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Letter to the Editor

Periodic outbursts in the peculiar X-ray binary 2S 0114+65

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Abstract. The peculiar X-ray binary system 2S 0114+65 has been observed by every X-ray satellite mission since its discovery by *SAS* 3 in 1977. A persistent feature of all the observations are outbursts on a time-scale of ~ 3 hours. We have utilized the archival *EXOSAT* data, as well as, published data and *ROSAT* all-sky survey data and show that the observed outbursts are describable by a 2.78 hour period at all epochs. From the data at hand we determine that the underlying clock mechanism has a Q value ≥ 10. The pulse shape is qualitatively similar to those observed in EXO 2030+375 and similar mechanisms may be at work in both systems. We speculate on the intriguing possibility that the underlying clock may be the pulsations of the early *B* star member of the system, LSI +65 10. If this hypothesis is the correct description of the system then LSI +65 10 should be observed to pulsate optically at the 2.78 hour outburst period making it a member of the β-cephei class of pulsating early *B* stars.

Key words: X-ray binaries – neutron stars – β Cep stars

1. Introduction

The X-ray source 2S 0114+65 was first identified in 1977 by the *SAS 3* galactic survey (Dower and Kelley 1977). The optical counterpart of the X-ray source was identified in 1977 (Margon 1977) as LSI +65 10, an 11th magnitude star of spectral class *B*0.5*III*. Further X-ray observations of the source were carried out by *Einstein*, *HEAO 1*, and *OSO 8* (Koenigsberger et. al. 1983); *EXOSAT* (van Kerkwijk and Waters 1989, Apparao *et al.* 1991), *GINGA* (Yamauchi *et al.* 1990), and 2S 0114+65 was detected in the *ROSAT* all sky survey (Motch *et al.* 1991). 2S 0114+65 can be characterized by a mean flux in the 2-10 keV band of $\sim 2\times10^{-11}$ $erg\ cm^{-2}\ s^{-1}$ with outbursts to ~ 10 times that level while spectral studies indicate a power law spectrum above 1 keV of photon index -1.2. With an assumed distance of 1.4 kpc the intrinsic source luminosity is $L_x \sim 4\times10^{34}$ $erg\ s^{-1}$, typical of the luminosities of the *Be*/X-ray binary systems in quiescence. The *Einstein* observations indicated the presence of pulsations with a period of ~ 895 s but the *HEAO 1*, *OSO 8* and *EXOSAT* data failed to confirm them. The *GINGA* mission marginally detected pulsations at a period of ~ 850 seconds but the short duration of the observation (~ 3000 seconds) compared to the detected period does not rule out the possibility that this period is an artifact (Yamauchi *et al.* 1990). Searches for quasi-periodic oscillations (QPO) have been carried out with only a marginal detection at a period of ~ 2000 seconds (Apparao *et al.* 1991).

The low luminosity, identification with a *B* class star, and the suggestion of a long period pulsar led to the classification of this source as a *Be*/X-ray binary system in which a compact object, most likely a neutron star, orbits the *B* primary. The observed X-rays in these systems are believed to arise as a result of accretion of matter onto the compact object from the wind of the early primary star which is deep inside its Roche lobe. Optical observations of the primary LSI +65 10 reported in 1985 determined that the system was indeed binary with an orbital period of 11.59 d (Crampton et. al. 1985). Additionally it was found that the optical spectrum and estimated rotational velocity of LSI +65 10 was far more similar to the supergiant X-ray binary systems than it was to the classic *Be*/X-ray binary systems. The authors classified the *B*0.5 primary to be in class *II*, i.e. a "bright giant". It is speculated that the low X-ray luminosity for a supergiant system is a result of the primary being widely seperated from its compact companion and it is in a low mass loss phase.

An overview of the literature reveals that a persistent feature of all the X-ray observations is the presence of outbursts on a time scale of ~ 2.8 hours with a factor 10 increase in luminosity. The spectral class *B*0.5 *III* of LSI +65 10 and the presence of an ~ 2.8 hour periodicity of the X-ray outbursts are suggestive of the β-cephei class of stars. Briefly, the β-cephei stars are *B* stars in the narrow spectral range *B*0.5 *II* to *B*2 *IV* with optical light curves displaying coherent pulsations of between 3-6 hours (Rountree Lesh 1982). The cause of the optical modulation is believed to be radial or non-radial pulsations whose physical origin still remains a mystery. In this *Letter* we present an analysis of archival *EXOSAT* data which indicate that the outburst episodes repeat with the same periodic signature. We draw support from the published *GINGA* results, as well as, from the *ROSAT* all-sky survey data. Section 2 will contain a description of the observations and analysis while a discussion of possible physical models which may describe this peculiar system is contained in the final section.

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2. Analysis

The investigation of the nature of the X-ray outbursts in 2S 0114+65 was initiated with archival data from *EXOSAT*. The HEASARC ME data base at the NASA Goddard Space Flight Center was searched for pointed observations having a quality factor (QF) ≥ 3 (this choice indicates that background subtractions were deemed satisfactory). Four observations satisfied the QF cut and are listed in Table 1. The observations on day 209, 1983, day 1, 1986 and day 2, 1986 displayed clear outbursts and the corresponding background light curves showed no procedural artifacts. However, during the observation of day 363, 1985 the source was in a low count rate state and inspection of the background light curve for that observation indicated that some artifacts of the background subtraction procedure still remained in the data. During intervals when the background was lower than average the subtracted on source light curve displayed increases in the count rate. For that reason only the observations of day 209, 1983, day 1, 1986 and day 2, 1986 were retained for subsequent analysis. The first step in the analysis involved an arrival time analysis of the outburst times. Relating the arrival times (chosen to be the central time of peak emission of the outburst) on days 1 and 2 of 1986 led to an outburst period of 2.78±0.01 hours. The epoch of the period is T_0=2,446,433.632±0.006 JD corresponding to the time of peak emission. The interval between outbursts on day 209, 1983 was found to be consistent with a 2.78 hour periodicity. Significant pulse number ambiguities (±16 pulses) exist for the data in 1983 when related to the 1986 data so that arrival time analysis was deemed inappropriate for these data. To estimate the significance we calculated the Z_1^2 statistic (Buccheri *et al.* 1983) for the combined data set at the 2.78 hour period. Due to the long gaps and short intervals of data a monte carlo method was applied to estimate the average value of Z_1^2 in the absence of a truly periodic signal. The observed Z_1^2 of 663 was found to deviate from the expectation for random data, $Z_1^2 = 114 \pm 36$, at the 15σ level of significance. The light curves and the data folded at the 2.78 hour period for the *EXOSAT* ME data are presented in Figure 1. The time scale of the light curves was compressed for display purposes. We now turn to the larger body of existing X-ray data to find supporting evidence for the persistence of the 2.78 hour outburst period.

The X-ray astronomy satellite *GINGA* observed 2S 0114+65 on two days in 1989, October 16 and 17, with the Large Area Counters (LAC) (Yamauchi *et al.* 1990). Their published light curves display the outbursts clearly on October 17 with a good exposure of 15,500 seconds. The October 16 observation is shorter with an effective exposure of 3500 seconds and does display a rise in the counting rate during one uninterrupted interval. We tested the 2.78 hour periodicity of the outbursts by marking the expected times of outburst over the time span of the *GINGA* observations relative to the peak emission of the outburst occurring at ~ 10 hours. The light curve from Yamauchi *et al.* (1990) for the October 17 observation is displayed in Figure 2. The arrows mark the predicted outburst times. It can be seen in Figure 2 that the 2.78 hour period does adequately describe the data. The predicted outburst times on October 16 were not covered by the observation but the rising count rate interval occurs just prior to a predicted outburst when extrapolating from the October 17 data. The pulse shape of the bursts as seen in the *GINGA* observations display the same general characteristics as observed by *EXOSAT*; a sharp rise to maximum emission with a decay timescale of ~ 1 hour and a possible secondary emission on the trailing edge (see Figure 1).

The *ROSAT* all-sky survey detected 2S 0114+65 when it was in the field of view of the Position Sensitive Proportional Counter (PSPC) between JD 2448103.283 and JD 2448106.153 (Motch *et al.* 1991). A detailed description of the satellite and detectors can be found in Trümper (1983) and Pfeffermann *et al.* (1986). The effective exposure time was 780 seconds. LSI +65 10 was detected at a mean counting rate of 0.15 counts/sec with peak rates of ~ 0.50 counts/sec. Due to the characteristics of the *ROSAT* survey, the source was in the field of view for intervals of ≤ 30 seconds every orbit of the satellite (96 min). For analysis purposes only observation intervals of ≥ 17 seconds exposure were chosen yielding an effective exposure of ~ 595 seconds. The source counts were extracted from a 5.5′ radius circle centered on the position of LSI +65 10. Because of the extremely low background rate above 0.4 keV in the PSPC (~ 0.02 cts/s in the extracted circle), no background subtraction was performed. The total number of photons for the analysis was 56. The light curve of the data is displayed in Figure 3. Due to the very sparse coverage we merely folded the data at the 2.78 hour period derived from the *EXOSAT* data. Figure 3 displays the folded light curve and it can be seen that it is consistent with a modulation at a 2.78 hour period. The pulse shape of the *ROSAT* data displayed in Figure 3 is also seen to be qualitatively similar to the shape of the *EXOSAT* data. Additional published data from *Einstein* and *HEAO-1* are consistent with a 2.78 hour outburst period as well.

Table 1. *EXOSAT* ME Observations of 2S 0114+65

year	day	start UT	exposure (sec)	count rate (cts/sec)
83	209	7h 0m 8s	24,320	0.59±0.03
85	363	6h 27m 38s	27,110	0.19±0.03
86	1	7h 40m 0s	3,240	12.75±0.16
86	2	0h 26m 32s	30,326	6.48±0.04

3. Discussion

We have presented evidence based on *EXOSAT* data, published literature and recent *ROSAT* data that the X-ray outbursts observed in 2S 0114+65 can be described by a 2.78±0.01 hour period at all observational epochs. The data upon which this conclusion is drawn covers the period from late 1983 to late 1990, some seven years. The periodic outbursts in 2S 0114+65 are reminiscent of the 3.96 hour outburst episode seen in EXO 2030+375 (Parmar *et al.* 1989). In both EXO 2030+375 and 2S 0114+65 the outburst period shows no relation to the orbital period and calls into question the assumption that regular outbursts necessarily imply an underlying orbital period. An important measure of the stability of the underlying clock mechanism is its Q value ($Q = P/\triangle P$). While the available data do not allow us to establish coherence over the seven year span of the data we can place some lower limits on the Q value of the underlying clock mechanism. The *EXOSAT* data from 1986 and the *GINGA* data imply $Q \geq 10$. Projection of the *EXOSAT* ephemeris derived from the 1986 data to the data in 1983 predicts the observed outburst times to within 5% of a

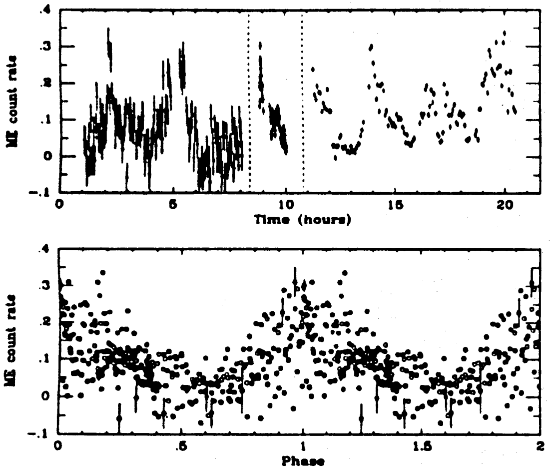

Fig. 1. The *EXOSAT* ME light curves for day 209 1983, day 1, 1986 and day 2, 1986 (top, time scale compressed) and the data folded at the 2.78 hour period (bottom) as described in the text. The epoch is 2,446,433.632 JD. Counting rates have been normalized to peak values of 0.3 cts/sec for economy of presentation.

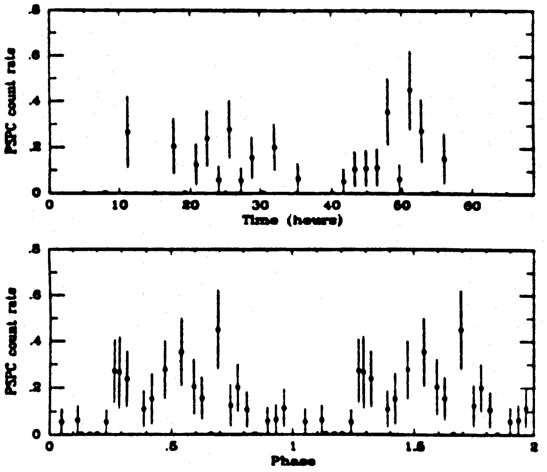

Fig. 3. The *ROSAT* all-sky survey light curve (top) for 2S 0114+65 and the data folded at the 2.78 hour flare period (bottom). The ordinate of the light curve is in hours elapsed since 2,448,103.283 JD and the epoch of the folded data is 2,446,433.632 JD.

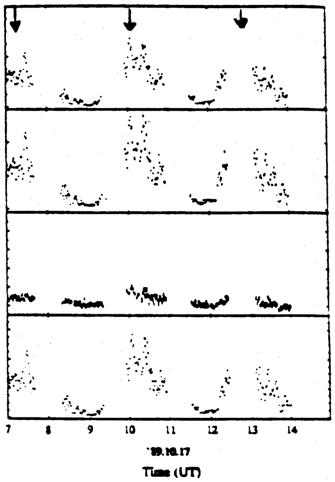

Fig. 2. The *GINGA* light curve from Yamauchi *et al.* (1990) for the observation of October 17, 1989. The arrows mark the 2.78 hour flare interval relative to the flare peak at ~ 10 hours.

phase. If not a fortuitous result the necessary Q value would have to be $\geq 10^4$. Projection ahead to the epoch of the *GINGA* data produces a similar result, alignment to within 2% of a phase, again requiring $Q \geq 10^4$. The phasing of the *ROSAT* data in Figure 3 is also consistent with this value of Q. Such a high Q phenomenon in a system such as this, i.e. unrelated to an orbital period, would be difficult to understand.

It is interesting to speculate on the nature of the clock mechanism in this system. The sharp rise and exponential decay of the outbursts suggest the possibility that an accretion disk around the compact object acts as a draining reservoir fed by magnetospheric instabilities (Lamb *et al.* 1977), or possibly an accretion disk instability (Taam & Lin 1984). These two mechanisms were proposed to explain the short type 2 bursts from the rapid burster (Lewin *et al.* 1976) but the ability to provide long timescale steady outbursts with these mechanisms needs to be addressed. Asymmetric flow from a stellar wind past a compact object has been numerically modeled (Taam & Fryxell 1988) and has been shown to lead to time dependent accretion phenomena due to the rapid formation and dissipation of an accretion disk as the sense of the flow reverses around the compact object. Taam, Fryxell & Brown (1988) were able to produce outbursts with sharp rises and exponential decays similar to those observed in EXO 2030+375 with this model if the velocity of the outflowing material is around 550 km s^{-1}. For the primary in the 2S 0114+65 system, LSI +65 10, a wind speed at infinity of 1000-1500 km s^{-1} (the escape speed is ~ 500 km s^{-1}) could easily be accomodated and such a model could be applied to the observed outbursts in 2S 0114+65. However, such a mechanism providing a repetitive clock must be reconciled.

An intriguing possibility for the clock mechanism is periodic structure in the wind from the massive *B*0.5 *III* primary LSI +65 10. This was suggested by Parmar *et al.* (1989) as a possible cause of the outbursts seen in EXO 2030+375 where the underlying periodicity arises as a result of non-radial pulsations of the companion star. The formation of multiple shocks in a radiatively-driven, isothermal stellar wind has been studied by Owocki, Castor, and Rybicki (1988) while the temperature structure, effects of radiative cooling and electron conduction, and X-ray properties of a driven shock propagating in a stellar wind have been calculated by MacFarlane and Cassinelli (1989). The results of MacFarlane and Cassinelli (1989) show that there should be a forward/reverse pair of strong shocks in the region where a faster wind collides with a slower pre existing wind. The reverse shock occurs where the freely flowing fast wind collides with a shock "zone". A forward shock forms where this shock zone collides with the slower wind. A cold region in which density is enhanced by two or more orders of magnitude forms at a "contact surface" where material flowing from the forward and reverse shocks meet. They suggest that in a star with a periodicity in its mass loss, a sequence of such shock structure should form. MacFarlane *et al.* (1991) have recently calculated shock models for the Extreme Ultraviolet and X-ray emission of nearby B stars (β C Ma, α Vir, β Cen A) which are known soft X-ray sources (Agrawal *et al.* 1984), and are also pulsating stars. Presumably in such stars, as the shock structure propagates through the system another forms at the subsequent occurence of a fast wind slow wind interface. If the star has a compact companion there should be a periodicity in the hard X-ray flux as the high density contact region is accreted. In the work of Owocki, Castor, and Rybicki (1988) on shock formation a periodic boundary condition at the base of the wind was found to be temporally preserved in the outer wind but the spatial structure tended toward a chaotic behavior as the period of the boundary condition was increased. More detailed calculations of the relation between the pulsation period of the primary star and the shock structure in the winds are necessary to address their correlation in a quantitative manner.

The X-ray luminosity for a compact object accreting from a stellar wind is given by

$$L_X \sim \frac{G^3 M_{NS}^3 \dot{M}_*}{R_{NS} a^4 V_W^4} \qquad (1)$$

where M_{NS} is the mass of the compact companion, R_{NS} is the radius of the compact companion, $\dot{M}_*$ is the mass loss from the primary, a is the orbital seperation, V_W is the velocity of the stellar wind, and G is the gravitational constant. For typical mass loss rates of $10^{-7}\ M_{\odot} yr^{-1}$ for a B0.5 star and slow wind speeds of 1500 km s^{-1} the luminosity is expected to be $\sim 10^{34}$ erg s^{-1}. The enhancement over this quiescent luminosity assuming a density enrichment at the shock boundary due to swept up material by the fast wind of $\sim$ 100 and a fast wind speed of 1800 km s^{-1} would be $\sim 15L_X$. It is seemingly not unreasonable then that the outbursts in 2S 0114+65 are a reflection of this periodic structure of the stellar wind from LSI +65 10. Photometric and spectroscopic variations on time scales of from hours to days have been observed in many *O* and early *B* stars (Smith & Ebbets 1981 and references therein) which are believed to arise from radial or non-radial pulsations (Baade 1984, Baade 1991). Pulsating stars with periods in the 3-6 hour range and confined to the narrow spectral class *B*0.5 *II* to *B*2 *IV* are the β-cephei, deriving the name from the canonical member of the class. It has been speculated elsewhere that the β-cephei phenomenon may give rise to a periodic modulation at the stellar pulsation period of the X-ray flux in the stars of this class (Gry *et al.* 1984, MacFarlane *et al.* 1991). The clock is provided by the periodic "puffing" of the star which sets up a cool wind, hot wind structure as described above. LSI +65 10 resides in the appropriate luminosity class at *B*0.5 *III* to be considered a candidate for inclusion amongst the β-cephei. To date it is not known if LSI +65 10 is a member of the β-cephei class. A detection of LSI +65 10 optically pulsating at a period of 2.78 hours would lend valuable support to this hypothesis.

In summary, we have shown that the X-ray outbursts in 2S 0114+65, while reminiscent of the outbursts observed in EXO 2030+375, are a persistent feature since 1978 and is describable by a 2.78 hour period at all observational epochs. The Q value of the underlying clock is ≥ 10 and Q values $\geq 10^4$ can not be ruled out but are challenging to understand. The clock mechanism may be related to instabilities of an accretion disk around the compact companion of LSI +65 10 or asymmetries in the stellar wind of LSI +65 10 which lead to rapid formation and dissipation of such an accretion disk. We entertain the possiblity that the clock is the periodic formation of shocks in the stellar wind of LSI +65 10 related to its being a member of the β-cephei class of pulsating early *B* stars. The enhanced X-ray luminosity in that scenario arises as the compact companion accretes from the shock enhanced wind structure. If this is indeed the correct picture of this system then LSI +65 10 should show optical modulation at the outburst period of 2.78 hours. Other massive X-ray binaries containing pulsating stars may display similar X-ray emission features to those we have described here with possible candidate being 4U 0236+61 (LSI +61 303). If this turns out to be the case then the compact objects in these systems are a valuable analytical tool in studying the structure of the winds from these massive stars.

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