ASM light curve by 2.39 ± 0.5 days, equivalent to a phase difference of 0.125 ± 0.026 for a period of 2P. The results of the fits to the non-folded light curves are also plotted over the folded light curves in Fig. 6.

To investigate any changes in periodic modulation in the ASM light curve we calculated power spectra for subsets of the data using a sliding box. Power spectra were calculated for
two year long subsets of ASM data starting from the first observations and incrementing the
start of the data subset by one year, resulting in a total of 10 power spectra. The results of
this procedure in a region covering both 9.6 days and 2P are shown in Fig. 7. We note that
the modulation at 9.6 days is, in general, stronger in the first five years of ASM observations.
In the power spectra from the most recent subset the strongest power in this frequency range
is found at 2P, consistent with the BAT results. We also folded the data in the same subsets
on a period of 2P and these are shown in Fig. 8. We note that the earlier subsets show the
expected two peaks while the last subset shows a profile comparable to that seen with the
BAT with a single maximum at similar phase. In order to evaluate changes in the profile we
first constructed a template using the mean of the first two statistically independent profiles
(those shown in Fig. (a) and (c)). This template was then subtracted from all profiles and
these new profiles are shown in Fig. 9. None of the profiles shows large systematic deviations
from the template profile with the exception of the profile from the most recent observations
(Fig. 9 (j)) where a pronounced feature near phase 0.3 is present.

3.3. PCA and HEXTE

The light curves obtained with the PCA and HEXTE are shown in Fig. 10. The
modulation of the PCA light curve is consistent with the folded ASM light curve. However,
the HEXTE light curves, which cover similar energy ranges to the BAT, do not show similar
behavior to the folded BAT light curve and appear to follow the PCA light curve. In
particular the HEXTE light curves do not show a minimum near phase 0.5 which would be
expected if they followed the behavior seen with the BAT. However, some caution should
be taken in interpreting these observations as 4U 2206+54 shows significant apparently non-
periodic behavior which can affect a short data set such as this.

4. Discussion

4.1. Periodic Modulation and the Orbital Period

The BAT light curve of 4U 2206+54 shows modulation at a period twice that previously
derived from RXTE ASM data. If this modulation is orbital in origin then it suggests
that the underlying orbital period may actually be double the previously proposed value.
The BAT light curve covers 282 days, equivalent to more than 14 “2P” cycles and thus
the apparent period doubling is unlikely to be a purely stochastic effect caused by a small
number of unusually bright maxima. 4U 2206+54 thus shows either an energy dependent
number of X-ray maxima per orbit, or else it underwent a transition between exhibiting two maxima per orbit to a state of a single maximum per orbit. The energy-dependent modulation hypothesis may be supported by the shape of the folded BAT “A” band light curve which has an appearance suggestive of a mix of the two types of modulation. Thus a change in the nature of the periodic modulation may occur in the range of 14 - 24 keV. However, evidence that argues against this hypothesis is: (i) The shape of the HEXTE light curve (Fig. 7) does not follow the folded BAT light curve (although non-periodic modulation presumably also contributes to the observed light curve). (ii) The most recent ASM data folded on 2P show the same morphology as the BAT light curve (Fig. 6).

In principle, optical radial velocity measurements could be used to determine the orbital period of 4U 2206+54 unambiguously. Blay (2006) presents such measurements obtained in 2002, 2003, and 2004. However, none of the individual campaigns cover substantially more than 9.6 days. Blay (2006) reports that the power spectrum of the complete set of radial velocity observations does not show a clear peak at 9.6 days, but instead shows a maximum at 14.89 ± 0.07 days which he interprets as an artifact, perhaps related to noisy data. The currently published radial velocity measurements are thus not yet capable of independently determining the orbital period of 4U 2206+54.

It could be possible that the periodic changes in the high-energy emission from 4U 2206+54 are not due to orbital effects but are caused by super-orbital modulation. For example, a 30.7 day super-orbital period is seen the peculiar high-mass X-ray binary 2S 0114+650 (Farrell, Sood, & O’Neill 2006) in which accretion occurs from the wind of a supergiant B1 star (Reig et al. 1996). However, it would still be difficult to understand how a period doubling would occur. If the periodic modulation in 4U 2206+54 is indeed a super-orbital effect then modulation at the orbital period is apparently lacking.

Modulation of X-ray emission on the orbital period in a high-mass X-ray binary may occur in several different ways (e.g. White, Nagase, & Parmar 1995 and references therein). If the orbit is eccentric then enhanced emission can occur at periastron passage. For 4U 2206+54 Ribó et al. (2006) attributed the periodicity in the X-ray flux seen with the ASM to modulation caused by an eccentric (e = 0.15) orbit but the difference between the BAT and ASM periods cannot be explained by this simple model alone. If the primary star is large compared to the orbital dimensions (e.g. it is a supergiant) then eclipses are often observed. Variable absorption may also be seen as the neutron star moves in its orbit. In addition, if the orbital plane is inclined to the plane of an equatorial circumstellar disk, such as can be present in Be stars, then two outbursts per orbital period may be possible when the neutron star passes through this disk. If the disk shrinks or expands this could potentially change the number of outbursts observed per orbit. Similar effects could arise if there is a
change in the angle between the orbit of the neutron star and the disk.

We next summarize results on some X-ray binaries which have the characteristics of either showing two maxima per orbital cycle, energy dependent modulation, or phase change in the epoch of flux maximum, and so might provide an insight into the variability of 4U 2206+54.

The Be/neutron star binary GRO J2058+42 was initially reported to have a 110 day period seen in CGRO BATSE (20 - 50 keV) data. Strong outbursts every 110 days were accompanied by weaker outbursts halfway between these. However, RXTE ASM observations showed an underlying 55 day period (Corbet, Peele, & Remillard 1997). Wilson et al. (1998) find that there is a clear energy difference in the size of the outbursts detected and these authors proposed that the orbital period of the system is 110 days with outbursts occurring at both periastron and apastron passage. The energy dependence of the underlying period in GRO J2058+42 has some apparent similarities to what is seen in 4U 2206+54. However, for GRO J2058+42 no phase shift is observed. Wilson et al. (2005) also report that pulse frequency changes seen during the outbursts are consistent with a 55 day period.

The supergiant system 4U 1907+09 was found by Marshall & Ricketts (1980) to exhibit two outbursts per orbital cycle, separated by approximately 0.45 in phase. Marshall & Ricketts noted that: “the amplitudes of the secondary maxima are more variable than those of the primary maxima ranging from being approximately equal in flux down to insignificance.” in ’t Zand, Baykal, & Strohmayer (1998) speculated that the two flares per orbital cycle might indicate that the wind from the supergiant primary is not isotropic and the flares may occur when the neutron star crosses the equatorial plane of the primary where there is an enhanced wind. In the supergiant high-mass X-ray binary 4U 1223-62 (GX 301-2) evidence has also been reported for the presence of flares at apastron in its eccentric 41.5 day orbit in addition to the large flares that occur shortly before periastron (Pravdo et al. 1995, Pravdo & Ghosh 2001). For 4U 1223-62 the size of the apastron flare has always been observed to be much smaller than the periastron flare.

The phase difference between the ASM and BAT light curves could also potentially be a secular or an energy dependent effect. For the Be/neutron star binary EXO 2030+375, which has an orbital period of 46 days, a temporary change in the phase of maximum flux was seen to occur in both RXTE ASM and BATSE data (Wilson et al. 2002) with a difference of about 10 days. No period change accompanied this temporary phase shift. Corbet (2003) reported evidence for a 24 day period in the low-mass X-ray binary GX 13+1 from RXTE ASM observations and that the higher energy (5 - 12 keV) emission trailed the lower energy (1.5 - 5 keV) by a phase difference of 0.2 ± 0.03.
Of the sources considered above, while none exhibits exactly the same behavior shown by 4U 2206+54, a possible similarity with GRO J2058+42 may exist in the apparent factor of two difference in orbital periods found by two different instruments at different times. However 4U 2206+54 has several differences including the presence of pulsations in GRO J2058+52 and the possible difference in the nature of the mass donor. The variable secondary maxima exhibited by 4U 1907+09 may also be similar to the behavior shown by 4U 2206+54 although there is again a difference in the nature of the mass donor.

While the systems discussed here provide hints of how an underlying orbital period at 2P might show itself as modulation at half that period, it appears even more difficult to understand how a ∼9.6 day long orbital period could produce modulation at twice that period. We therefore suggest that it is more likely that the orbital period of 4U 2206+54 is 2P, that is, it is ∼19.2 days.

If 4U 2206+54 is at least similar to Be star systems, then the correlation between orbital period and pulse period for these objects (Corbet 1986) predicts a pulse period of a few seconds for an orbital period of 19.2 days. However, a 19.2 day period is still relatively short for a Be star system. The only two objects currently known with shorter orbital periods are A0538-66 with an orbital period of 16.7 days which has an exceptionally short pulse period of 69 ms (Skinner et al. 1982) and SAX J2103.5+4545 with an orbital period of 12.7 days and a pulse period much longer than expected from the pulse/orbital period correlation of 358.6s (Baykal, Stark & Swank 2000). These two unusual sources may provide a hint that the orbital period correlation could break down at short orbital periods,

4.2. Luminosity

Corbet & Peele (2001) considered the 2 - 10 keV luminosity of 4U 2206+54 at ∼10^{35} ergs s^{-1} to be surprisingly low for the assumption of a 9.6 day orbital period and a Be star mass donor. In contrast, Ribó et al. (2006) determine the mass donor not to be a Be star and thus they consider the “high” luminosity in need of explanation due to the relatively weak wind they predict compared to the extensive circumstellar envelope that would be present around a Be star. With a 19.2 day orbital period the luminosity would be expected to be lower than for a ∼9.6 day period, due to the expected lower mass transfer rate, and therefore not atypical for a Be star system. The modeling of Ribó et al. (2006) would need to be reevaluated for the new system parameters to determine whether their model is still tenable. For comparison, two Be star systems with orbital periods close to 19.2 days are 4U 1901+03 (22.6 days; Galloway, Wang, & Morgan 2005) and 4U 0115+63 (24.3 days; Rappaport et al. 1978, Bildsten et al. 1997). The luminosity ranges exhibited by both these sources are
very large and thus very different from the variability seen so far from 4U 2206+54. 4U 0115+63 has been detected at luminosities between $\sim10^{38}$ and $\sim10^{38}$ ergs s$^{-1}$ (Campana et al. 2001 and references therein). Although the distance to 4U 1901+03 is unknown, this source also exhibits considerable variability. Galloway et al. (2005) report RXTE PCA and ASM observations where 4U 1901+03 reached a peak luminosity of $\sim10^{38}$ $(d/10$ kpc)$^2$ ergs s$^{-1}$ before fading to a level $>\sim 100$ times less.

5. Conclusion

The ASM and BAT light curves show that strong modulation at a period of 9.6 days is not a persistent feature of the light curve of 4U 2206+54. The BAT light curve of 4U 2206+54 shows a modulation at twice the period previously found from RXTE ASM observations. A detailed examination of the ASM light curve also demonstrates a change in the nature of the modulation. The orbital period of 4U 2206+54 might thus be twice the originally proposed value of 9.6 days. Although the mechanism causing the variable modulation in 4U 2206+54 is not yet clear, a model where there is an equatorial concentration of the wind from the primary star and the equatorial and orbital planes are offset may be able to explain at least some of the observed properties. It would be very valuable if a radial velocity orbit could be obtained from optical observations as this should conclusively give the value of the orbital period, show the relative orientation of the binary components at the times of X-ray maxima, and give the orbital eccentricity. If the period doubling is caused by a change in the circumstellar environment in the system, then this may also show effects in the optical spectrum such as the strength or shape of the H$\alpha$ emission line. Continued high-energy monitoring of 4U 2206+54 with the BAT and/or ASM will show how long the change to the period doubled state continues which may assist in understanding its cause.

The nature of 4U 2206+54 continues to be puzzling and the determination that the 9.6 day modulation is not a persistent feature of the light curve adds to the peculiarities of the source. The exceptional properties of 4U 2206+54 may be related to the unusual nature of the mass donor in the system. 4U 2206+54 may thus provide a new parameter regime where models of wind accretion may be tested.

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Figure Captions

Fig. 1.— Comparison of power spectrum weighting techniques in detecting periodic modulation in BAT light curves. The black circles show the ratio of signal peak sizes between power spectra weighted with simple weighting and no weighting, and the blue crosses show the ratio between “modified weighting” and no weighting. Details are given in Section 3.1. The horizontal dashed line shows the division between weighting being better or worse for peak detection, i.e. whether the peak in the weighted or unweighted power spectrum is larger. The vertical dashed line shows the count rate of 4U 2206+54. Systems on this plot and their mean count rates are: X 0726-260 (3.8×10^{-5}), IGR J11435-6109 (0.0001), IGR J19140+0951 (0.00035), EXO 1722-363 (0.00036), XTE J1855-026 (0.00047), IGR J16320-4751 (0.00055), X 1907+097 (0.00069), LMC X-4 (0.00078), X 1538-522 (0.00079), EXO 2030+375 (0.0019), SMC X-1 (0.0022), Cen X-3 (0.0023), OAO 1657-415 (0.0026), GX 301-2 (0.0075), X 1700-377 (0.0085), and Vela X-1 (0.0089).

Fig. 2.— RXTE ASM (lower panel) and Swift BAT (upper panel) observations of 4U 2206+54. Both light curves are heavily smoothed one day averages.

Fig. 3.— RXTE ASM (lower panel) and Swift BAT (upper panel) observations of 4U 2206+54 from the time around the BAT observations only. Both light curves are two day averages with no additional smoothing. Only points which contain at least two “snapshots” are plotted.

Fig. 4.— Power spectra of BAT light curves of 4U 2206+54 for the entire BAT energy range and the two lower energy range bands. Results from the two higher energy bands are not plotted due to their low count rates. The blue dashed lines indicate the 9.6 day period previously found from the RXTE/ASM and the red dashed lines show twice this period. No peak is present in any power spectrum at the 9.6 day period.

Fig. 5.— Power spectrum of the RXTE/ASM light curve of 4U 2206+54. The blue dashed line shows the period previously found with the ASM and the red dashed line indicates twice this period (“2P”).

Fig. 6.— RXTE/ASM and BAT light curves of 4U 2206+54 folded on “2P”. The dashed lines in the top and bottom panels indicate the results of sine wave fits to the non-folded light curves. The upper panel shows the RXTE ASM full energy range light curve for just the region that overlap the BAT light curve folded on 2P.

Fig. 7.— Power spectra of the RXTE/ASM light curve calculated from two year subsets of the data with each subset offset by one year from the next. The vertical dashed lines
indicate “2P” (red) and the previously reported 9.6 day period (blue). The time ranges used for analysis in each section were: (a) MJD 50087 - 50817; (b) 50452 - 51182; (c) 50817 - 51547; (d) 51182 - 51912; (e) 51547 - 52277; (f) 51912 - 52642; (g) 52277 - 53007; (h) 52642 - 53372; (i) 53007 - 53737; (j) 53372 54102.

Fig. 8.— RXTE/ASM light curves of 4U 2206+54 folded on a period of 2P. The ASM light curve was divided into the same sections used in Fig. 7.

Fig. 9.— RXTE/ASM light curves of 4U 2206+54 folded on a period of 2P with the mean profile in Fig. 8 (a) and (c) subtracted. The light curve was divided into the same sections used in Figs. 7 and 8.

Fig. 10.— RXTE PCA, ASM, and HEXTE light curves of 4U 2206+54 obtained in 2001. The 15 - 30 and 30 - 250 keV HEXTE light curves were rebinned by factors of 2 and 4 respectively compared to the original standard products. The boxes indicate the mean count rate, plus and minus the standard error on this value during each of the four PCA and HEXTE observations.
Power (BAT Counts/s) $^2$ Power (BAT Counts/s) $^2$

Frequency (day $^{-1}$)
Phase (period = 19.1184)

ASM: 1.5 − 5 keV

Counts/s

ASM Overlap

Counts/s

BAT: 24 − 50 keV

Counts/s

BAT: 14 − 24 keV

Counts/s

ASM: 5 − 12 keV

Counts/s

ASM: 1.5 − 5 keV

Counts/s

Phase (period = 19.1184)