Super-orbital Period in the High Mass X-ray Binary 2S 0114+650

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ABSTRACT

We report the detection of a stable super-orbital period in the high-mass X-ray binary 2S 0114+650. Analyses of data from the Rossi X-ray Timing Explorer (RXTE) All-Sky Monitor (ASM) from 1996 January 5 to 2004 August 25 reveal a super-orbital period of 30.7 ± 0.1 d, in addition to confirming the previously reported neutron star spin period of 2.7 h and the binary orbital period of 11.6 d. It is unclear if the super-orbital period can be ascribed to the precession of a warped accretion disc in the system.

Key words: accretion, accretion discs - stars: neutron - X-rays: binary

1 INTRODUCTION

The X-ray source 2S 0114+650 was discovered in 1977 during the SAS 3 Galactic survey (Dower & Kelley 1977). Its optical counterpart, LSI +65° 010 was identified as an 11 mag B star with a broad Hα emission line (Margon & Bradt 1977). Spectroscopic observations by Crampton, Hutchings & Cowley (1985) from 1979 to 1985 led these authors to conclude that optically this system resembled supergiant X-ray binaries similar to Vela X-1, while its X-ray properties were more aligned to those of Be X-ray binaries. Reig et al. (1996) carried out further long term optical and infrared studies in the period 1990-1995, and reclassified the optical counterpart as a supergiant of spectral type B1 and luminosity class Ia, at a distance of 7.0 ± 3.6 kpc.

The binary nature of 2S 0114+650, with a period of 11.59 d was also optically confirmed by Crampton et al. (1985). Koenigsberger et al. (1983) using Einstein, HEAO 1, and OSO 8 data, and Yamauchi et al. (1990) using Ginga data had reported compact object pulse periods of 894 s and 850 s respectively. However, analysis of EXOSAT data by van Kerkwijk & Waters (1989) and Apparao, Bish & Singh (1991) failed to confirm these periodicities. X-ray data from EXOSAT and ROSAT spanning seven years from 1983 to 1990 were analysed by Finley, Belloni & Cassinelli (1992), who discovered a 2.78 h periodicity and attributed it to β Cephei-type pulsations of the donor star. Corbet, Finley & Peele (1999) analysed Rossi X-ray Timing Explorer (RXTE) All Sky Monitor (ASM) data covering the period 1996 January 5 to 1998 July 3 and concluded that the X-ray pulse properties at the period of 2.7 h could be best explained if they emanated from accretion on to a slowly rotating, highly magnetised neutron star. These authors also confirmed the orbital period reported by Crampton et al. (1985), but with a difference of 0.04 ± 0.01 d between the optical and X-ray periods. The 2.7 h spin period is by far the slowest known for an X-ray pulsar, and compares with the other known periods between 69 ms and 1400 s. Li & van den Heuvel (1999) have shown that such a slow pulsar is possible within the lifetime indicated by the early type companion if the pulsar was born as a magnetar with a magnetic field of ≥ 10¹⁴ G. The field would have decayed to a present value of ~ (2-3) × 10¹² G on a timescale of ≤ 10⁵ yr. In this paper we report the results of analyses of RXTE ASM data covering a period of more than 8 years, which have revealed a strong modulation at 30.7 ± 0.1 d.

2 DATA AND ANALYSIS

Archived data from the ASM in the public domain¹ (Levine et al. 1996) obtained for the period MJD 50087 (1996 January 5) to MJD 53242 (2004 August 25) were used in these analyses. The ASM consists of three wide-angle Scanning Shadow Cameras (SSC’s) each with a 6° × 90° field of view and spatial resolution 3′ × 15′, equipped with proportional counters sensitive to X-rays in the nominal energy range 1.5 – 12.0 keV (A. M. Levine 2004, private communication). The spectral data are binned into three energy bands corresponding to 1.5 – 3.0 (soft, A), 3.0 – 5.0 (medium, B), and 5.0 – 12.0 keV (hard, C). RXTE is in a low-earth circular orbit of inclination 23°, and period ~95 min. The ASM performs 90 s pointed observations (dwell) of individual sources. ~80% of the sky is covered every orbit, with a duty cycle of ~40%.

Data from the ASM are available in two forms: count rates from individual 90 s dwells, and one-day averages for a source. Though the daily averages are more suitable for

¹ http://heasarc.gsfc.nasa.gov/docs/xte/xtegof.html
probing long-term flux variability, as the errors on flux measurements are reduced compared to the individual dwell measurements (Corbet 2003), we used the 90 s dwell data in order to investigate the spin period at a higher time resolution. The SSC3 data were not used because of that detector's performance degradation over time. Linear trends were subtracted from the SSC1 and SSC2 light curves before and after a gain adjustment that took place on MJD 51548 (Corbet 2003). Data points which had count rate errors of 1σ greater than the mean error were removed from the light curve. The correlation between flux and error in the ASM data points is very weak. The error values are determined from a model that represents the coded aperture analysis of the instrument, where it is presumed that the sources and the response functions (i.e. shadow patterns) are known (A. M. Levine 2005, private communication). A plot of the flux against errors showed no apparent correlation between the two, confirming that our screening method is not biased against times when the source flux is low. In addition, power spectra using a filtered light curve were very similar to those obtained using a weighted light curve. The reduced light curve for 2S 0114+650 for the 8.5 years of ASM data from the SSC1 and SSC2 detectors is shown in Fig. 1. The mean intensity is 0.3 counts s⁻¹ (4 mCrab) and the mean error is 0.99 counts s⁻¹.

After carrying out background subtraction and barycentric corrections we performed a Lomb-Scargle periodogram (LSP) analysis (Lomb 1976; Scargle 1982) for the SSC1 and SSC2 data. As the False Alarm Probability of a given peak in a LSP power spectrum depends on the sampling pattern of the data (Horne & Baliunas 1986), we used Monte Carlo simulations to determine the 99.9% white noise significance levels (e.g. Kong, Charles & Kuulkers 1998). The resulting power spectrum for the complete energy range 1.5 – 12.0 keV is shown in Fig. 2. The strongest peak in the spectrum is at 11.60 ± 0.02 d FWHM. This value is in agreement with the value of the orbital period as deduced by Crampton et al. (1985) from optical observations. As noted above, a previous analysis of the first two years of ASM data by Corbet et al. (1999) had revealed a value of 11.630 ± 0.02 d as the optimum value for the folded light curve. We find that the orbital period has remained stable at 11.60 ± 0.02 d during the 8.5 yr observation period discussed in this paper. Fig. 2 also shows a marginally significant peak at 2.73 h, which has previously been associated with the pulse period of the neutron star. In their analysis, Corbet et al. (1999) had noted the broad profile of this peak. They had also seen a subsidiary peak at 25.65 h which they had provisionally attributed to daily variations in background levels. This peak is not significant in our data (Fig. 2). We have made a detailed investigation of the occurrence of peaks around 24 h in ASM data for several celestial sources, and ascribe them primarily to spectral leakage of low frequency power present in the light curves (Farrell, O’Neill & Sood 2005).

We have examined the evolution of the neutron star spin period in 2S 0114+650 using ASM data over the period MJD 50087 – 53242. The ~8.5 yr light curve was split into 14 smaller overlapping data sets each 400 d in length. These sections were then analysed separately using the LSP technique. The results are shown in Fig. 3. While the ~2.7 h period was not significantly detected in all the data sub-sets, we confirm the neutron star spin values previously derived by Corbet et al. (1999), Hall et al. (2000), and Bonning & Falanga (2005) for overlapping time intervals. A decrease in the spin period of the secondary was first noted by Hall et al. Our detailed analysis shows two episodes of torque reversal, each on a time scale of ~400 days. These episodes are not accompanied by a significant change in the X-ray flux from the source.

In addition to the previously reported periodicities in the ASM data as described above, Fig. 2 shows a strong peak at ~30 d period. This peak is well above the 99.9% white noise significance level as determined from Monte Carlo simulations. We also simulated a light curve, using the same sampling as our data, with modulations at both the 2.7 h pulse and the 11.6 d orbital periods. A periodogram calculated from this light curve showed no power at around 30 d, confirming that the observed 30.7 d peak is not a result of spectral leakage from the pulse or orbital periods. A follow-up χ² epoch-folding search of the data yielded a best-fit period of 30.7 ± 0.1 d FWHM. The analysis gave an ephemeris of MJD 50108.2 (± 0.4) + 30.7 (± 0.1)N, where N is the cycle number. The phase variability of 2S 0114+650 over this period is shown in Fig. 4. Phase zero is defined as the modulation minimum, and the modulation has full amplitude of 66 ± 25%. We interpret this modulation as a previously
Following the announcement of this discovery in ATEL #283, albeit at an unspecified length of ASM data set by Benlloch (PhD thesis, Univ. of T¨ ubingen, 2004), the unreported super-orbital period in the 2S 0114+650 system (Farrell, Sood & O’Neill 2004)².

In order to confirm that there was no contamination in the 2S 0114+650 data from other neighbouring known sources, we performed a similar analysis on ASM data from the nearby 3.6 s X-ray pulsar 4U 0115+634, and the LMXB pulsar 4U 0142+614. While the LSP showed a strong peak at ~24 h (discussed above) in 4U 0115+634, no significant power was found in either source at any of the periods associated with 2S 0114+650.

The 2S 0114+650 data for the three energy bands were analysed separately to investigate the energy dependence of the temporal variation of the X-ray flux. The power spectra for the individual energy bands are shown in Fig. 5. There are no significant periodicities in the 1.5 – 3.0 keV (A) band. The 11.6 d orbital period is highly significant in the 3.0 – 5.0 keV (B) band, with the 30.7 d super-orbital period appearing at the > 99% significance level. Both the orbital period, and the super-orbital period stand out strongly in the 5.0 – 12.0 keV (C) band, while the spin period marginally exceeds the 99% white noise significance line. The A, B and C channel light curves folded at the 30.7 d super-orbital period are shown in Fig. 6.

We also checked to see if the C/B and B/A hardness ratios revealed any periodic modulation. We generated power spectra after discarding ~15% of the hardness ratio data points which had B and A values close to zero. The power spectra showed no significant modulation at any period. Note that Corbet et al. (1999) also found that the ASM data are not of a sufficient quality to establish whether the hardness ratio varies with the orbital period.

It is useful also to investigate explicitly whether the X-ray spectrum varies as a function of the phase of the super-orbital period because these flux variations might be owing to changes in absorption. Using the A, B and C channel light curves, folded at 30.7 d (see Fig. 6), we calculated the folded time-series of the C/(A + B) hardness ratio. First, we fitted the time-series with a constant hardness, which yielded a satisfactory fit ($\chi^2$/D.O.F. = 16.3/9; null hypothesis probability 0.061). We then added a sine curve to the model with the same phase as the observed 30.7 d flux modulation. The 90% confidence interval ($\Delta \chi^2 = 2.71$) of the amplitude was found to be from −0.4 to 0.4. This confidence interval corresponds to a 90% upper limit on the peak-to-peak amplitude of 0.8, either in phase or $\pi$ radians out-of-phase with the intensity modulations. We conclude that the ASM data are not of sufficient quality to confirm or preclude variable absorption as the mechanism behind the super-orbital modulation.

We also confirmed that the 11.6 d orbital period modulation was not distorting the results obtained for the super-orbital modulation. The orbital period was removed by subtracting a sine curve fitted to the light curve folded at 11.6 d. This procedure produced only a slight amplitude shift of the super-orbital modulation from 0.20 c/s (66%) p-p to 0.19 c/s (64%) p-p.

In order to determine whether the 30.7 d super-orbital period is persistent and coherent, we split the light curve into four ~800 d sub-sets covering the ranges MJD 50134 – 50934, MJD 50935 – 51733, MJD 51735 – 52534, and MJD 52535 – 53242. Each sub-set was analysed using the LSP technique, and then folded at the 30.7 d period with an epoch of MJD 50108.2. Fig. 7 shows the folded light curve sections. The super-orbital period is not significantly present in the power spectrum of the first two years of the RXTE ASM data (the MJD 50134 – 50934 data set), although there does appear to be a very small amplitude modulation in the folded light curve. This would explain why the 30.7 d period did not show up in the power spectrum of these data in the work of Corbet et al. (1999). The modulation does however show up clearly in the other three data sets with minimal variation in phase, although the amplitudes vary considerably.

We have examined the evolution of both the super-orbital and orbital periods using the same method described earlier for the spin period, with the results shown in Fig. 8. The spin evolution trend has been overlaid for comparison. The super-orbital period appears to have varied slightly throughout the mission lifetime, although the relatively large error bars prohibit a definitive conclusion. It is quite clear however that the 30.7 d period has not been.

² Following the announcement of this discovery in ATEL #283, it was brought to our attention by Dr. J. Wilms that this periodicity had been seen for an unspecified length of ASM data set by Benlloch (PhD thesis, Univ. of Tübingen, 2004), albeit at a much lower significance level.
evolving in concert with the spin period. As expected the orbital period has not been varying over time, although the location of the peaks in the LSP power spectra appear to shift slightly in unison with a similar periodic shift in the super-orbital period.

3 DISCUSSION

Super-orbital (long) periods are known to exist in more than 20 high-mass and low-mass X-ray binaries, and their values range from 24 to 600 d (e.g. Ogilvie & Dubus 2001). Her X-1, LMC X-4, and SS 433 have super-orbital periods which are very stable (Paul & Kitamoto 2002), and we have demonstrated above that 2S 0114+650 is the fourth such system with a stable period. The mechanism behind these periods is generally not well-understood, though the precession of a radiation-warped accretion disc modulating the X-ray flux from the compact object is the favoured model (e.g. Clarkson et al. 2003). Ogilvie & Dubus (2001) have shown that radiation driven warping gives a coherent picture of super-orbital periods, but that the model does not explain the phenomenon in all X-ray binaries. Other models for super-orbital periods include (i) variations in the rate of Roche-lobe overflow caused by stellar pulsations of the donor (Weiler et al. 1992), (ii) the precession of the magnetic axis of the compact object (Trümper et al. 1986), (iii) a triple star system (Chou & Grindlay 2001), and (iv) variations in the location of an accreting hot-spot (Rutten, van Paradijs & Tinbergen 1992). We now discuss the likely phenomenon leading to a super-orbital period in 2S 0114+650.

2S 0114+650 shares luminosity ($3.4 \times 10^{35}$ erg s$^{-1}$ at 3 – 20 keV) and spectral characteristics with systems that contain pulsars in wind-driven HMXRBs, though some uncertainty remains over its optical spectral characteristics. The hydrogen column density is estimated at $(1.3 – 9.4) \times 10^{22}$ cm$^{-2}$, with the lower value being an upper limit to interstellar absorption (Reig et al. 1996). It is therefore clear that significant and variable absorption takes place in the vicinity of the X-ray source. However, the structure of the absorbing region is not certain. It may be in the form of a precessing accretion disc, or a dense circumstellar environment. There are arguments against the existence of an accretion disc in 2S 0114+650. The formation of an accretion disc is expected only when the Keplerian radius $r_k$ of orbiting matter of specific angular momentum $l$ is larger than the magnetospheric radius $r_m$ of the neutron star of mass $M_x$, where $r_k = l^2 / GM_x$ (Nagase 1989). The value of the stellar wind velocity (1200 km s$^{-1}$) far exceeds the calculated upper limit value ($\sim 280$ km s$^{-1}$) necessary for the formation of an accretion disc in 2S 0114+650. Additionally, the HeII 4686Å line emission, a common feature of the inner regions of a heated disc in X-ray binaries, has not been observed from this system (Koenigsberger et al. 2003).

The fractional amplitude of the variations of the X-ray flux arising from the precession of an accretion disc should be largest in the low energy bands of the ASM, because the soft X-rays are absorbed more than the hard X-rays. As
that optical variability on the time scale of months to years was not a feature of 2S 0114+650. Variations in mass loss rate are also not expected to show precision timing at the super-orbital period when considered over a period of several years.

More significant is the fact that there is one other report in the literature of a periodicity in 2S 0114+650 at ~30 d. This relates to the work of Beskrovnaya (1988) who carried out UBVRI polarimetry of the optical counterpart LSI +65° 010 over a two month period in 1986. He confirmed the variability of the normalised Stokes parameters Q/I and U/I over the 11.6 d orbital period, and stated that “there also seems to be an auxiliary source of variability, with a characteristic time scale of roughly a month”. The donor star has a strongly ionised wind, and this could be a dominant source of the linear polarisation, resulting from single electron scatter. Note that the presence of an accretion disc cannot be ruled out on the basis of the polarisation observations, as a correlation between the polarisation parameters and the orbital phase is expected in X-ray binaries that contain accretion discs (e.g., Phillips & Meszaros 1986). Alternatively, the precession of the magnetic axis of the neutron star could conceivably result in varying irradiation of the circumstellar material, leading to a natural explanation for the 30-d variation in the polarisation, and the observed super-orbital period. This mechanism was initially proposed for Her X-1, in which the 1.24 s pulse profile changes with the system’s super-orbital phase (Trümper et al. 1986). These authors showed that the necessary external torque supplied by an accretion disc in Her X-1 to cause forced precession was deficient by a factor of 10⁶. Similar consideration must apply to 2S 0114+650, even though a correlation between the pulse and super-orbital periods is difficult to establish because of the limitations of the ASM data for this source, and due to the weakness of its flux density (Fig. 1 and 2). When internal magnetic stresses are large enough, the free precession of a rotating neutron star with an oblique magnetic field has been shown to be inevitable (Wasserman 2003). However, the predicted precession period for the neutron star in 2S 0114+650, with a slow spin period of 2.7 h, turns out to be orders of magnitude larger than 30.7 d for accepted values of the parameters involved.

The picture is further complicated if one plots the spin/orbital behaviour of 2S 0114+650 on the Corbet diagram (Corbet 1986), which shows the relation between the spin period $P_s$ and the orbital period $P_o$ for accreting neutron stars. The expected relationship (Corbet 1986) is explained by the neutron star being in a state of quasi-equilibrium in which the Alfven and co-rotation radii of the neutron star are approximately equal. The size of the Alfven radius depends on the density of the circumstellar material, which in turn will depend on the binary separation. The observed relationship is shown in Fig. 9 for various classes of X-ray binaries (Bildsten et al. 1997). Trends are evident for Be transients, and for Roche-lobe filling supergiants. There is no correlation for under-filled Roche-lobe supergiants. In this scheme, 2S 0114+650 belongs to the latter class of binaries, wherein an accretion disc is not present (Fig. 9). The system may be spinning up to its equilibrium state. If on the other hand, the system was near the equilibrium state, then the neutron star would need to possess a present value...
of the magnetic field of $>10^{13}$ G (Waters & van Kerkwijk 1989).

Chou & Grindlay (2001) have shown that a long period ($\sim 176$ d) in 4U 1820-30 is produced by a hierarchical triple outer companion star modulating the eccentricity of an inner binary orbit. 4U 1820-30 consists of a white dwarf / neutron star inner system with $P_{\text{orb,inner}} \approx 685$ s, with a third star orbiting the inner system with a period of $\sim 1.1$ d. If this model (Mazeh & Shaham 1979) is applied to 2S 0114+650 taking $P_{\text{orb,inner}} = 11.6$ d, it yields a long period of $\gg 30.7$ d.

4 CONCLUSIONS

We have identified a third stable period in the high mass X-ray binary 2S 0114+650 of value $30.7 \pm 0.1$ d, making this system the fourth known X-ray binary to possess a stable super-orbital period. Such a period is usually classified as originating from modulation of the X-ray flux by a warped precessing accretion disc. However, the observational evidence for the presence of an accretion disc in this system is not conclusive. Optical polarisation and spectroscopy studies, and radio observations are in progress to better understand the properties of this complex system.

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