

## ROSAT/OPTICAL OBSERVATIONS OF 2S 0114+65: A STUDY OF THE 2.8 HOUR PERIODIC OUTBURSTS

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### ABSTRACT

Observations of the massive X-ray binary 2S 0114+65 acquired in 1992 July with the *ROSAT* PSPC in the 0.1–2.4 keV X-ray band and in 1992 September with the 0.9 m telescope at KPNO in the optical *V* band are reported. The X-ray data confirm the presence of persistent 2.78 hr outbursts as previously deduced from archival data. The X-ray source displays apparent orbital effects consistent with noncircularity. Variable intrinsic absorption and intrinsic spectral variations are excluded as the cause of the observed X-ray modulation. The optical *V*-band photometric data do not reveal any periodic modulation. The possibility that the 2.78 hr period is the rotation of the neutron star component is entertained.

*Subject headings:* stars: individual (2S 0114+65) — stars: neutron — X-rays: stars

### 1. INTRODUCTION

The X-ray source 2S 0114+65 was first identified in 1977 by the *SAS 3* galactic survey (Dower & Kelley 1977). The optical counterpart of the X-ray source was identified in 1977 (Margon 1977) as LS I +65 10, an eleventh magnitude star of spectral class B0.5 III. The 11.59 day binary orbit of the system was first revealed in spectroscopic observations by Crampton, Hutchings, & Cowley (1985). The orbital solution yields a best-fit eccentricity of 0.16, but a circular orbit cannot be ruled out by the data. Further X-ray observations of the source were carried out by *Einstein*, *HEAO 1*, and *OSO 8* (Koenigsberger et al. 1983), the *EXOSAT* observatory between 1983 and 1986 (van Kerkwijk & Waters 1989; Apparao, Bisht, & Singh 1991), and with the Large Area Counters aboard *Ginga* in 1989 (Yamauchi et al. 1990). The *ROSAT* all-sky survey detected 2S 0114+65 during the 3 days of 1990 in which it was in the field of view (Motch et al. 1991). A recent reanalysis of the *EXOSAT*, *Ginga*, and *ROSAT* all-sky survey data by Finley, Belloni, & Cassinelli (1992) showed that the X-ray outbursts from 2S 0114+65 displayed a 2.78 hr periodicity, the presence of which is consistent with all the extant data. The *Q*-value ( $Q = P/\Delta P$ ) of the clock was determined to be  $\geq 10$ , but much higher values could not be ruled out. The presumed clock mechanism driving the outbursts was a variable mass-loss rate from the B0.5 III primary. Finley et al. (1992) speculated that the 2.78 hr timescale of the outbursts may indicate that LS I +65 10 is a member of the  $\beta$  Cephei class of pulsating early B stars. In that scenario the X-ray outbursts are a result of accretion from a periodic shock structure in the outflowing wind which results from the star “puffing” with a 2.78 hr period.

In this paper we report on observations acquired in the summer of 1992 in the X-ray band with the Position Sensitive Proportional Counter (PSPC) aboard *ROSAT* and optical

photometry acquired in the fall of 1992 at KPNO. The observations are described in § 2, while § 3 details the analysis and results. A discussion can be found in § 4.

### 2. OBSERVATIONS

The X-ray binary 2S 0114+65 was observed with the PSPC at the focus of the X-ray telescope aboard *ROSAT*. Detailed descriptions of the satellite, X-ray mirrors, and detectors can be found in Trümper (1983) and Pfeffermann et al. (1986). Briefly, *ROSAT* contains an X-ray mirror assembly with a 2° field of view. The PSPC is a gas-filled proportional counter sensitive over the energy range 0.1–2.4 keV with an energy resolution  $\Delta E/E \sim 0.43$  at 0.93 keV, and a spatial resolution of  $\sim 25''$  in the center of the focal plane. The effective timing resolution is  $\sim 130 \mu\text{s}$ , electronics limited, and the accuracy of absolute timing with respect to UTC is a few milliseconds. The X-ray observations reported here were obtained between 1992 July 26 (JD 2,448,830.27) and 1992 July 28 (JD 2,448,832.34) with a total effective exposure time of 28,438 s. Due to earth occultation, radiation belt passage, and observations of other targets, the data consist of 17 uninterrupted intervals covering the 3 days of observation. The reduction of the *ROSAT* data has been performed with the EXSAS package (Zimmermann et al. 1993). The 2S 0114+65 source counts were extracted from a circle of radius 1.5 which included more than 99% of the source counts. The background was determined from a source-free annulus of inner radius 1.7 and outer radius 3.3 centered on the source. The X-ray source was highly variable during the 3 day interval with counting rates varying between  $0.02 \text{ s}^{-1}$  at the beginning of the observation to  $0.6 \text{ s}^{-1}$  at the end. The mean background-subtracted, vignetting-corrected, and deadtime-corrected count rate for the whole observation was  $0.109 \pm 0.002 \text{ s}^{-1}$ .

V-band photometric measurements of 2S 0114+65 were obtained with the 0.9 m telescope at KPNO on 1992 September 13 (JD 2,448,879) using the f/7.5 secondary. A Tektronix 2048 × 2048 CCD with 24 μpixels was utilized. In order to minimize the readout time, we positioned 2S 0114+65 and the two comparison stars near the bottom of the CCD, restricting the necessary portion of the chip to a 600 × 1024 section (5'8 × 11'6 FOV). A 5 s integration was used for each of the 170 observations obtained over 3.7 hr. Each science frame was bias-subtracted and flat-fielded using an average of 10 bias frames and 5 dome flats taken at the beginning of the night. Aperture photometry using the DAOPHOT package in IRAF was then carried out to determine the time-series photometry of 2S 0114+65 (V) and of two comparison stars (C1 and C2). The position and V magnitudes of 2S 0114+65, C1, and C2 as given in the guide star catalog are presented in Table 1. The

average seeing for the night was about 1".5, with a FWHM of the point-spread function of just over two pixels. In order to include as much starlight as possible, we used an 8".2 diameter aperture and measured the sky around each object through an annulus with inner and outer diameter of 13".6 and 17", respectively.

3. RESULTS

3.1. X-Ray

The background-subtracted, vignetting-corrected, and deadtime-corrected X-ray light curve for the ROSAT observation is displayed in Figure 1 (top three panels). The variability of the source is clearly evident. The mean counting rate is observed to be increasing over the course of the observation, and in Figure 1 (bottom panel) we show the average counting

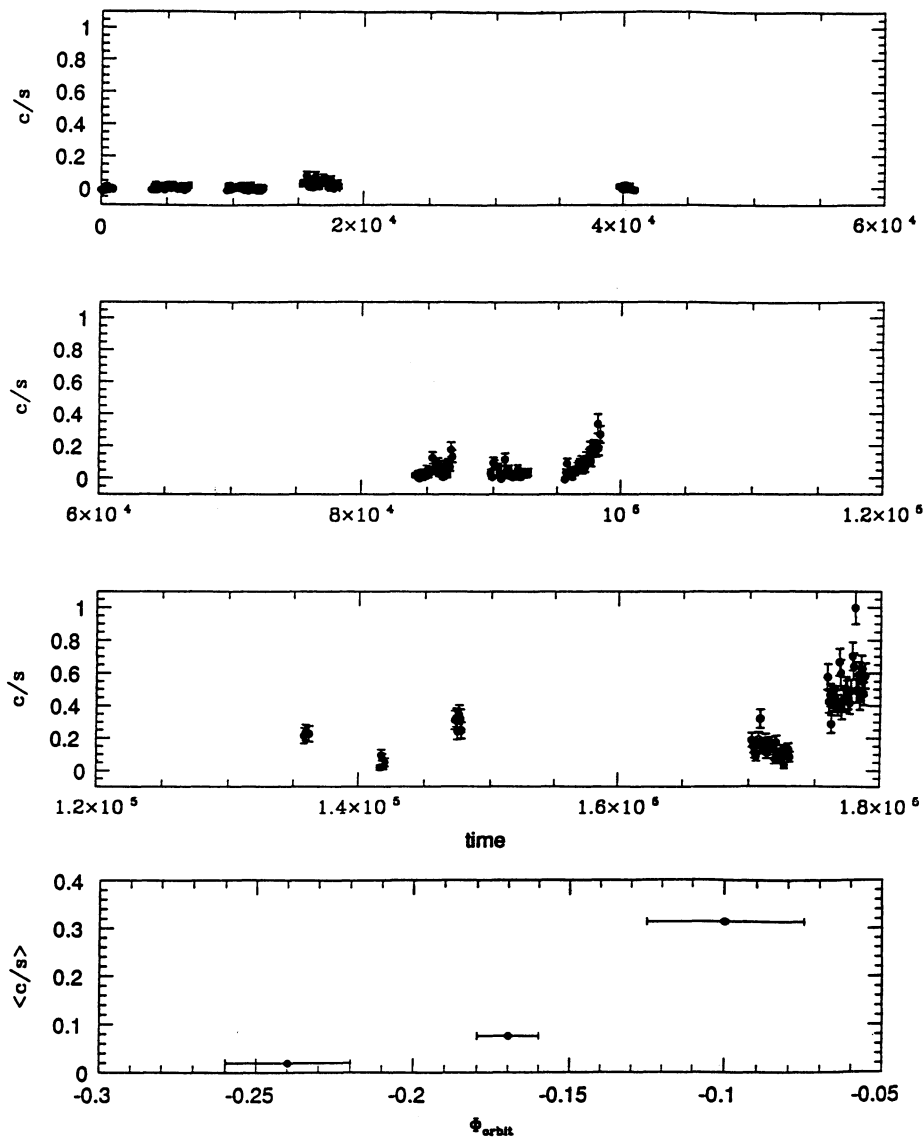


FIG. 1.—Background-subtracted, vignetting-corrected, and deadtime-corrected light curve for the ROSAT observations (top three panels). The start of the observation is JD 2,448,830.27, and the time is seconds since the beginning of the observation. The three panels are roughly the 3 days of observation. The bottom panel is the mean counting rate for each of the top three panels as a function of the projected 11.59 day orbital phase. Phase 0 is defined as the time of periastron passage for the elliptical orbit solution of Crampton et al. (1985). The horizontal error bars represent the uncertainty in extrapolating the orbital ephemeris forward to the date of the observation. The vertical error bars are smaller than the size of the points.

TABLE 1  
POSITIONS AND APPARENT VISUAL MAGNITUDES OF 2S 0114+65 AND  
THE TWO COMPARISON STARS

Star	R.A. (2000)	Decl. (2000)	$m_V$
V (2S 0114+65) .....	01 <sup>h</sup> 18 <sup>m</sup> 2 <sup>s</sup> .6	+65°17'29".9	10.76
C1 (GSC 4038-365) .....	01 18 45.3	+65 21 46.5	10.31
C2 (GSC 4038-049) .....	01 18 3.2	+65 12 35.1	10.36

rate as a function of the 11.59 day orbital phase,  $\Phi_{\text{orb}}$ , for the top three panels. The error bars on the orbital phase in Figure 1 represent the uncertainty due to extrapolating the ephemeris for the orbit ahead to the epoch of the observation. If we interpret the increase in the counting rate as due to progression toward periastron, then a circular orbit (i.e.,  $\epsilon = 0$ ) is clearly excluded. However, without the benefit of full orbital coverage a determination of the eccentricity of the orbit is not possible.

To test for the presence of the 2.78 hr outburst period, the data from each of the top three panels in Figure 1 were folded separately. In this way we can demonstrate that the outburst periodicity is independent of the overall flux level. The folded light curves are displayed in Figure 2 where each panel covers 4, 2, and 4 periods, respectively, from top to bottom. The 2.78 hr periodicity is clearly present in all three subsets of the data. The folded light curve from the entire data set is displayed in Figure 3. The pulse shape is not well determined for this observation due to incomplete coverage resulting from the orbital characteristics of *ROSAT* (the orbital period of the satellite is 5760 seconds), but it is qualitatively similar to the shape derived from the *EXOSAT* and *Ginga* data (Finley et al. 1992). The mean flux increase over the baseline at the peak of the outburst is  $\sim 8$  and independent of the absolute flux level. To ascertain the stability of the clock mechanism, we fit for the pulse minima using a cubic approximation for each of the three subsets displayed in Figure 2 and derived a lower limit to the

TABLE 2  
RESULTS OF X-RAY SPECTRAL FITTING

Model	$N_{\text{H}}$ ( $10^{22} \text{ cm}^{-2}$ )	$F_X$ ( $10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ )
Thermal bremsstrahlung		
$kT = 10 \text{ keV}$ .....	1.39–1.56	6.06–7.10
Power law		
$\Gamma = 1.2$ ( <i>Einstein</i> ) .....	1.31–1.48	5.56–6.50
Power law		
$\Gamma = 1.0$ ( <i>Ginga</i> ) .....	1.24–1.40	5.16–6.00

$Q$ -value ( $Q = P/\Delta P$ ) of  $Q \geq 17$ . Unfortunately, due to the incomplete coverage of the pulse, we were not able to derive a corresponding upper limit to the  $Q$ -value.

The  $\sim 3100$  counts from 2S 0114+65 were sufficient to allow statistically meaningful determination of the spectral properties of the source in the 0.4–2.4 keV band. The pulse height distribution of counts is displayed in Figure 4. The source has a very hard spectrum and is heavily absorbed. Because of the strong correlation between neutral hydrogen column density and power-law photon index or thermal bremsstrahlung temperature, we chose to fix those parameters and fit for the absorbing column density of neutral hydrogen,  $N_{\text{H}}$ , and total flux,  $F_X$ . The model fits utilized power-law model parameters previously published in the literature from *Einstein* (Koenigsberger et al. 1983) and *Ginga* (Yamauchi et al. 1990), as well as a 10 keV thermal bremsstrahlung plasma which we take as typical of X-ray binary systems. The results of the model fits are presented in Table 2. The 90% confidence level range of parameters which are consistent with the data in the 0.4–2.4 keV band independent of the model choice are  $N_{\text{H}} = (1.2\text{--}1.6) \times 10^{22} \text{ cm}^{-2}$  and  $F_X = (5.2\text{--}7.1) \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ . The implied source luminosity for a distance of 2.5 kpc is  $L_X = (3.8\text{--}5.4) \times 10^{33} \text{ ergs s}^{-1}$  in the 0.4–2.4 keV band.

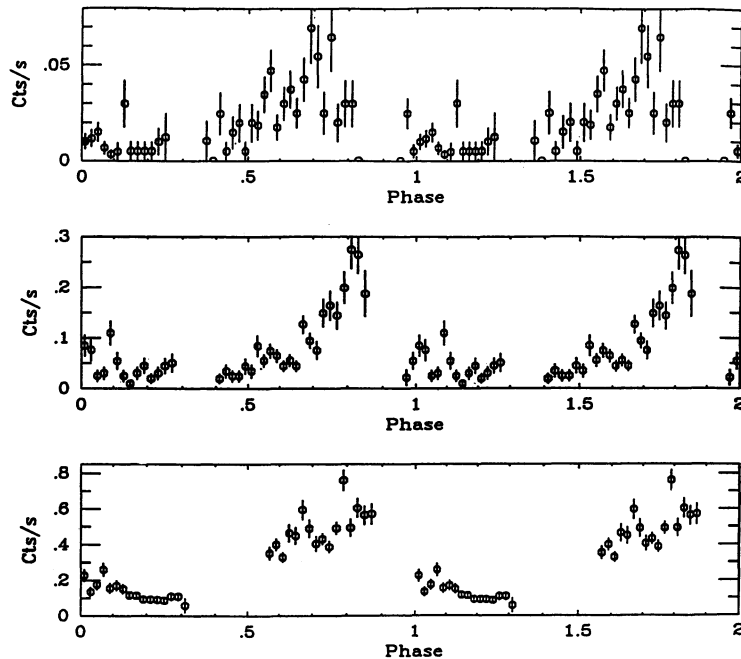


FIG. 2.—Data from the top three panels in Fig. 1 folded with a period of 2.78 hr. The epoch for the folding was the beginning of the observation. Note the change in the vertical scale for the three figures. Two cycles are plotted for clarity of presentation.

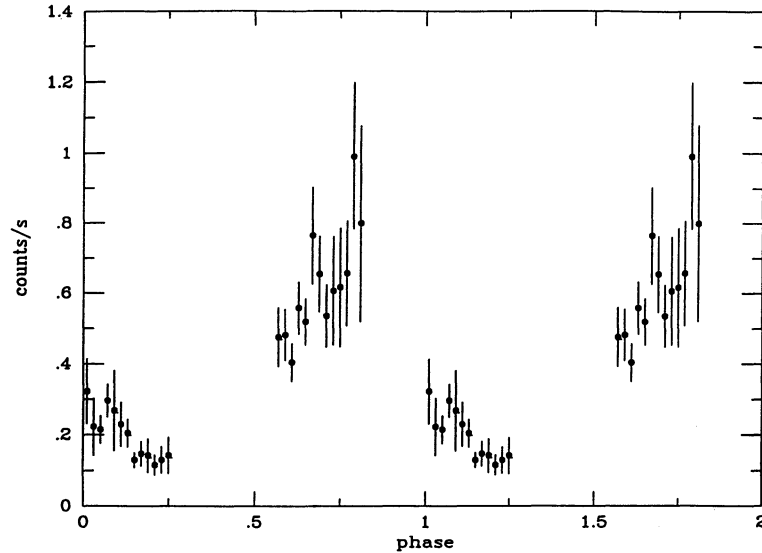


FIG. 3.—Total data set folded on the 2.78 hr period. Each data point represents 2% of the 2.78 hr cycle. Only fully exposed bins are shown, and two cycles are plotted for clarity of presentation.

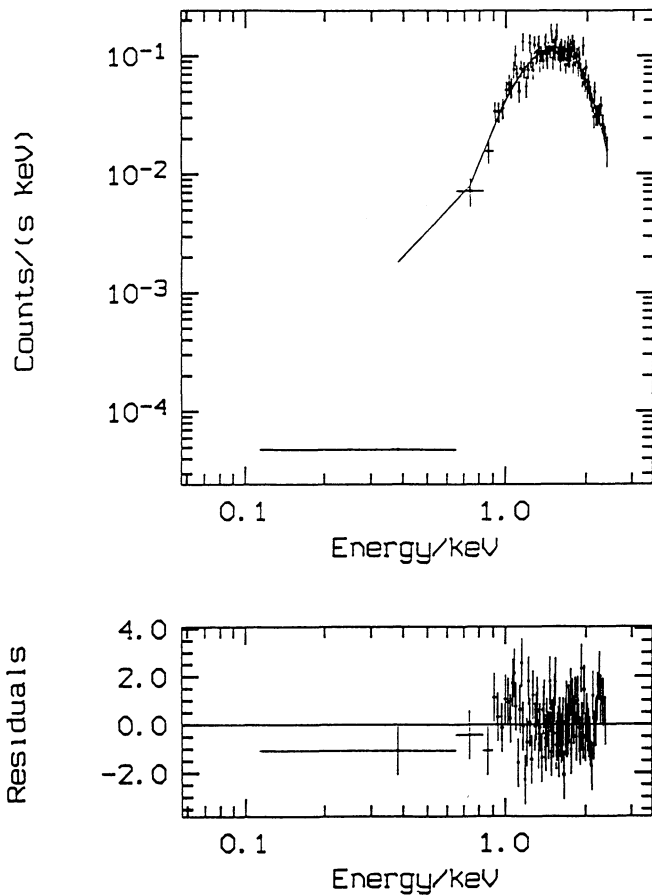


FIG. 4.—*Top panel*: Background-subtracted, vignetting-corrected, and deadtime-corrected spectrum of 2S 0114+65 (points) and the best-fitting power-law model (solid line) with the photon index,  $\Gamma$ , fixed at the value 1.0 (see the text). The reduced  $\chi^2$  of the fit was 1.03 per DOF for the 87 degrees of freedom. *Bottom panel*: Residuals of the fit in units of  $\sigma$ .

To ascertain whether the flaring is a result of intrinsic source absorption or spectral variation we utilized a hardness ratio. We defined the hardness ratio as the ratio of counts in channels 151–240 ( $\sim 1.5$ – $2.4$  keV) to counts in channels 41–150 ( $\sim 0.4$ – $1.5$  keV). This choice of channels divides the spectrum into approximately equal numbers of counts and, in the absence of any absorption effects or spectral variability, should produce a hardness ratio of approximately unity. The hardness ratio as a function of intensity is displayed in Figure 5 for the three intervals chosen as in Figure 1. If the observed flaring were a result of a spectral or absorption variability we would expect the distributions of Figure 5 to show a correlation. Examination of Figure 5 reveals no statistically significant correlation between the intensity and the hardness ratio. The mean values of the hardness ratio in the three panels are  $1 \pm 1$  (*top*),  $1.1 \pm 0.7$  (*middle*), and  $1.1 \pm 0.2$  (*bottom*) and indicate that the change in the mean counting rate during the course of the observation is also not a result of absorption or spectral variation effects.

### 3.2. Optical

The differential  $V$ -band photometric magnitudes plotted as a function of Julian date for V-C1 (*top panel*), V-C2 (*middle panel*), and C1-C2 (*bottom panel*) are displayed in Figure 6. The mean and standard deviation of each of these three data sets are also listed in the figure. The Fourier transform of each data set was computed for  $\nu < 550$  cycles per day with a frequency resolution of 6.5 cycles per day. We find no evidence for periodic variations in these data. However, our optical data set covers only 3.7 hr and detection of a 2.78 hr periodicity is difficult at best.

## 4. DISCUSSION

The ROSAT data presented in this paper demonstrate clearly that the 2.78 hr outburst period of 2S 0114+65 is an intrinsic property of the X-ray component of this system, as first described by Finley et al. (1992), and not a sporadic phenomenon. The lack of any detectable variations in the

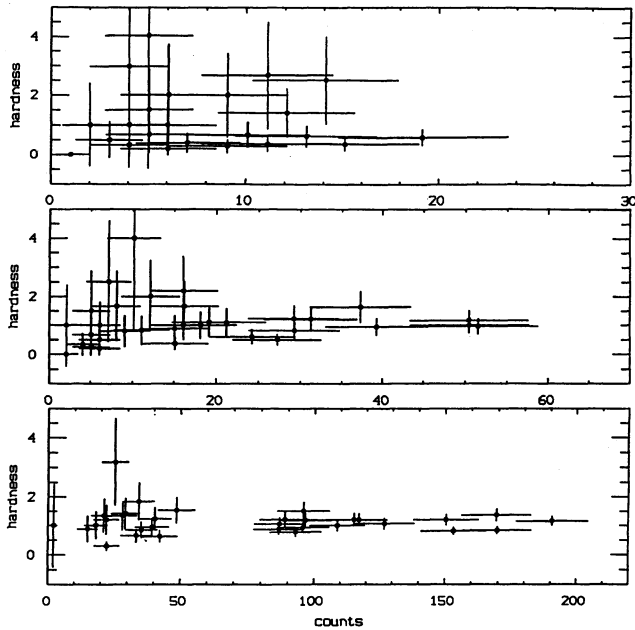


FIG. 5.—Hardness ratio as a function of source intensity defined in 2.78 hr phase intervals of 0.02 for the 3 days of observation, as in Fig. 1. The hardness ratio is defined as the ratio of counts in pulse height channels 151–240 ( $\sim 1.5$ –2.4 keV) to counts in pulse height channels 40–150 ( $\sim 0.4$ –1.5 keV).

*EXOSAT* observations of 1985 day 363 can be understood if the source was in a low-intensity state as observed here and thus undetectable against the much larger *EXOSAT* ME background. The persistence and the derived  $Q$ -value of  $\geq 17$  suggest that the underlying clock in this system is stable over time periods of at least days. The mean X-ray intensity increase observed during the course of the 3 days of observation certainly suggests an eccentric orbit. However, the intensity modulation (a factor of  $\sim 8$  peak to valley) is not correlated with the mean flux level nor, consequently, with the orbital phase. We have also demonstrated that the modulations are not a result of intrinsic source absorption nor of spectral variations.

The optical  $V$ -band photometric observations do not show any periodic variability and we can establish a  $3\sigma$  upper limit on the amplitude variations in the system of  $\leq 18$  mmag. Since the variations observed in  $\beta$  Cepheid variables range from a few millimagnitudes to hundreds of millimagnitudes (Rountree Lesh 1982), our limit does not exclude the periodic mass-ejection model for this system as proposed by Corral & Koenigsberger (1987) and Finley et al. (1992). Further optical observations of the system are scheduled for the fall of 1993 and will cover the full orbital cycle of 11.59 days. These observations will provide a much deeper limit on the presence of the 2.78 hr variability and should reveal any orbital period dependence if it exists.

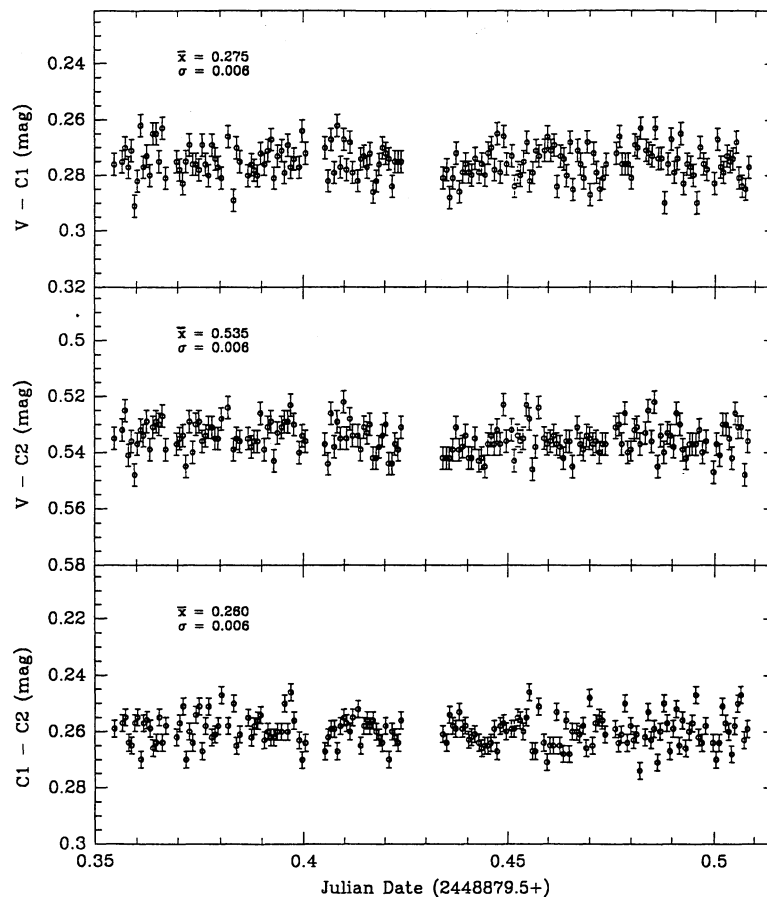


FIG. 6.— $V$ -band photometry plotted as a function of Julian date. The top two panels show differential photometric measurements between 2S 0114+65 and two different comparison stars. The bottom panel shows the differential photometry between the two comparison stars. The scatter in each of the three plots is about the same at a level of  $\pm 0.006$  mag.

The coherence of the underlying clock leads us to contemplate other mechanisms which may be responsible for the observed periodic emission. Since the X-ray source is assumed to be a neutron star, we can speculate that the 2.78 hr period is the equilibrium rotation rate that was acquired by the neutron star as it interacted with the stellar wind of the B0.5 primary. The subject of the spin periods of neutron stars in X-ray binary systems has received extensive discussion in the literature (see, e.g., Waters & van Kerkwijk 1989) with particular emphasis on the relation to orbital periods, a correlation first noticed for X-ray binary systems containing a Be primary by Corbet (1984). If we assume that the primary star, LS I +65 10, is a Be star with mass and radius of  $18 M_{\odot}$  and  $15 R_{\odot}$ , respectively (Crampton et al. 1985), and interpret the 2.78 hr (10,008 s) period as the rotation of the neutron star component, we can determine the required mass-loss rate,  $\dot{M}_{\star}$ , from the primary and the surface magnetic field,  $B_0$ , of the neutron star since the equilibrium period,  $P_{\text{EQ}}$ , is proportional to  $B_0^{6/7} \dot{M}_{\star}^{-3/7}$  (Waters & van Kerkwijk 1989). Adopting a velocity law for the stellar wind of  $v(r) = v_{\text{inf}}(1 - R_{\star}/r)^{\beta}$  (Castor, Abbott, & Klein 1975) with  $\beta = 0.8$  and a terminal velocity,  $v_{\text{inf}}$ , of  $2000 \text{ km s}^{-1}$  yields the constraint  $B_0^{6/7} \dot{M}_{\star}^{-3/7} \sim 5 \times 10^4$ . If we take the mass loss to be  $10^{-9} M_{\odot} \text{ yr}^{-1}$ , typical of the fast polar winds in Be stars (Snow 1981), then the surface field of the neutron star must be  $\sim 2-3 \times 10^{13} \text{ G}$ . Smaller field strengths would, of course, imply smaller mass loss from the primary. While no evidence exists for such large fields on the surface of accreting neutron stars [observations of cyclotron lines imply surface fields of about  $(1-6) \times 10^{12} \text{ G}$ ], a few isolated radio pulsars do have surface fields in the range of a few  $10^{13} \text{ G}$  (Taylor, Manchester, & Lyne 1993), so the possibility cannot be ruled out off-hand. However, the small mass loss from the primary does pose a problem with respect to the observed X-ray luminosity. Such low mass-loss rates would only be expected to yield X-ray luminosities of  $\sim 10^{33} \text{ ergs s}^{-1}$ , some 10–100 times less than what is observed in this system with the hard X-ray detectors (e.g., *Einstein*, *EXOSAT*, and *Ginga*) if the distance is 2–3 kpc. It has been remarked in the literature that LS I +65 10 is a peculiar star displaying some of the properties of a supergiant and some of a Be star (van Kerkwijk & Waters 1989). Optical data (see Crampton et al. 1985; van Kerkwijk & Waters 1989) indicate that LS I +65 10 is presently displaying Be star-like behavior. In that case, the X-ray luminosity may arise as 2S

0114+65 accretes from the dense, low-velocity equatorial wind of the Be star. Since the equilibrium period for a neutron star accreting from a dense, slow equatorial wind is shorter than the equilibrium period for accretion from a radiatively driven wind, we would expect 2S 0114+65 to be presently spinning-up.

An alternative scenario could involve a white dwarf as the accreting object. Such Be/WD systems are expected to be relatively numerous on the basis of binary evolution studies, although none has been clearly identified yet (see Waters et al. 1989; Pols et al. 1991; Meurs et al. 1992). However, the expected X-ray luminosities are in the range  $10^{29}-10^{33} \text{ ergs s}^{-1}$  (Waters et al. 1989), and the spectrum should be rather soft, contributing mainly in the XUV regime. The X-ray luminosity and spectrum of 2S 0114+65 seem to exclude such a possibility.

In summary, the observations presented here indicate that the 2.78 hr X-ray periodicity persists. The coherence is a timescale of at least days, but the data do not allow us neither to establish an upper limit nor to rule out very large values which would be the case for a stable rotator like a neutron star. No evidence exists in the optical *V*-band photometry of a 2.78 hr modulation from the B0.5 primary. The periodicity, if very coherent, can be explained as the equilibrium period of a neutron star accreting from a radiatively driven stellar wind. This interpretation, however, requires a large, but not unwieldy, surface magnetic field strength for the neutron star while the low mass-loss rate would seemingly not provide the necessary fuel to power the observed X-ray luminosity. However, this difficulty can be circumvented if the equilibrium period is determined by the fast, radiatively driven polar wind. The currently observed X-ray luminosity then arises from accretion of the dense, slow equatorial wind arising from the star's current Be phase. Detailed spectral and photometric studies of the optical component of the system may help to unravel the properties of the primary which are feeding the X-ray engine in 2S 0114+65.

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