

## OPTICAL PHOTOMETRIC VARIABILITY OF 2S 0114+65

M. TAYLOR

Department of Physics and Engineering, Loras College, 1450 Alta Vista, P.O. Box 178, Dubuque, Iowa 52004-0178 and Space Astronomy Laboratory, University of Wisconsin, Chamberlin Hall, 1150 University Ave., Madison, Wisconsin 53706-1390  
Electronic mail: mjtaylor@lcacl.loras.edu

J. P. FINLEY AND C. KURT

Department of Physics, Purdue University, 1396 Physics Building, West Lafayette, Indiana 47907-1396  
Electronic mail: finley@purdus1.physics.purdue.edu

G. KOENIGSBERGER

Instituto de Astronomía, Universidad Nacional Autónoma de México, Mexico

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## ABSTRACT

In this paper we present Johnson  $V$  photometry of the Be/x-ray binary star system 2S 0114+65. Although this star exhibits periodic variations in x rays, optical studies have failed to reveal fluctuations greater than 5 millimag. The data presented in this paper provide the first evidence for periodic optical variability in 2S 0114+65. On each of four nights in October 1993, we find low amplitude variations with a period of  $2.77 \pm 0.48$  h and with a semi-amplitude of 4 millimag. This period is in good agreement with results of a comprehensive study of the x-ray data. We explore the possibility that this period represents the pulsational period of the B-star primary and the possibility that it is the rotational period of the neutron star. If the latter is the correct interpretation, we calculate a spin-up time scale of  $5 \times 10^5$  yr.

## 1. INTRODUCTION

2S 0114+65 is a Be/X-ray binary star system discovered by Dower & Kelly (1977) in the SAS 3 galactic survey. Later that year the optical counterpart of 2S 0114+65 was identified with the 11th magnitude early-type star, LSI+65 10 (Margon 1977). Although the spectral type of the primary is well established at B0.5, its luminosity classification is more ambiguous with possibilities ranging between Ia and III. Radial velocity measurements by Crampton *et al.* (1985) yielded an orbital period of 11.591 days for a circular orbit and 11.588 days for an eccentric orbit with  $e = 0.16 \pm 0.07$ . It was not possible for Crampton *et al.* to ascertain which of these two models fit the data better. Corral & Koenigsberger (1987) reported photometric variability of 2S 0114+65 on time scales of minutes. However, this variability has not yet been confirmed (Finley *et al.* 1994; Bell *et al.* 1993). In addition to optical studies, 2S 0114+65 has been observed extensively in the x-ray regime with *Einstein*, *HEAO1*, and *OSO 8* (Koenigsberger *et al.* 1983), *EXOSAT* (van Kerkwijk & Waters 1989; Apparao *et al.* 1991), *GINGA* (Yamauchi *et al.* 1990), and *ROSAT* (Motch *et al.* 1991). A reanalysis of the comprehensive x-ray data set by Finley *et al.* (1992) revealed a 2.78 h periodicity. In addition, Finley *et al.* (1994) report on a possible longer-term variation in the x-ray data that may be correlated with an eccentric orbit. The time scale of the 2.78 h fluctuations, coupled with the early spectral type of the primary, led Finley *et al.* (1992) to suggest that the primary may belong to a class of pulsating stars known as  $\beta$  Cepheids. If this period results from radial pulsations, one should see variations on similar time scales at optical wavelengths. In this paper we report on results of optical

photometric measurements of 2S 0114+65 obtained in 1993. The paper is organized so that the observations are discussed in Sec. 2 with the analysis of the data explained in Sec. 3. Section 4 includes a discussion of the results of the data analysis together with possible interpretations for this system that are consistent with both the x-ray and optical photometry.

## 2. OBSERVATIONS

Johnson  $V$ -band photometry of 2S 0114+65 was obtained on four nights in October 1993 with the two-star photometer on the 84 cm telescope at the National Observatory in San Pedro Martir, Mexico. Table 1 lists the Julian Date, the integration time, and the length of time spanned by each observation. Table 2 gives the right ascension and declination, and the  $V$  magnitude of the variable and comparison star. The comparison star we used is the same as C3 used by Bell *et al.* (1993). During the observing run the second channel of the two-star photometer was unstable and we were unable to exploit the advantages of simultaneous observation of the comparison and variable. Instead, we were restricted to doing single channel photometry, measuring the variable, the comparison, and a nearby region of the sky with the primary channel, a 2" RCA8850 photomultiplier tube. The dark counts were less than 100 counts per second and very stable during the course of a night and from one night to the next. We used a 0.9 mm aperture, which, for this  $f/13.6$  telescope, corresponds to 2.7 arcmin on the sky. The typical observing sequence included about two minutes of observing time on

TABLE 1. Journal of *V*-band photometry of 2S 0114+65.

Julian Date (2440000+)	Integration Time (s)	Length of Observation (h)
9265	5	6.96
9266	5	5.28
9267	5	2.40
9270	5	2.88

each of the sky and comparison, followed by a longer observation on the variable, followed by two minutes on the sky and comparison, etc. The integration time for each measurement was 5 s and successive data points are separated by 10 s. The count rate for the variable was approximately 3600 counts per second while that for the comparison source was slightly higher at about 4000 counts per second. In order to remove first-order extinction variations from the variable star data, we time averaged each two-minute group of comparison star values and fit a second-order polynomial to these data. We will refer to this model as our extinction curve.

The 5 s variable star measurements were rebinned to 10 s samples and then corrected for extinction. This was accomplished by dividing each variable star sample by an appropriate value calculated from the time-dependent extinction curve. The data were then normalized to 1. The four panels in Fig. 1 show the reduced data for each night of observation as percent fluctuation vs time in Julian Days.

### 3. DATA ANALYSIS

The main objective of the present work is to search for photometric variability that occurs on a time scale similar to that seen in the x-ray data, namely, 2.78 h. For numerous reasons, Fourier Transform analysis is not the best technique to use for the detection of periodic behavior in this data set (e.g., the period we are looking for is in the low frequency part of the spectrum where there is substantial power introduced by variations in earth's atmosphere; also, the uneven data sampling coupled with the long interruptions due to the day-night cycle complicate the spectral window function, significantly introducing possible spurious periods in the power spectrum). Instead, we assume that the variations can be sufficiently described with a sinusoidal function of the following form:

$$X(t) = A \sin(2\pi\omega\Delta t + \Phi). \quad (1)$$

In Eq. (1),  $A$  is the semiamplitude of the sine function,  $\omega$  is the frequency of the variation,  $1/P$ , where  $P$  is the period,  $\Delta t$  is the time elapsed since the beginning of the data set, and  $\Phi$  is a phase offset of the sine function. We use the Levenberg-Marquardt (Press *et al.* 1986) method of nonlinear least

TABLE 2. Comparison and variable star.

Star name	RA (2000)	Dec (2000)	<i>V</i> mag.
2S 0114+65	01 <sup>h</sup> 18 <sup>m</sup> 2.64 <sup>s</sup>	+65° 17' 29.93"	10.76
Comparison	01 <sup>h</sup> 18 <sup>m</sup> 3.23 <sup>s</sup>	+65° 12' 35.09"	10.36

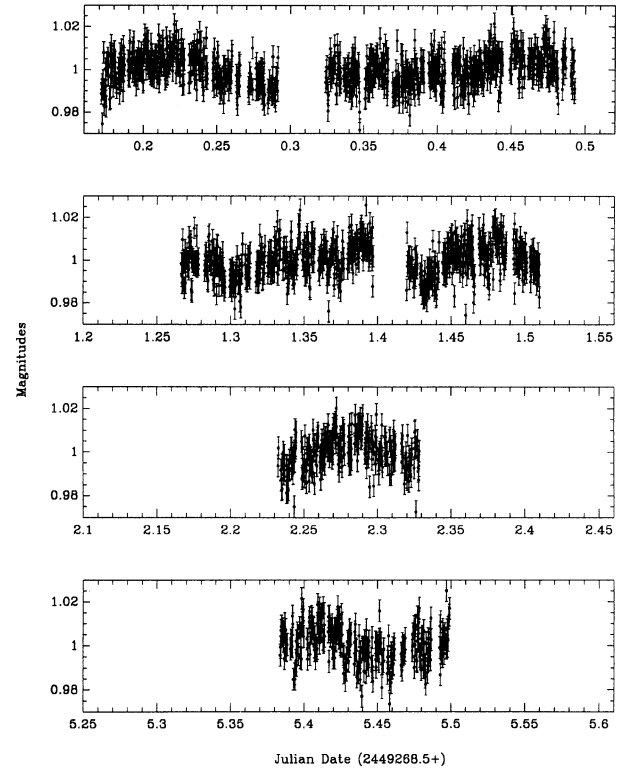


FIG. 1. A plot of the raw data for 2S 0114+65 corrected for atmospheric extinction. Each panel represents a different night of observation and each data point represents a 10 s integration. The data for each night has been normalized to unity. The error bars on each point are based on photon statistics.

squares to obtain the best set of parameters that fit the data. This approach involves selecting initial guesses to the unknowns in Eq. (1), namely,  $A$ ,  $\omega$ , and  $\Phi$  and iterating with small adjustments to each parameter until  $\chi^2$  minimizes. Initial estimates for the amplitude and period were obtained from plots of the raw data. That is, an estimate of the period is simply the time interval between successive peaks in the data stream, and the semiamplitude is one-half the difference between the minimum and maximum values in a single cycle. The initial guess for the phase offset was zero. The model converges to a minimum  $\chi^2$  when  $A_1 = 0.004 \pm 0.001$ ,  $2\pi\omega = 54.5 \pm 0.1 \text{ rad s}^{-1}$ , which corresponds to a period,  $P$ , of  $2.77 \pm 0.01 \text{ h}$ , and  $\Phi = -0.8 \pm 0.2$ . The phase dispersion minimization method outlined by Stellingwerf (1978) was also used to calculate the best period to the data. This method yields a similar period of  $2.77 \pm 0.48 \text{ h}$ . Although the sine model appears to fit the overall trend of the data reasonably well (Fig. 2), the value of reduced chi square,  $\chi_{\text{red}}^2$  is only marginally better than that for a straight line through the data. This is likely to be a result of the fact that the scatter in the data is quite large compared to the amplitude of the variability. Figure 3 is a light curve of the optical variations of 2S 0114+65, plotting phase vs normalized magnitude. The phases were calculated using the start of our observations as the initial epoch, JD 2449268.617 and period,  $P = 2.77 \text{ h}$ . In an attempt to characterize the statistical significance of this

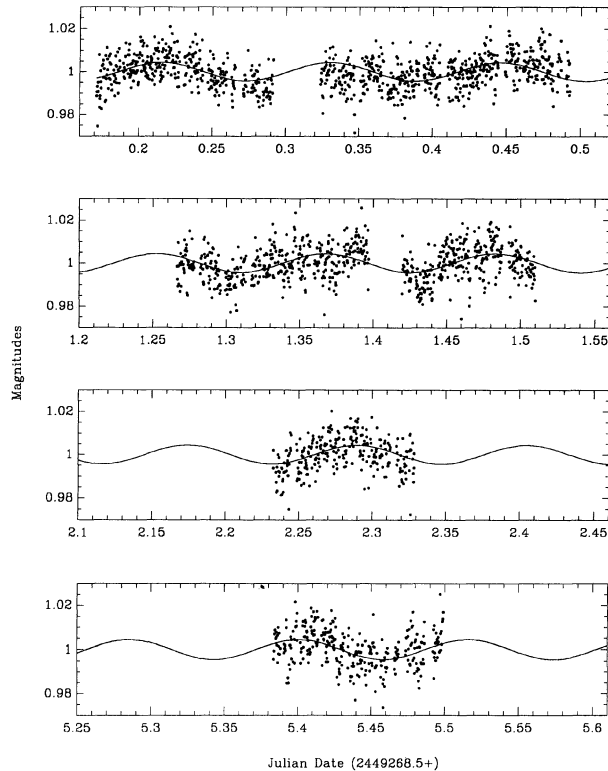


FIG. 2. The reduced photometric data for 2S 0114+65. The solid line shows the best-fit sine model to the data. The period of oscillation is 2.77 h and the peak-to-peak amplitude is 0.009 mag. The period is identical to the x-ray period for 2S 0114+65.

variability, we have carried out a Monte Carlo analysis. One hundred different data streams were created by scrambling the amplitude measurements while holding the times fixed. With this method, the time resolution as well as the statistical properties of the simulated data sets were preserved. Each of the resulting data sets were then folded on a 2.77 h period and the  $\chi^2_{\text{red}}$  calculated for a straight line. The distribution of

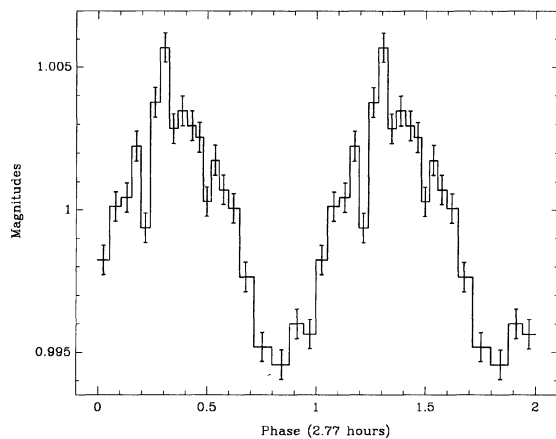


FIG. 3. A phase-magnitude diagram calculated for 2S 0114+65 using the best period obtained by the phase dispersion minimization method,  $P=2.77$  h. The epoch is the start of the observations at JD 2449268.617.

the resulting values of the  $\chi^2_{\text{red}}$ s is Gaussian with a mean of 2.49 and a standard deviation of 0.36. As a comparison, the value of the  $\chi^2_{\text{red}}$  for a straight line fit to the data in Fig. 3 is 3.52. In order to determine the minimum amplitude of variability that could be detected by this folding technique, we multiplied the data stream by various constants to simulate different amplitudes. We find that if the period is known, an oscillation with a peak-to-peak variation of only 4 millimag can be detected at the  $3\sigma$  level. Given the above tests of the data, we conclude that there is evidence that the 2.78 h period detected in the x-ray data is also seen in the optical photometry of 2S 0114+65 presented in this paper.

#### 4. DISCUSSION

We have presented *V*-band photometric measurements of the Be/X-ray binary star system, 2S 0114+65. On four nights in October 1993, we find convincing evidence for periodic variability on a time scale of 2.77 h, which is in excellent agreement with x-ray studies of this object (Finley *et al.* 1992; 1994). The peak-to-peak amplitude of variability is about 9 millimag, which is consistent with the null result reported by Finley *et al.* (1994), who established a  $3\sigma$  upper limit on the variability of  $\leq 18$  millimag. In nine hours of *V*-band CCD photometry, however, Bell *et al.* (1993) failed to detect variability above 5 millimag. They conclude that either the B star is not a  $\beta$  Cepheid or that the pulsations were not active at the time their observations were made. Be stars are known to exhibit different photometric and spectroscopic characteristics when they are in a Be, non-Be, or shell phase of evolution. Balona & Rozowsky (1991) report the discovery of a 2.2 h period of variability with a peak-to-peak amplitude of 7.6 millimag in optical observations of 27 CMa. Balona & Rozowsky (1991) note that their data were obtained when the star was in a normal Be star phase or perhaps near the beginning of a shell episode. Previous observations of 27 CMa, obtained when the star was in a shell phase, failed to show periodic variability. Their interpretation is that during the Be star phase when H $\alpha$  is in emission, the star is hidden behind a thick layer of stellar material which obscures the photosphere and prevents the detection of pulsations. When the shell is ejected, however, the photosphere is unveiled and the pulsations become visible. Based on spectroscopic observations of 2S 0114+65, van Kerkwijk & Waters (1989) report that the primary companion of this system may have undergone a shell episode in 1989. The time scales between shell episodes in Be stars range between months to years and it is therefore reasonable to expect that another such episode may have occurred between 1992 and 1994. This might help to explain why the 2.77 h variations were not detected by Bell *et al.* (1993).

The optical observations of 2S 0114+65 suggest that the photometric variations may be modulated with the orbital period of the binary system. Although the ephemeris given by Crampton *et al.* (1985) has accrued significant errors over the last decade, it is good enough to establish that the different data sets cover different portions of the binary orbit. Specifically, using the eccentric orbital ephemeris, our observations span periastron passage while those obtained by

Bell *et al.* (1993) and Finley *et al.* (1994) were obtained near apastron. The distance between the neutron star and the B star,  $r_{\text{orb}}$ , varies between  $49R_0$  and  $67R_0$ . The mass accretion rate at the neutron star is proportional to  $r_{\text{orb}}^{-2}$  and can be calculated from the following expression (Rappaport & van den Heuvel 1982):

$$\dot{M}_{\text{acc}} = 7 \times 10^{-6} \dot{M}_{\text{B}} \left( \frac{M_{\text{ns}}}{M_{\odot}} \right) \left( \frac{v}{10^3} \right)^{-4} \left( \frac{r_{\text{orb}}}{5 \times 10^{12}} \right)^{-2}. \quad (2)$$

Here,  $\dot{M}_{\text{B}}$  and  $v$  are the mass loss rate and wind velocity of the B star,  $M_{\text{ns}}$  is the mass of the neutron star, and  $r_{\text{orb}}$  is the separation distance between the two stars. If we let  $\dot{M}_{\text{B}} = 10^{-9} M_{\odot} \text{ yr}^{-1}$ , and  $v = 2000 \text{ km s}^{-1}$ , typical values for B stars, and  $M_{\text{ns}} = 1.4 M_{\odot}$ , we find that the accretion rate onto the neutron star varies by a factor of 1.9; at periastron,  $\dot{M}_{\text{acc}} = 1.3 \times 10^{-15} M_{\odot} \text{ yr}^{-1}$  and at apastron,  $\dot{M}_{\text{acc}} = 7.0 \times 10^{-16} M_{\odot} \text{ yr}^{-1}$ . Although it is difficult to believe that at such low accretion rates, a factor of two in  $\dot{M}$  could give rise to significantly different photometric characteristics in the system, it is possible that tidal forces could excite pulsations when the stars are physically closest to each other. Tidal forces are proportional to  $r^{-3}$ , which implies a force on the B star that is 2.6 times larger at periastron than at apastron. This increase in tidal distortion of the B star by the primary decreases as the stars recede from each other. It is when the tidally distorted material falls back on the B star that stellar pulsations might be excited.

Another mechanism that could explain the 2.8 h period seen in both the x-ray and optical data is the rotation period of the neutron star. The magnetic field of the neutron star may be as large as  $10^{13} \text{ G}$  (Finley *et al.* 1994). Consequently, the B star material accretes directly onto the poles of the degenerate star, emitting x rays that are beamed along our line of sight once every rotation period. In the optical, we see the x rays reprocessed off the outer regions of the B star atmosphere which vary at the neutron star rotation period. However, because of the geometry of the system, the hot spot in the B-star atmosphere is eclipsed during certain orbital phases which may explain why Bell *et al.* (1993) and perhaps Finley *et al.* (1994) did not detect significant variability in their data. Intrinsic mass loss in Be stars occurs in two ways: (1) through a radiatively driven stellar wind and (2) through an equatorially enhanced outflow that is rotationally driven. The spin periods of neutron stars have been extensively investigated by Ghosh & Lamb (1979). These authors calculate the rate of change of the rotation period of a neutron star due to stellar wind accretion,  $\dot{P}_{\text{wind}}$  and due to disk accretion,  $\dot{P}_{\text{disk}}$ .

$$-\dot{P}_{\text{disk}} = 5.0 \times 10^{-5} \mu_{30}^{2/7} n(\omega_s) R_6^{6/7} (M_{\text{ns}}/M_{\odot})^{-3/7} \times I_{45}^{-1} (PL_{37})^2 \text{ s yr}^{-1}, \quad (3)$$

$$-\dot{P}_{\text{wind}} = 3.8 \times 10^{-5} R_6 (M_{\text{ns}}/M_{\odot})^{-1} \times I_{45}^{-1} (l_a/10^{17} \text{ cm}^2 \text{ s}^{-1}) P^2 L_{37} \text{ s yr}^{-1}, \quad (4)$$

where  $n(\omega_s)$  is the dimensionless accretion torque and  $\omega_s$  is the ratio of the Keplerian angular velocity at a distance  $r_0$  from the neutron star to the angular velocity of the star. Ghosh & Lamb (1979) give the following approximations for these two parameters:

$$n(\omega_s) \approx 1.39 \{1 - \omega_s [4.03(1 - \omega_s)^{0.173} - 0.878]\} \times (1 - \omega_s)^{-1},$$

$$\omega_s \approx 1.35 \mu_{30}^{6/7} R_6^{-3/7} (M/M_{\odot})^{-2/7} (PL_{37}^{3/7})^{-1}. \quad (5)$$

In Eqs. (3) and (4),  $\mu_{30} = 1$ , the magnetic moment in units of  $10^{30} \text{ G cm}^3$ ,  $R_6 = 1$ , the radius of the neutron star in  $10^6 \text{ cm}$ ,  $M_{\text{ns}} = 1.4 M_{\odot}$ , the mass of the neutron star,  $I_{45} = 2.78$ , the moment of inertia of the star in  $10^{45} \text{ g cm}^2$ ,  $P = 10^4 \text{ s}$ , the rotational period of the neutron star,  $L_{37} = 1.17 \times 10^{-6}$ , the accretion luminosity in units of  $10^{37} \text{ erg s}^{-1}$ , and  $l_a$ , is the specific angular momentum, which is approximately  $2.5 \times 10^{14} \text{ cm}^2 \text{ s}^{-1}$  assuming a capture radius of  $9 \times 10^9 \text{ cm}$ . We find that  $\dot{P}_{\text{disk}} = -0.02 \text{ s yr}^{-1}$  and  $\dot{P}_{\text{wind}} = -2 \times 10^{-5} \text{ s yr}^{-1}$  implying a spin-up time scale of some  $5 \times 10^5 \text{ yr}$ .

2S 0114+65 has proven to be a very interesting Be/x-ray binary that should be monitored more intensively. Data spanning the entire 12 day binary orbit would help to determine whether or not the variations are related to orbital phase. In addition, simultaneous, or near-simultaneous spectroscopy and photometry would be useful in correlating shell episodes with the persistence of the 2.8 h period. If the variations represent the rotation period of the neutron star, however, this would be the longest spin period of any neutron star studied to date. Typical spin periods of neutron stars in Be/x-ray binaries are on the order of hundreds of seconds. However, only about a dozen or so of these kinds of binaries are presently known and of these, the spin periods of only half have been identified. Perhaps this is a consequence of the fact that the periods are relatively long and the optical amplitudes are quite small.

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