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RXTE OBSERVATIONS OF THE X-RAY BINARY 2S 0114+650

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ABSTRACT

Observations from the proportional counter array experiment on board the *Rossi X-Ray Timing Explorer* (*RXTE*) of the temporal and spectral properties of the high-mass X-ray binary 2S 0114+650 are reported. We find highly variable X-ray emission modulated at a period of 2.73 hr. The temporal results indicate that 2S 0114+650 is the slowest neutron star rotator presently known. Spectral analysis reveals parameters typical of a high-mass X-ray binary system having an absorbed power law with an index of about 1.3 with a high-energy cutoff at approximately 8 keV. The introduction of a fluorescent iron line at 6.4 keV allowed better spectral fits, particularly during low states of emission. We have also determined that the intensity of 2S 0114+650 is strongly attenuated during part of the orbit, which makes it a member of the small class of eclipsing massive X-ray binaries.

Subject headings: stars: individual (2S 0114+650) — stars: neutron — X-rays: stars

1. INTRODUCTION

The discovery of the X-ray source 2S 0114+650 was reported by Dower et al. (1977) in the *SAS 3* Galactic survey. The optical counterpart was identified later that year as the 11th magnitude star LS I +65 010 (Dower et al. 1977) with a recent classification as a B1 supergiant of luminosity class Ia (Reig et al. 1996). Optical radial velocity measurements by Crampton, Hutchings, & Cowley (1985) revealed an orbital period of 11.59 days with an eccentricity of 0.16; however, a circular orbit could not be ruled out based on these data. In addition to optical studies, 2S 0114+650 has been the focus of numerous X-ray observations, including those by *Einstein*, *HEAO 1*, and *OSO 8* (Koenigsberger et al. 1983); *EXOSAT* (van Kerkwijk & Waters 1989; Apparao, Bisht, & Singh 1991); *Ginga* (Yamauchi et al. 1990); *ROSAT* (Motch et al. 1991; Finley, Belloni, & Cassinelli 1992; Finley, Taylor, & Belloni 1994); *ASCA* (Ebisawa 1997); and the *Rossi X-Ray Timing Explorer* (*RXTE*) all-sky monitor (ASM; Corbet, Finley, & Peele 1999). Past spectral studies have indicated an absorbed power-law spectrum with a photon index of ~ 1, a high-energy cutoff, and a fluorescent iron line. There have been reports of pulse periods at 895 (*Einstein*) and 850 s (*Ginga*) and quasi-periodic oscillations at 2000 s (*EXOSAT*); however, none have been confirmed. A common feature of all data sets were outbursts on a timescale of ~ 3 hr. Exploiting archival *EXOSAT* data, published data, and *ROSAT* all-sky survey data, Finley et al. (1992) determined that the outbursts were describable by a 2.78 hr period at all observational epochs. Pointed *ROSAT* PSPC observations (Finley et al. 1994) and a 2 yr baseline of *RXTE*/ASM observations (Corbet et al. 1999) confirmed that these pulsations were a persistent feature of 2S 0114+650.

This study continues a monitoring of 2S 0114+650 to achieve a better understanding of the long-period pulsations present in the system. We present the results of observations acquired with the *RXTE* satellite with observations and analyses described in § 2 and a discussion of the results in § 3. A summary and concluding statements are given in § 4.

2. OBSERVATIONS AND ANALYSIS

The high-mass X-ray binary 2S 0114+650 was observed with the proportional counter array (PCA; Jahoda et al. 1996) on board the *RXTE* satellite during 1996 October. The array consists of five nearly identical Xe proportional counter units (PCUs) sensitive in the energy range 2–60 keV with 18% energy resolution at 6 keV and a collection area of ~ 6700 cm^2. The PCA has a field of view of 1° FWHM with no imaging capabilities. The data were taken in the GOOD XENON collection mode (all events are individually time stamped and assigned an energy) and analyzed using FTOOLS available from NASA/GSFC. Twelve observations, spaced roughly 1 day apart, were made sampling the 11.59 day orbital period. Each observation was approximately 10 ks in duration, yielding a total effective exposure of 113 ks after selection of good time intervals. After background subtraction, the average counting rate during these exposures was approximately 72 counts s^{-1}. However, 2S 0114+650 does display high variability, with X-ray flares producing counting rates of over 1000 counts s^{-1}. Figure 1 displays the background-subtracted light curve of 2S 0114+650 taken with the *RXTE*/PCA as well as the folded light curve from the *RXTE*/ASM observations (Corbet et al. 1999). The decreased counting rates of both data sets near phase 0 signify a temporally repeating attenuation of the X-ray source and may be indicative of an eclipse in the system.

To study the temporal behavior of 2S 0114+650, we applied a Fourier transform to the barycentered, background-subtracted time series to search for possible periods present in the binary system. Figure 2 displays the power spectrum of the data and the transform of the window function. Significant power was observed in both the window and time series transforms at a 25 hr period (corresponding to the sampling period of the observations) and a 96 minute period because of passage of the *RXTE* satellite through the South Atlantic Anomaly. The transform of the data revealed a 2.73 ± 0.01 hr period similar to

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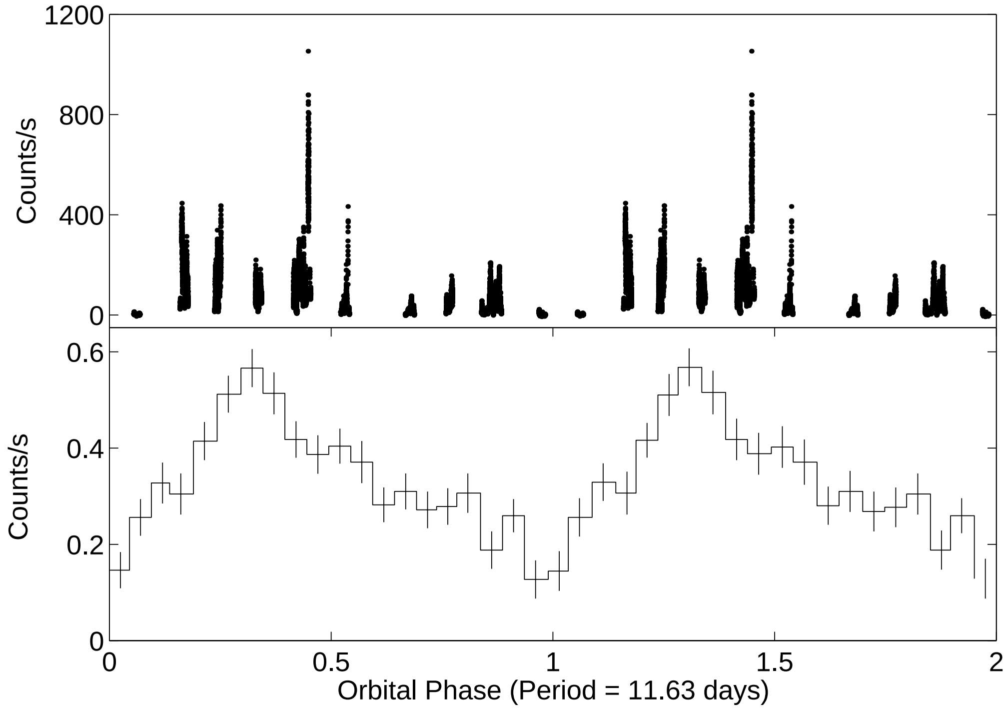

FIG. 1.—*Top:* Background-subtracted light curve for the *RXTE*/PCA observations of 2S 0114+650 folded about the orbital period given by Corbet et al. (1999) at epoch $T_0 = 50091.36$ MJD. *Bottom:* Folded light curve of the *RXTE*/ASM data taken from Corbet et al. (1999).

that seen by Finley et al. (1992, 1994) and Corbet et al. (1999). A folded light curve was produced over the 2.73 hr period and is displayed in Figure 3. The folded light curve is characterized by a broad sinusoidal shape, as observed in previous studies. Superimposed on this sinusoidal shape is the beating of the three major frequencies detected in the power spectrum. Each observation, except those near phase 0 (observations 7 and 8), exhibited evidence of the 2.73 hr period and an intensity modulation of approximately a factor of 8, peak to valley (as noted by Finley et al. 1994). The duration of the observations, which are comparable to the pulse period, and the projected size of the neutron star orbit of ∼130 lt-s (corresponding to only 1% of the length of the pulse period) preclude determination of the orbital

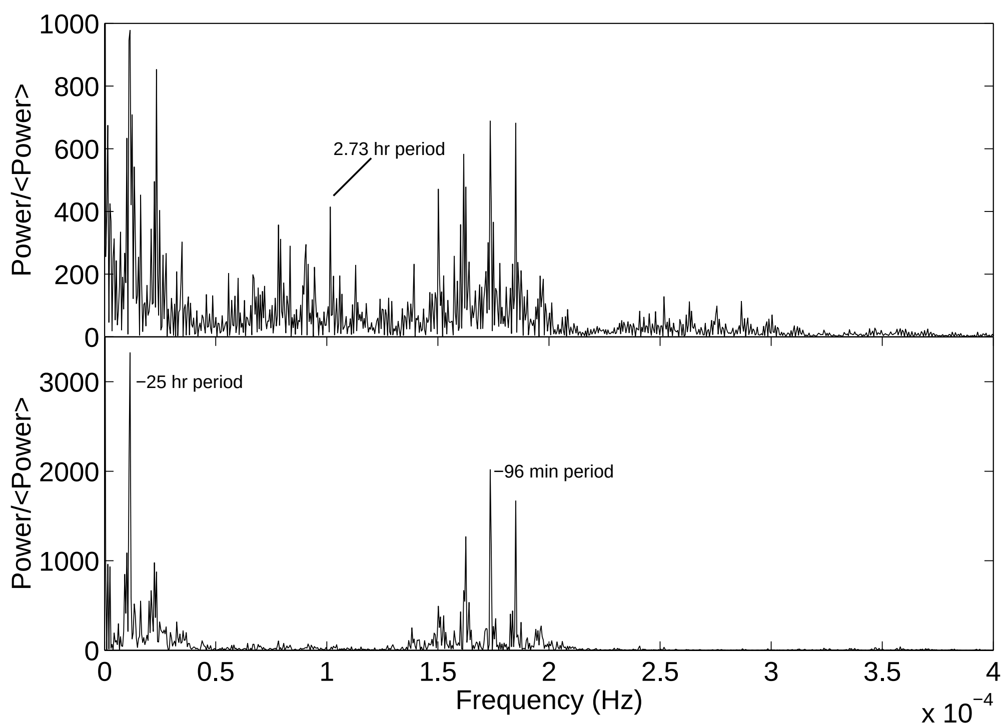

FIG. 2.—*Top:* Power spectrum of the barycentered, background-subtracted light curve of 2S 0114+650. *Bottom:* Power spectrum of the window function showing the 25 hr and 96 minute periods, as well as their harmonics.

TABLE 1

SPECTRAL FIT PARAMETERS AND 68% CONFIDENCE ERRORS OF 2S 0114+650

Data Set	N_H ($\times 10^{22}$ cm^{-2})	Photon Index	Cutoff Energy (keV)	Folding Energy (keV)	Flux ($\times 10^{-10}$ ergs cm^{-2} s^{-1})
All Data	$3.5^{+0.3}_{-0.3}$	$1.37^{+0.04}_{-0.05}$	$8.4^{+0.4}_{-0.4}$	$20.3^{+1.2}_{-1.1}$	1.09
Low State	$4.1^{+0.4}_{-0.4}$	$1.63^{+0.04}_{-0.02}$	$11.3^{+0.8}_{-0.9}$	$22.4^{+6.7}_{-4.7}$	0.34
High State......	$3.2^{+0.3}_{-0.3}$	$1.28^{+0.04}_{-0.05}$	$8.1^{+0.4}_{-0.4}$	$19.2^{+1.1}_{-1.0}$	2.13

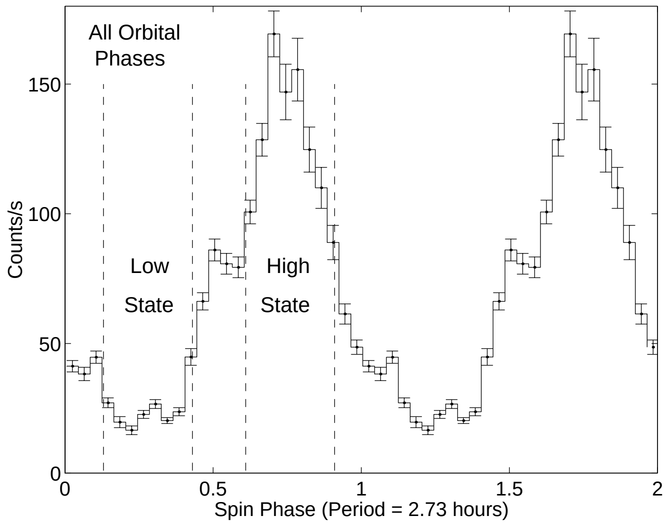

FIG. 3.—Light curve of 2S 0114+650 folded about the 2.73 hr period present in the power spectrum. Dashed lines indicate phases defined as the low state (0.13–0.43) and the high state (0.61–0.91) of the spin period. Phase 0 corresponds to epoch $T_0 = 50363.859$ MJD.

parameters because of Doppler shifting. Data in different energy bands were also folded about the 2.73 hr period (see Fig. 4). Little variation in pulse shape is observed, and the factor of 8 modulation persists. This behavior is not exhibited by some other B supergiant–neutron star binaries, such as Vela X-1 (Kreykenbohm et al. 1999) and GX 301-2 (Haberl 1991); however, it is not unprecedented in this energy range, and similar behavior is seen in 4U 1907+09 (In't Zand, Baykal, & Strohmayer 1998).

Spectral analysis was performed on the data using the method described by R. Remillard (1998, private communication) in which PCUs 0, 1, and 4 were used in the energy band 3–20 keV to provide stable and reliable results. The best-fit spectrum was an absorbed power law, an iron line (with central energy fixed at 6.4 keV), and a high-energy cutoff yielding an unabsorbed model flux of 1.85×10^{-10} ergs cm^{-2} s^{-1} (3–20 keV). Other model descriptions were applied to the spectra, but none yielded acceptable results. The pulse height distribution is shown in Figure 5, with the best-fitting parameters and their 68% confidence errors given in Table 1. Each observation was analyzed to ascertain the orbital phase dependence of the spectrum. The only correlation observed was between the neutral hydrogen column density and the orbital phase, which is displayed in Figure 6. Spectral fits indicate that as the system went into its quiescent state (near orbital phase 0) the neutral hydrogen column density increased by a factor of at least 2. Unfortunately, the virtual disappearance of the signal from 2S 0114+650 around orbital phase 0 did not allow us to constrain the spectral parameters in this region. Spectral fits were also carried out during the high and low states of the

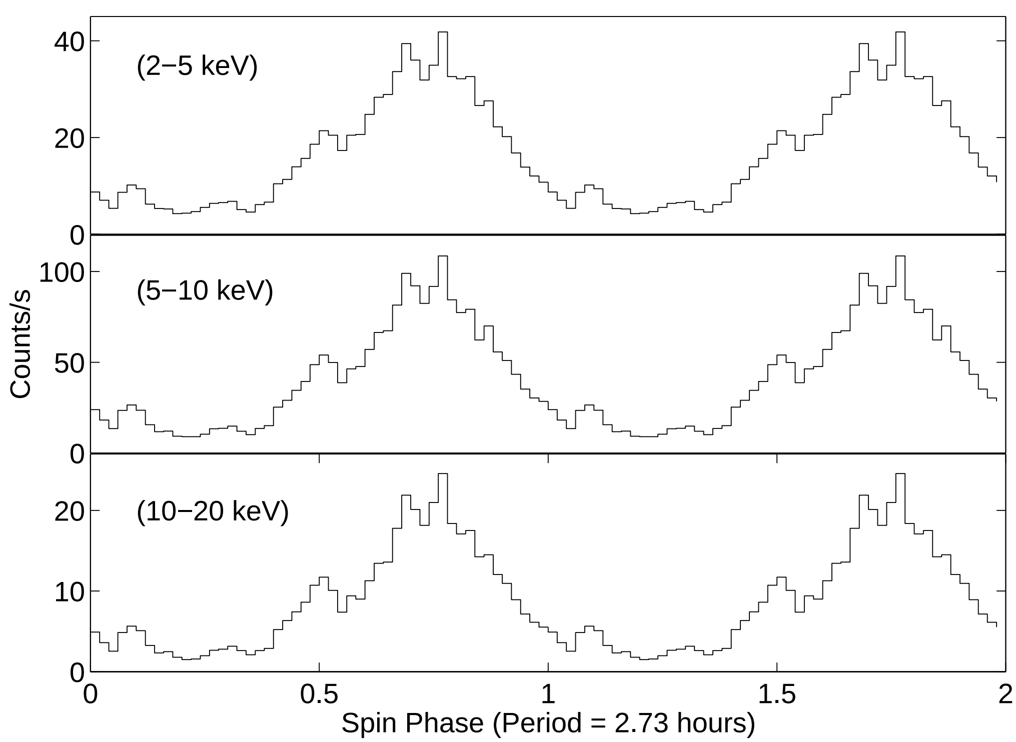

FIG. 4.—Light curve of 2S 0114+650 shown in three energy bands (2–5, 5–10, and 10–20 keV) folded over the 2.73 hr period

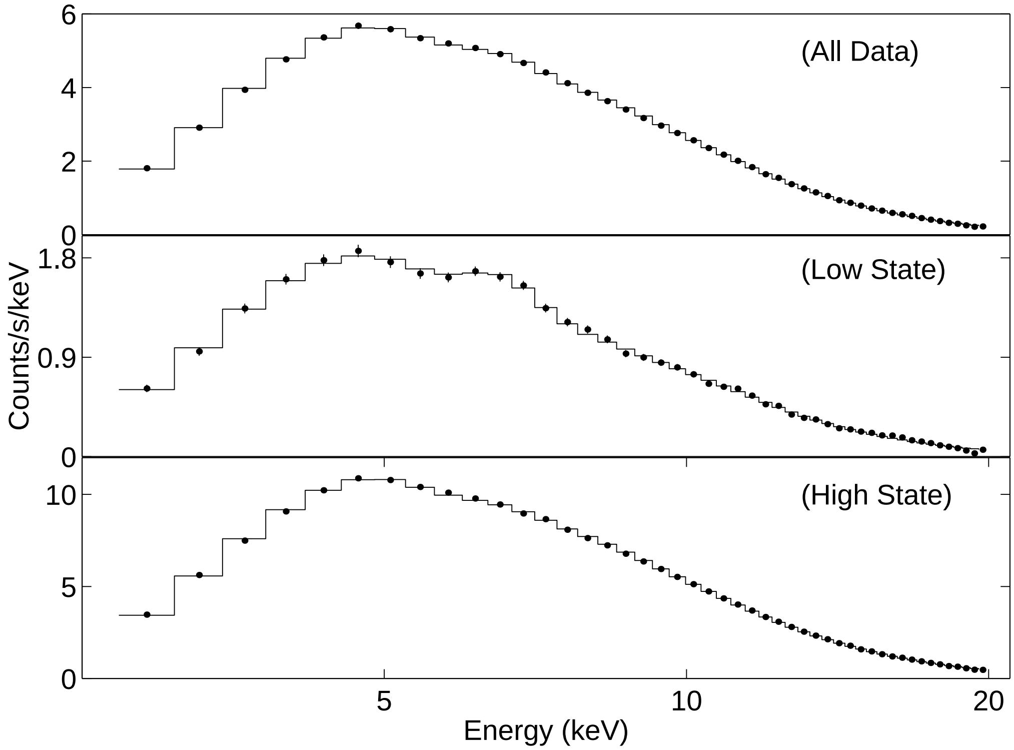

FIG. 5.—Spectrum of 2S 0114+650 (*circles*) and the best-fit model (*solid line*) of the complete data set, low state, and high state of the spin period. Parameters of these fits are given in Table 1.

spin phase (see Fig. 3 for definitions of these phase intervals). Both the high and low states were well fitted by the absorbed power-law model with a high-energy cutoff (see Fig. 4 and Table 1) yielding unabsorbed fluxes of 5.54×10^{-11} (low state) and 3.67×10^{-10} ergs cm^{-2} s^{-1} (high state) in the 3–20 keV energy band. During the low state of the spin period, the equivalent width of the iron line was found to be 0.25 ± 0.15 keV; however, spectral fits did not allow the width to be constrained when the X-ray source was in its high state of emission. These results are in good agreement with Yamauchi et al. (1990), who found the iron line widths to be 0.34 and 0.07 keV for the low and high states, respectively.

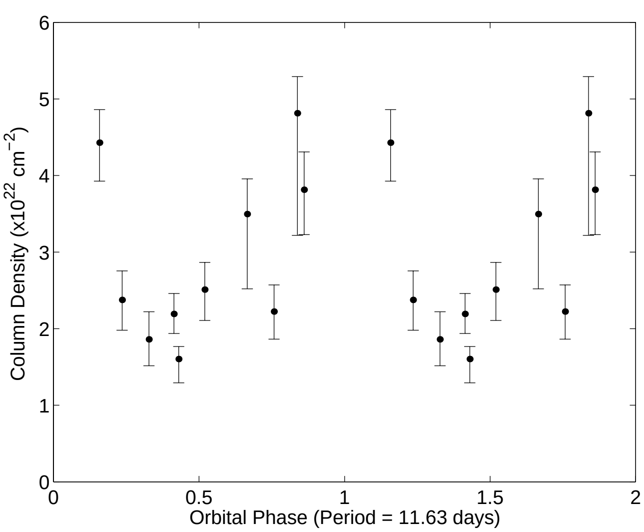

FIG. 6.—Column density shown as a function of orbital phase with 1 σ error bars. The intensities during observations 7 and 8 (phases 0.9673 and 0.0536, respectively) were too low to reliably constrain values for the column density.

3. DISCUSSION

Based on these data taken with the *RXTE*/PCA and data taken from other X-ray instruments since 1983, the 2.7 hr period has been shown to be a persistent feature of 2S 0114+650. Two suggestions have been put forward to explain the long period pulsations seen in 2S 0114+650.

First, the primary could be a member of the β-Cephei class of pulsating stars (as suggested and discussed in Finley et al. 1992). Reports made by Taylor et al. (1995) suggest that the system may brighten optically at the same 2.7 hr period as the X-ray pulses. Bell, Hilditch, & Pollacco (1993) and Finley et al. (1994) failed to find evidence of periodic optical brightening from this system. The interpretation of the primary as a β-Cephei class star to explain the underlying clock in the system continues to be plagued by the lack of persistent optical modulations and an insufficient understanding of the processes enabling a pulsating primary to give rise to periodic X-ray emission. Also, the classification of 2S 0114+650 as a B1 Ia supergiant by Reig et al. (1996) does not fit the characteristics necessary for it to be a member of the β-Cephei class of stars.

Second, the pulsations could arise from accretion onto a spinning, magnetized neutron star, which naturally leads to a modulation of X-rays. This description is supported by the fact that the X-ray source 2S 0114+650 has luminosity and spectral properties similar to systems that contain pulsars in wind-driven high-mass X-ray binaries. This interpretation requires an exceptionally long period as compared to other observed pulsar spin periods. Li & van den Heuvel (1999) have proposed that in order to obtain such a long period, 2S 0114+650 must have had a natal magnetic

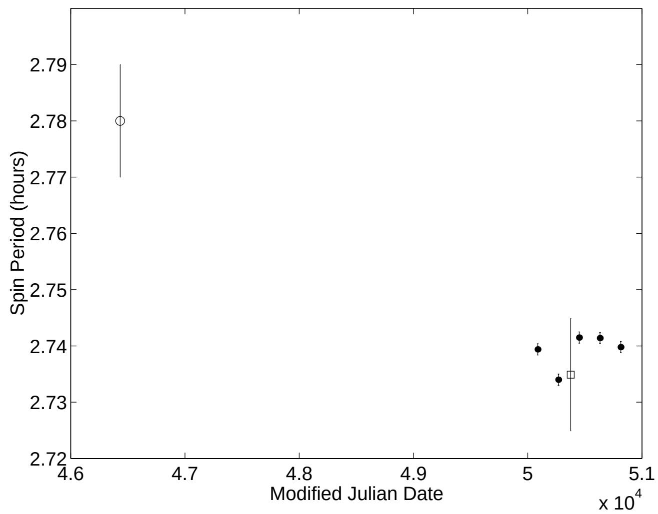

FIG. 7.—Spin history of 2S 0114+650. Open circle from Finley et al. (1992), filled circles from Corbet et al. (1999), and open square from this work.

field strength $\geq 10^{14}$ G; that is, it must have been born a magnetar. Once these fields decay, magnetars may not be distinguishable from pulsars born with normal magnetic field strengths except by their long spin periods.

The optical component of this system has displayed characteristics of both a Be star (Koenigsberger et al. 1983; van Kerkwijk & Waters 1989) and a B supergiant (Crampton et al. 1985; Reig et al. 1996). It has also been speculated that the primary could belong to a class of pulsating stars, the β-Cephei. However, based on the recent classification by Reig et al. (1996) this seems unlikely. Both Crampton et al. (1985) and Reig et al. (1996) have reported a $v_{rot} \sin i$ of ~ 100 km s^{-1}, which would be rather small for the current definitions of Be stars, especially given that sin i is close to 1 based on the presence of an eclipse in the system. It should also be noted that the classification by Reig puts the system at a distance of 7.2 kpc, giving an X-ray luminosity of 1.1×10^{36} ergs s^{-1} (3–20 keV), which is what one would expect for a neutron star accreting from the wind of a B class supergiant.

Crampton et al. (1985) reported the absence of an eclipse in the optical light curve of LS I +65 010; however, the data reported here and by Corbet et al. (1999) suggest a definite truncation of the X-ray signal near orbital phase 0 (see Fig. 1). This is supported by spectral fits, which indicate an increase in column density as the X-ray source nears phase 0 (see Fig. 6). The virtual disappearance of 2S 0114+650 around phase 0 puts it in the class of eclipsing high-mass X-ray binaries. However, because of the poor sampling around this eclipse, we cannot as yet quantify the duration nor the extent of the eclipse. The fact that this system is eclipsing supports its classification as a supergiant since the probability of seeing eclipses in the supergiants is much higher than that for smaller Be companions.

The spin history of 2S 0114+650 over ~ 10 yr is displayed in Figure 7. If the spin-up trend displayed in Figure 7 is interpreted as a secular one, then 2S 0114+650 has a value of $\dot{P}/P$ of $\sim -2 \times 10^{-3}$ yr^{-1}. This is not unlike other systems, which show a secular spin-up of the spin period (see Nagase 1989). Future measurements of the spin period will determine whether this is indeed a secular trend or is stochastic as in other high-mass systems.

4. SUMMARY AND CONCLUSIONS

The 2.7 hr period of 2S 0114+650 is a persistent feature of this system, indicating that the underlying clock is stable and not due to transient behavior. The luminosity and the temporal behavior preclude a white dwarf as the underlying engine, and we are thus led to conclude that 2S 0114+650 is a neutron star with a 2.7 hr rotation period accreting matter from a B class supergiant. Based on the signal's disappearance around phase 0 and the correlation of the neutral hydrogen column density with orbital phase, it can be concluded that 2S 0114+650 is at least a partially eclipsing system.

Recent work by Li & van den Heuvel (1999) suggests that 2S 0114+650 may be a magnetar system where the magnetic field has decayed. This interpretation is a plausible explanation for the long spin period. If they are correct, there may be other such systems with long spin periods that have yet to be discovered. Continued monitoring of 2S 0114+650 will determine the nature of the spin evolution, and eclipse mapping will allow the mass of the X-ray component to be determined. This very slow rotator may be the first of a new class of X-ray systems where the long spin period is the relic of a magnetar phase of evolution.

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