The Astrophysical Journal, 511:876–884, 1999 February 1

EVIDENCE FOR A VERY SLOW X-RAY PULSAR IN 2S 0114+650 FROM *ROSSI X-RAY TIMING EXPLORER* ALL-SKY MONITOR OBSERVATIONS

Robin H. D. Corbet,[1,2] John P. Finley,[3] and Andrew G. Peele[1,4]

Received 1998 May 29; accepted 1998 September 4

ABSTRACT

Rossi X-Ray Timing Explorer (*RXTE*) all-sky monitor (ASM) observations of the X-ray binary 2S 0114+650 show modulations at periods close to both the optically derived orbital period (11.591 days) and proposed pulse period (~2.7 hr). The pulse period shows frequency and intensity variability during the more than 2 years of ASM observations analyzed. The pulse properties are consistent with this arising from accretion onto a rotating neutron star, and this would be the slowest such period known. The shape of the orbital light curve shows modulation over the course of the entire orbit, and a comparison is made with the orbital light curve of Vela X-1. However, the expected phase of eclipse, based on an extrapolation of the optical ephemeris, does not correspond with the observed orbital minimum. The orbital period derived from the ASM light curve is also slightly longer than the optical period.

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

1. INTRODUCTION

The X-ray source 2S 0114+650 has an early spectral type supergiant optical counterpart, LS I +65°010, with a recent classification of B1 Ia (Reig et al. 1996) and this object is thus thought to be a high-mass X-ray binary. With a distance of 7.2 kpc derived from this spectral classification the X-ray luminosity is 1×10^{36} ergs s^{-1}. An orbital period of 11.591 ± 0.003 days was reported from optical radial velocity measurements made by Crampton, Hutchings, & Cowley (1985). However, the optical Doppler curve did not allow a distinction to be made between a circular orbit and one of small eccentricity ($e = 0.16 \pm 0.07$; orbital period = 11.588 ± 0.003 days). If the compact object in 2S 0114+650 is a neutron star then, in common with most other high-mass X-ray binaries, X-ray pulsations would be expected to be seen. Although there have been some reports of a pulsation period near 850–895 s (Yamauchi et al. 1990; Koenigsberger et al. 1983) the evidence for a period of this length appears to be, at best, weak. In contrast, Finley, Belloni, & Cassinelli (1992) reported a 2.78 ± 0.01 hr period for which there is evidence from observations with several satellites (*ROSAT*, *Ginga*, and *EXOSAT*) although the number of 2.78 hr cycles in each observation was limited. The same period was also apparent in further *ROSAT* observations (Finley, Taylor, & Belloni 1994) and a lower limit to the Q value ($P/\Delta P$) of 17 was derived. If this is indeed the pulse period of a neutron star then it would be the longest so far detected. The other known X-ray pulsators have periods between 69 ms and 1400 s (e.g., Bildsten et al. 1997). However, alternative interpretations of such a modulation such as instabilities in the primary star may be possible. Some earlier optical observations of 2S 0114+650 gave somewhat different spectral classifications, and van Kerkwijk & Waters (1989) have suggested that the optical counterpart of 2S 0114+650 displays some of the characteristics of a Be star and some of a supergiant (see also Guarnieri et al. 1994). For a main-sequence luminosity classification the distance to 2S 0114+650 would be ~2.5 kpc and the X-ray luminosity correspondingly less (cf. Reig et al. 1996).

Here we report on the results of an analysis of data obtained with the all-sky monitor (ASM) on board the *Rossi X-Ray Timing Explorer* (*RXTE*) covering a period of more than 2 years which shows modulation on both the orbital period and ~2.7 hr period.

2. DATA AND ANALYSIS

The all-sky monitor detector on board *RXTE* (Bradt, Rothschild, & Swank 1993) is described in detail by Levine et al. (1996). The ASM consists of three similar scanning shadow cameras, sensitive to X-rays in an energy band of approximately 2–12 keV, which perform sets of 90 s pointed observations ("dwells") so as to cover ~80% of the sky every ~90 minutes. The analysis presented here makes use of both daily averaged light curves and light curves from individual dwell data. Light curves are available in three energy bands: 1.3–3.0, 3.0–4.8, and 4.8–12.2 keV. ASM observations of blank field regions away from the Galactic center suggest that background subtraction may yield a systematic uncertainty of about 0.1 counts s^{-1} (Remillard & Levine 1997).

RXTE ASM observations of 2S 0114+650 have been obtained since 1996 January, with a short interruption due to instrumental problems in early 1996, and the ASM light curve of 2S 0114+650 is plotted in Figure 1. Because of the low count rate from this source we show a rebinned and smoothed version of the daily averaged light curve. The data discussed in this paper thus cover the period between MJD 50,087 (1996 January 5) and MJD 50,997 (1998 July 3). The mean intensity of 2S 0114+650 during this period is found to be 0.35 counts s^{-1} or ~4.7 mcrab.

In order to search for periodic modulation in the ASM observations we calculated a Fourier transform of the light curve obtained from individual dwell data weighting results by the errors on individual data points. We also investigated the "Lomb-Scargle" (Lomb 1976; Scargle 1982) variation of the Fourier transform, and both techniques gave comparable results. The resulting power spectrum

---

[1] Code 662, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

[2] Universities Space Research Association; corbet@lheamail.gsfc.nasa.gov.

[3] Department of Physics, Purdue University, 1396 Physics Building, West Lafayette, IN 47097-1396; finley@purds1.physics.purdue.edu.

[4] National Research Council Research Associate; peele@lheamail.gsfc.nasa.gov.

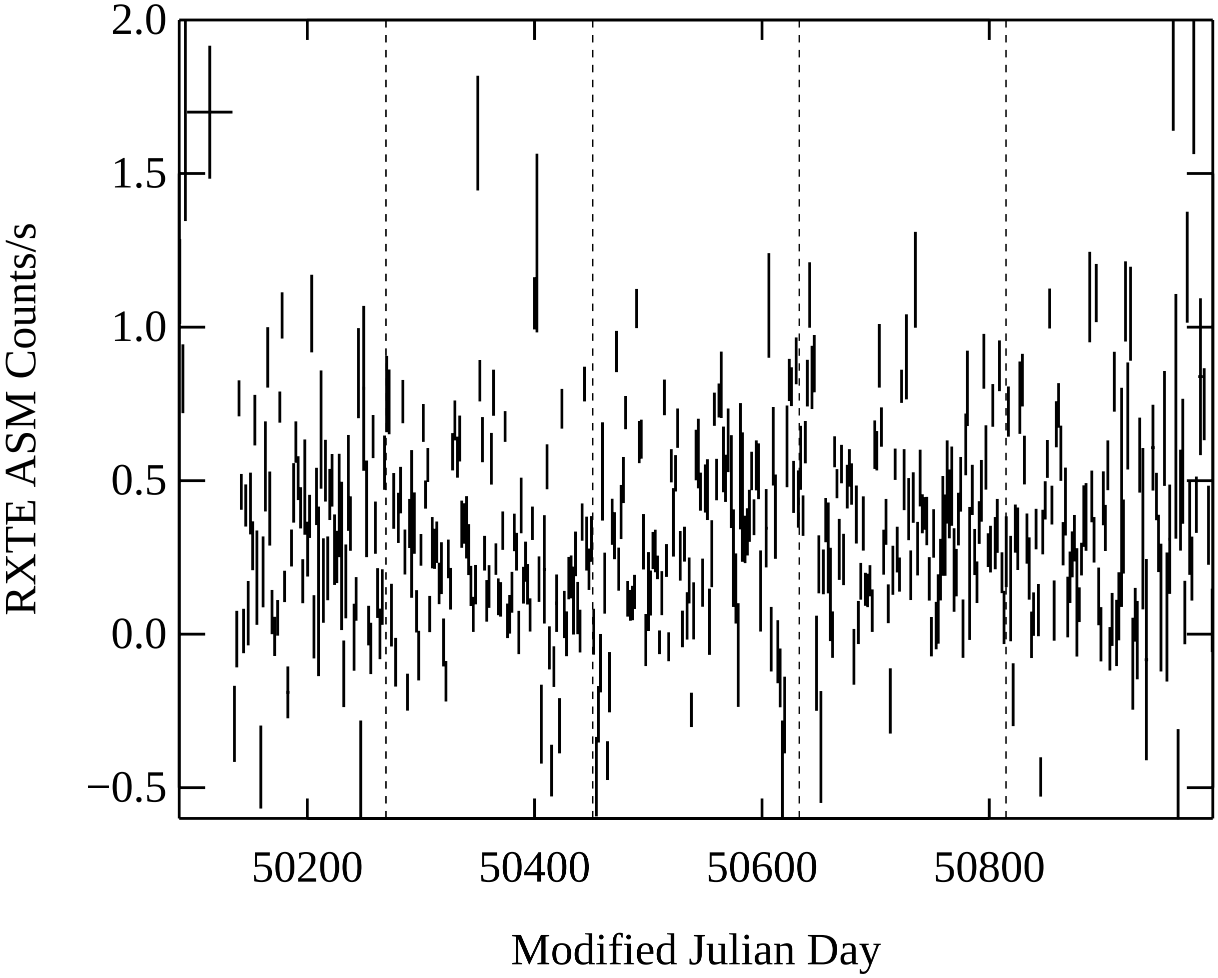

FIG. 1.—ASM light curve of 2S 0114+650. Data points are a rebinned and smoothed version of the standard 1 day light curves. The dashed lines indicate the sections the light curve was split into for computing the power spectra plotted in Fig. 5.

from the weighted Fourier transform technique is shown in Figure 2. The two strongest peaks in the power spectrum are located close to the 11.59 day orbital period of the system and the ∼2.7 hr period reported by Finley et al. (1992). In addition, there is modest evidence for power at peaks corresponding to harmonics of the orbital period. A peak is also present at ∼96 minutes that corresponds to the orbital period of *RXTE*. There is also a further peak of comparable strength at approximately 25.65 hr that we suspect may be related to daily variations in background levels we find variability at similar periods in at least some of the other sources that have been observed with the ASM. In Figure 3 we show a detail of the power spectrum near the proposed orbital period. We note that the strongest peak in the power spectrum is apparently slightly offset from the period reported by Crampton et al. (1985). A sine wave fitted to the *RXTE* ASM light curve yields a period of 11.630 ± 0.007 days.

In Figure 4 we show a detail of the power spectrum near the Finley et al. (1992) 2.7 hr period. In the figure it can be seen that the strongest peak is offset from the 2.78 ± 0.01 hr period found by Finley et al. (1992). In addition, rather than a single peak, there are multiple peaks suggesting period changes. To investigate period changes in more detail we split the ASM light curve into five sections of equal length and computed individual power spectra. These are shown in Figure 5 and demonstrate that the pulsations can exhibit significant changes in both pulse strength and period.

The average pulse profile derived from the ASM observations is shown in Figure 6, this was constructed by dividing the light curve into several sections and independently determining the period and phase of the modulation during that section of data before co-adding. The mean pulse profile appears to be approximately sinusoidal.

We also searched for variability on the proposed 850 s timescale in the ASM data. In the range 800–900 s we find no evidence for any periodic modulation with an amplitude greater than 0.062 counts s^{-1}. In contrast, ASM observations of the 837 s pulsator X Per, which has a mean flux of 0.66 counts s^{-1} (∼9 mcrab) in the ASM, do show a highly significant modulation with an amplitude of 0.13 counts s^{-1}, which demonstrates that, for a sufficiently large amplitude, a period of this length could have been detected with the ASM.

3. DISCUSSION

3.1. *Orbital Modulation*

In Figure 7 we show the *RXTE* ASM data folded on the period obtained by Crampton et al. (1985). By comparison with other high-mass X-ray binaries, two ways in which we might expect to see orbital modulation would be either (1)

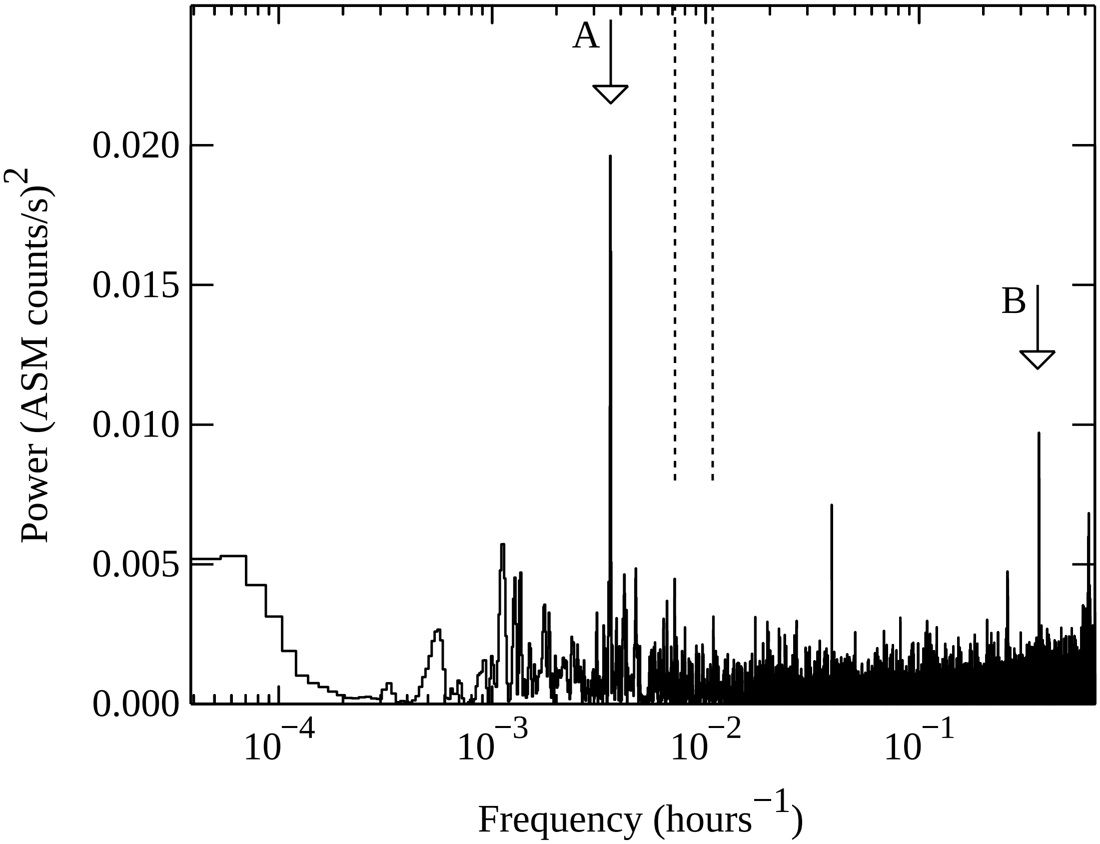

FIG. 2.—Power spectrum of the ASM light curve of 2S 0114 + 650. A and B indicate the periods reported by Crampton et al. (1985) and Finley et al. (1992), respectively. The dashed lines indicate harmonics of the Crampton et al. (A) peak.

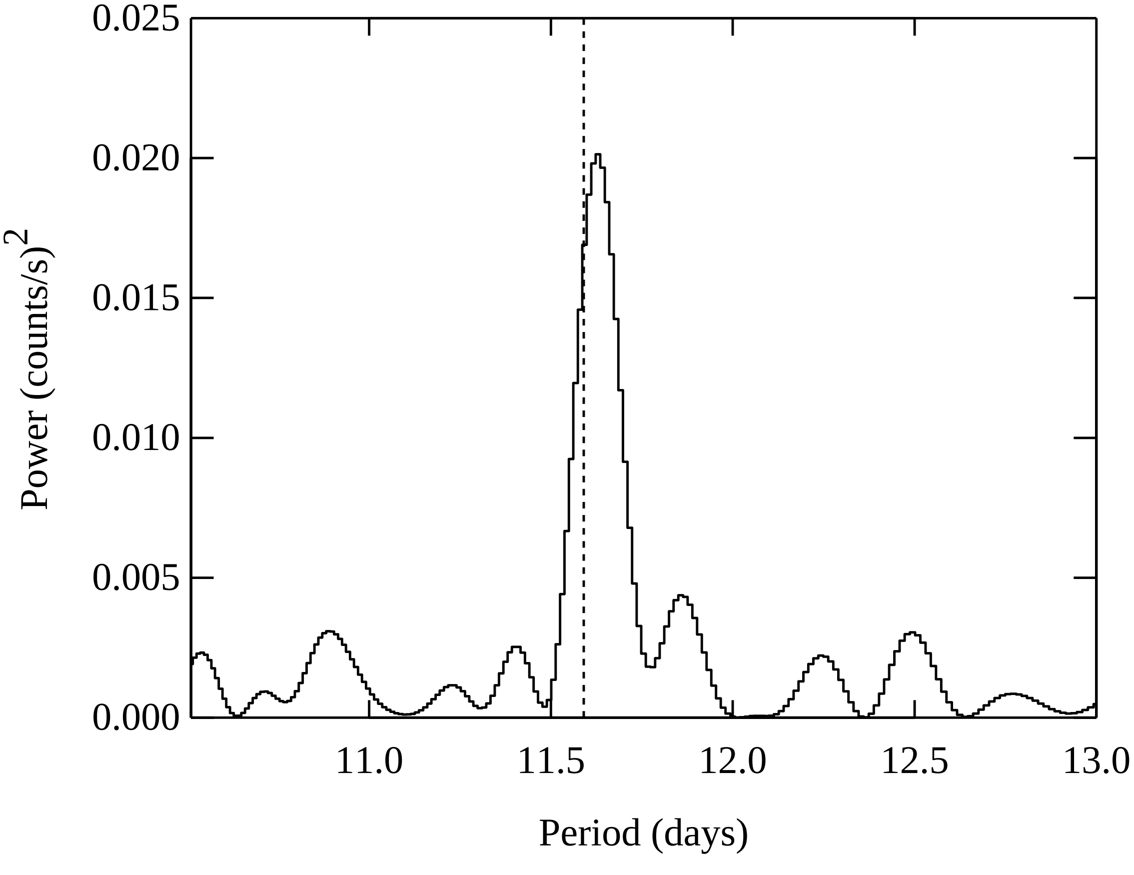

FIG. 3.—Close up of the peak in the power spectrum near the Crampton et al. (1985) optical period, which is indicated by the dashed line

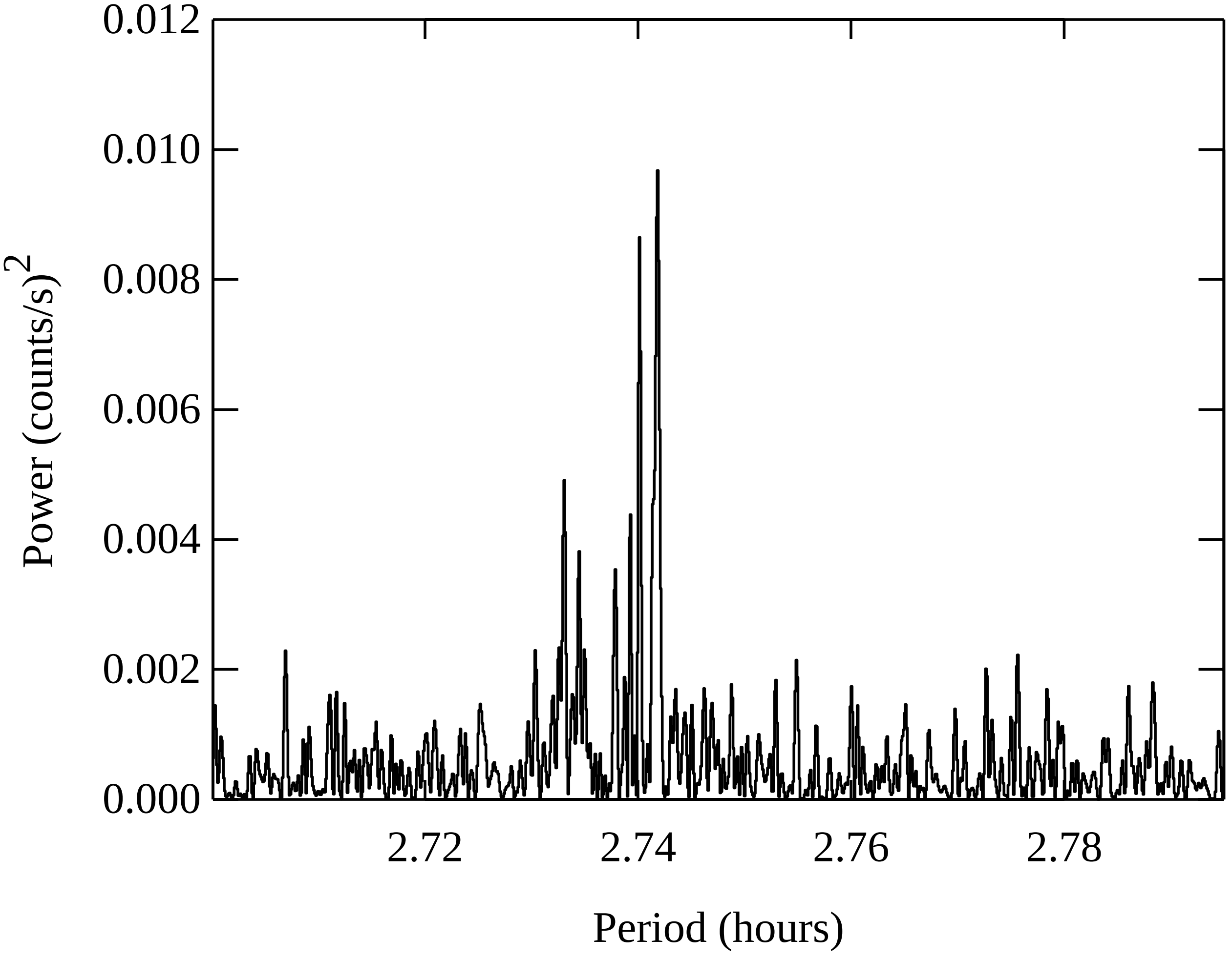

FIG. 4.—Detail of the power spectrum of the ASM light curve in the region around the period reported by Finley et al. (1992)

flares due to enhanced accretion at periastron passage if the orbit is significantly eccentric, or (2) an eclipse if the orbital inclination is sufficiently high. Marked on Figure 7 are the phases during which either periastron passage or an eclipse would be predicted based on the ephemerides reported by Crampton et al. (1985). We note that neither does the predicted periastron passage coincide with the maximum of the folded light curve nor does the predicted eclipse coincide with the minimum of the folded light curve. If we require the optical ephemeris to agree with the minimum of the ASM light curve we would require the optical period to be somewhat longer than that proposed by Crampton et al. (1985) at 11.597 days.

As the power spectrum of the ASM light curve also suggests a slightly different orbital period from that reported by Crampton et al. (1985), we show in Figure 8 the ASM light curve folded on our best period. We note that this shows somewhat more of a "sawtooth" profile than when folded on the optical period. We have examined the folded light curves of other high-mass X-ray binaries observed with the *RXTE* ASM and find a somewhat similar average behavior for Vela X-1, the folded light curve of which is shown in Figure 9. (See also the *ASCA* light curve from Feldmeier et al. 1996.) In the case of Vela X-1 there appear to be two components to the orbital variability: an eclipse plus a modulation that persists over the entire orbit with the X-ray flux peaking shortly after eclipse egress. Vela X-1 has a similar orbital period to that of 2S 0114+650 at 8.96 days and an eccentricity of 0.088 (Bildsten et al. 1997). The similarity of the light curves and orbital periods suggests that a common mechanism may be producing at least part of the modulation in both systems. In order to produce a modulation over the entire orbit a relatively large structure is required. This could take the form of a gas stream such as an accretion or photoionization wake (see, e.g., Kaper, Hammerschlag-Hensberge, & Zuiderwijk 1994). The low count rate of 2S 0114+650 prevents a clear determination of whether an eclipse also occurs in 2S 0114+650. However, an *RXTE* PCA observation of 2S 0114+650 by Finley et al. (1999) suggests that the flux is very close to zero at this orbital phase. We have searched for any possible energy dependence in the modulation of the light curve. However, this is difficult because of the relative hardness of the source—only the highest energy band (4.8–12.2 keV) shows a very clear orbital modulation. In addition, zero level offsets become even more important when the flux from this relatively faint source is split into several bands. We thus cannot draw any strong conclusions on spectral variability in 2S 0114+650 from the ASM data alone.

Given the failure of the optical ephemeris to match the folded X-ray light curve, we also fitted an orbit to the velocities reported by Crampton et al. (1985) and obtain essentially identical results. The orbital periods of 2S 0114+650 derived from the optical and X-ray measurements are thus

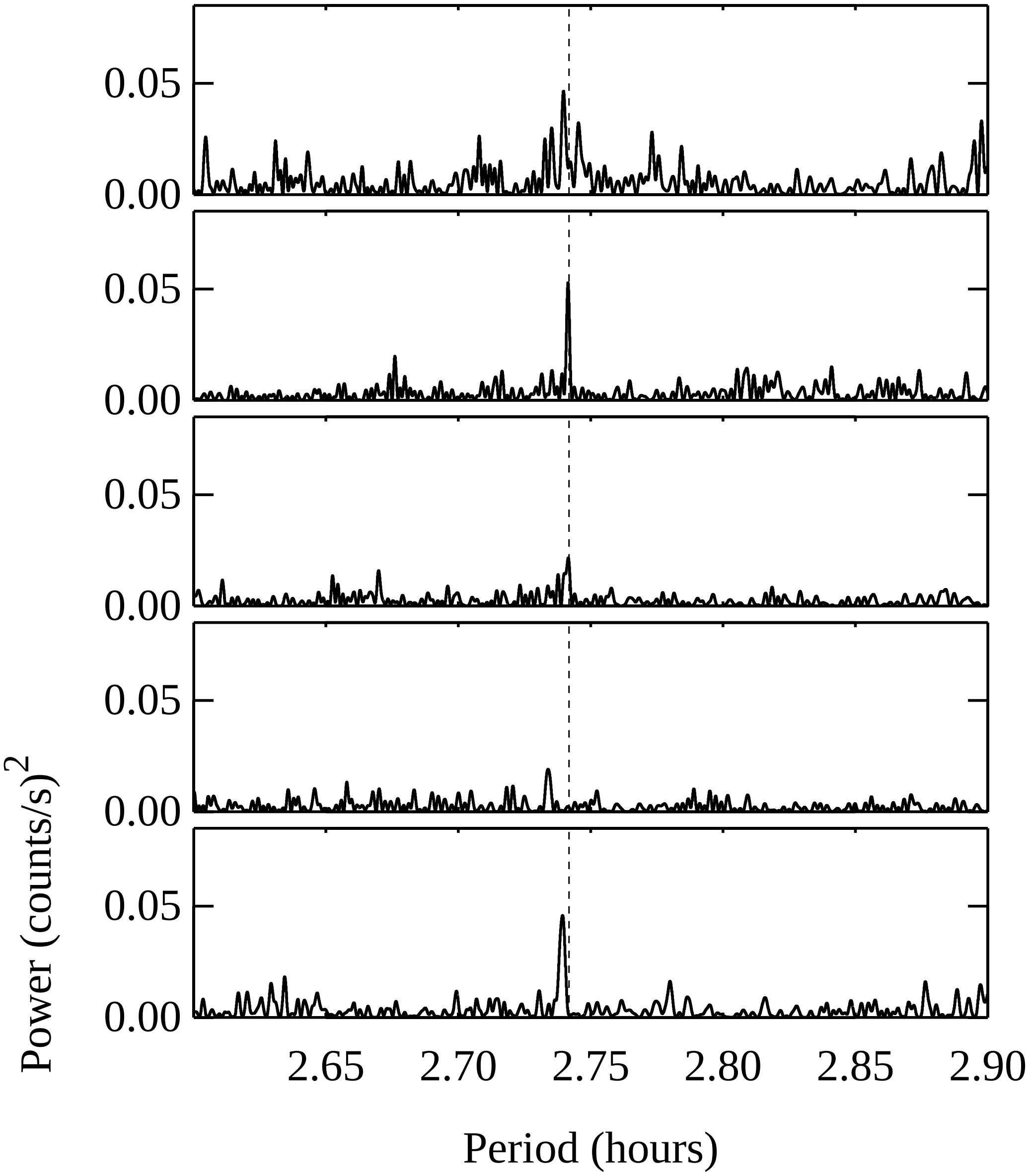

FIG. 5.—Power spectra of the ASM light curve around the Finley et al. (1992) period. The light curve was divided into five sections of equal length and power spectra calculated of each section individually. The dashed lines indicate the period of the strongest peak in a power spectrum of the entire data set. Time increases from the bottom to the top of the figure, and the intervals corresponding to the five data sections are indicated in Fig. 1 (MJD: 50,087.4, 50,269.2, 50,451.0, 50,632.9, 50,814.7, 50,996.6)

apparently inconsistent. The difference of 0.04 ± 0.01 days appears to be too large to be caused by a real change in the orbital period. This would correspond to an increase in the orbital period at a rate of $\sim 3 \times 10^{-5}$ yr^{-1}, an order of magnitude faster, and also a growth rather than a decay, compared to both theoretical predictions and observations of other similar systems (cf. Brookshaw & Tavani 1993; Rubin et al. 1997).

One possible explanation may be that the light curve and/or the radial velocity curve are subject to variable distortions. For example, X-ray irradiation could result in the variable contamination of absorption lines by low equivalent width emission lines. For comparison, Smale & Charles (1989) simulated such contamination in the high-mass X-ray binary A0538−66 and were able to produce apparent radial velocity shifts. Crampton et al. (1985) also note possible variations in the velocity difference between measurements of the Hβ and Hγ absorption lines. Alternatively, the cause of the discrepancy may be variability in the X-ray orbital modulation. If the X-ray modulation is produced by a mechanism that is not strictly locked to orbital phase, for example absorption in a gas stream, variations in the phase of X-ray modulation could produce an apparent shift from the true orbital period. To investigate changes in the orbital modulation of X-rays we fitted sine waves to the first and second halves of the ASM light curve separately. We obtained periods of 11.67 ± 0.02 and 11.62 ± 0.03 days, respectively. In addition, the amplitude of the modulation declined from 0.17 ± 0.02 to 0.11 ± 0.02 counts s^{-1}.

3.2. *Pulsations*

There are two principal models that have been proposed to explain the 2.7 hr period modulation in 2S 0114+650. These are as follows:

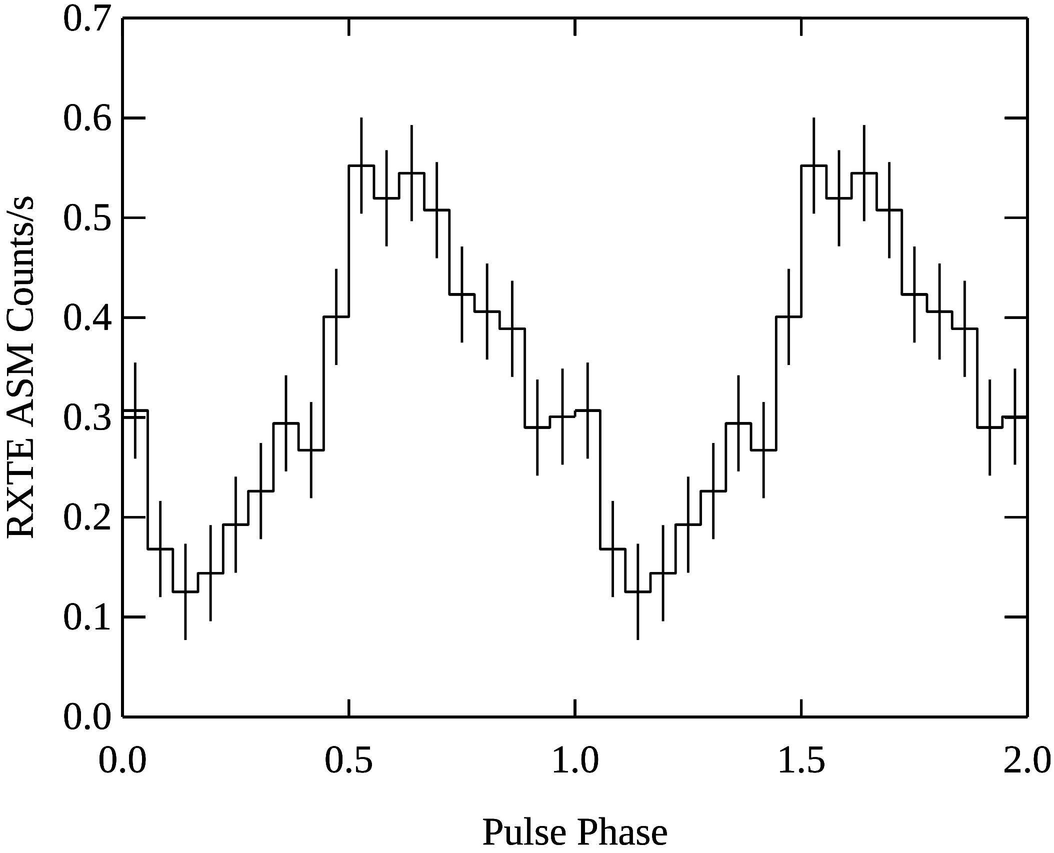

FIG. 6.—Mean ~2.7 hr pulse profile of 2S 0114+650. Each data section identified in Fig. 1 was individually folded and phase shifted to form this mean profile. Two cycles are shown for clarity.

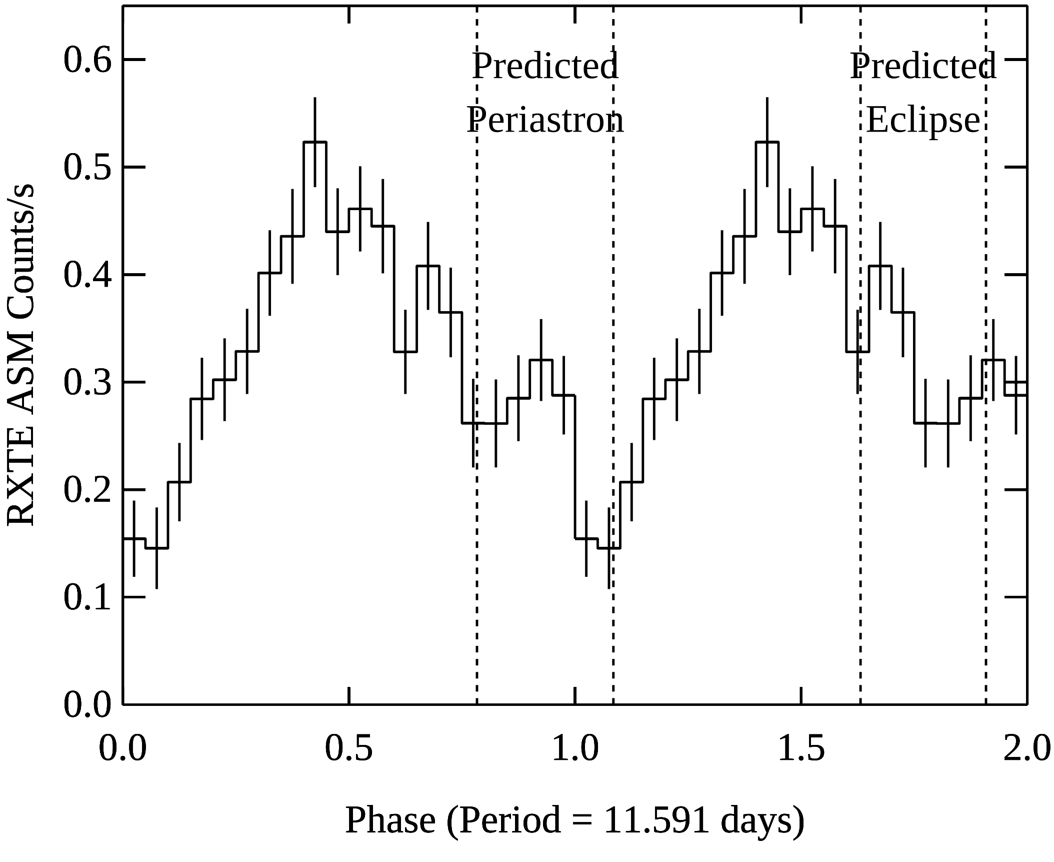

FIG. 7.—ASM light curve folded and binned on the Crampton et al. (1985) period. Times of predicted eclipse and periastron passage based on the Crampton et al. ephemeris are indicated. Two cycles are plotted for clarity.

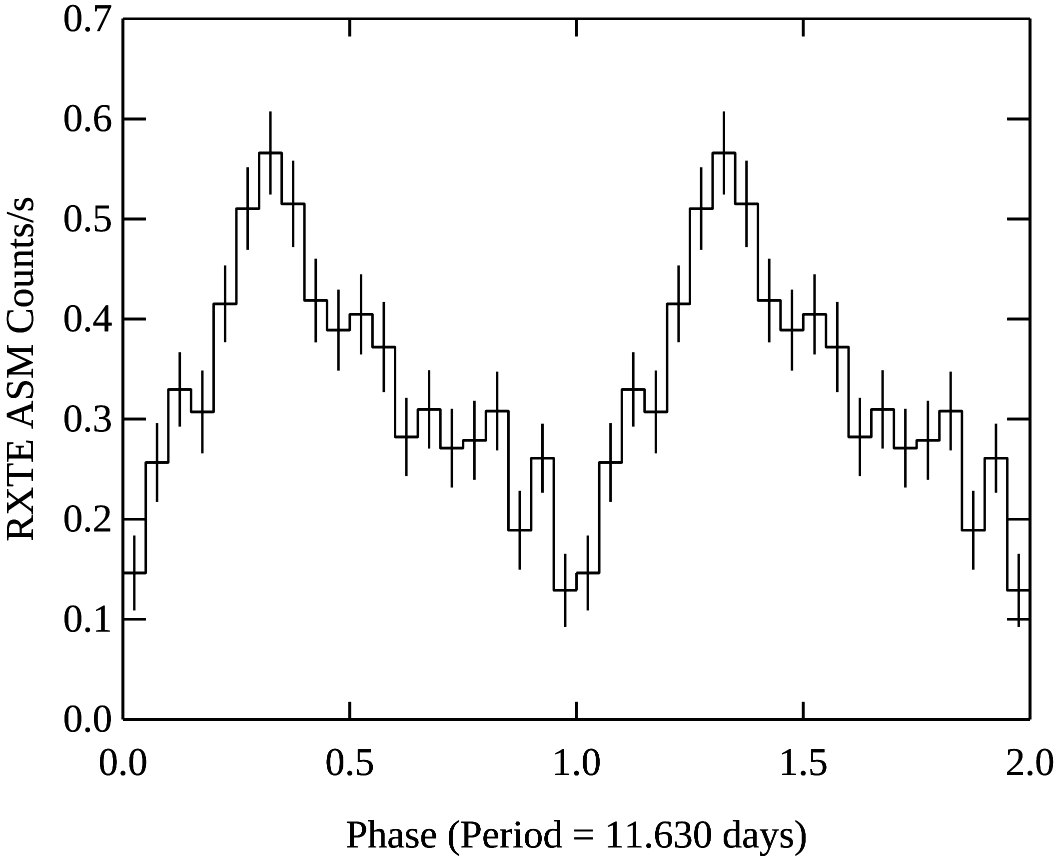

FIG. 8.—ASM light curve folded and binned on the strongest peak in the power spectrum, which is slightly different from the Crampton et al. (1985) period.

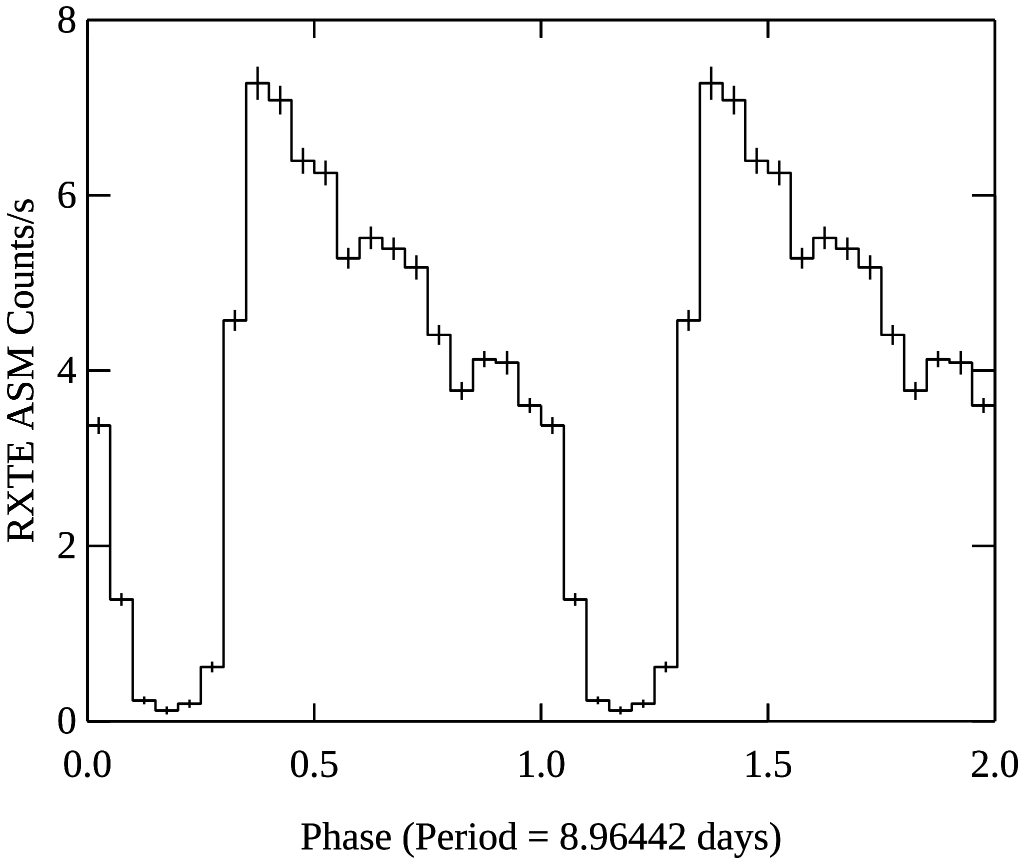

FIG. 9.—ASM light curve of Vela X-1 folded and binned on the orbital period of this system for comparison with 2S 0114 + 650. Phase is arbitrary.

Beta Cephei companion.—β Cephei stars lie along a narrow instability strip that encompasses late O and early B spectral types and subgiant through supergiant luminosity class and have optical photometric pulsation periods of 3–6 hr and "typical" amplitudes of a few hundredths of a magnitude. As some optical observations had suggested spectral types in the β Cephei range (e.g., B0.5 III, Crampton et al. 1985), Finley et al. (1992) and Taylor et al. (1995) considered whether the 2.7 hr period in 2S 0114+650 might arise from such pulsations in the primary star. Difficulties with this model are the lack of persistent optical photometric modulation on this period (Bell, Hilditch, & Pollacco 1993; Taylor et al. 1995) and a clear explanation of how this variability of the primary gives rise to a modulation of the X-ray flux.

Rotating neutron star.—The majority of high-mass X-ray binaries contain neutron stars, and the rotation of a magnetized neutron star naturally leads to X-ray modulation. The peculiarity here would be the exceptionally long period compared to the known pulsation periods that range from 69 ms to 1400 s. If a neutron star in 2S 0114+650 is rotating at an equilibrium period of 2.7 hr then a magnetic field of $\sim(2\text{–}3) \times 10^{13}$ G is implied. Although this field strength would be very high, some radio pulsars do have fields in this range (e.g., Taylor, Manchester, & Lyne 1993). However, if the neutron star is rotating more slowly than its equilibrium period, as may well be the case for most wind-accretion powered X-ray pulsars (e.g., Corbet 1986), then the magnetic field could naturally be lower. Waters & van Kerkwijk (1989) proposed that the spin periods in these systems are actually determined in an earlier evolutionary phase before the companion star becomes a supergiant. The peculiarities noted in the optical spectrum of LS I +65°010 could perhaps be an indication of an unusual evolutionary history for the system. Also in support of the rotating neutron star interpretation we note that the variability of the $\sim$2.7 hr period length appears consistent with the variations seen in other wind-accreting high-mass X-ray binaries (e.g., Nagase 1989).

We also briefly consider two other phenomena that could, in principle, give modulation on a timescale of a few hours:

"EXO 2030+*375–like variations.*"—The 2.7 hr period is somewhat reminiscent of the 3.96 hr periodicity seen on one occasion in the Be/neutron star system EXO 2030+375 by Parmar, White, & Stella (1989). In the case of EXO 2030+375 it is already known that the neutron star rotation period is less than this value at 42 s. We note that a power spectrum of the *RXTE* ASM light curve of EXO 2030+375 does not show any modulation on the 3.96 hr timescale reported by Parmar et al. (1989) even though the source was active with a mean flux of 0.35 counts s^{-1} ($\sim$4.6 mcrab) and the orbital modulation was clearly detected. For 2S 0114+650 possible periodicities of $\sim$895 s (*Einstein*) and $\sim$850 s (*Ginga*) were reported, but these are not present in either our observations or *HEAO 1*, *OSO 8*, or *EXOSAT* data (Finley et al. 1992, and references therein). In contrast the 2.7 hr period is clearly a persistent property of the source, although variable in strength and period length.

Accreting White Dwarf.—As noted above, at 2.7 hr this would be the longest known neutron star rotation period. However, nonsynchronously rotating accreting white dwarfs are known to have, in some cases, relatively long rotation periods (e.g., Patterson 1994). The primary difficulty with interpreting the 2.7 hr period as a white dwarf rotation period is the implied X-ray luminosity that is too large to be explained by accretion onto a white dwarf. In addition, changes in the length of the 2.7 hr period are also difficult to explain with a white dwarf model due to the larger moment of inertia of a white dwarf compared to a neutron star.

X-ray spectral data also appear to indicate some support for interpreting the 2.7 hr period as a neutron star rotation period. Yamauchi et al. (1990) obtained observations of 2S 0114+650 with *Ginga* and detected an iron line at $\sim$6.4 keV. The equivalent width was 0.34 keV during "low" states and 0.07 keV during "flares" (i.e., 2.7 hr pulse maxima). Yamauchi et al. (1990) report that during the flares the equivalent width of the line decreased while the number of photons in the line remained constant. As 6.4 keV is the energy for a fluorescent iron line, one interpretation would be that the intrinsic source luminosity remains constant and the variability is caused by geometric factors—for example the pulsar beam moves out of our line of sight while continuing to cause fluorescence in the cool wind of the primary star. This iron line behavior is apparently also present in observations made with *ASCA* (Ebisawa 1997).

Although the presence of persistent 2.7 hr pulsations, together with optical spectra, makes the system a "double lined binary" it does not appear feasible to use the pulsations to determine the binary parameters. The projected size of the orbit of the neutron star, $a_X \sin i$, is estimated to be $\sim$130 lt-s, assuming the optical velocity amplitude of 17 km s^{-1} of Crampton et al. (1985) and a mass ratio of 15. This size corresponds to only $\sim$1% of the length of the pulse period.

4. CONCLUSIONS

The X-ray light curve of 2S 0114+650 shows the presence of modulation on both the proposed orbital and 2.7 hr pulse periods of this system, although with a small difference in the value of the orbital period compared to that previously proposed. Additional optical radial velocity measurements will be important to enable an exact comparison between the phasing of the X-ray light curve and time of expected eclipse. The continued presence of the 2.7 hr modulation suggests that it does indeed represent the rotation period of a neutron star.

This paper made use of quick look data provided by the *RXTE* ASM team at MIT and GSFC. We thank many colleagues in the *RXTE* team for useful discussions.

REFERENCES

Bell, S. A., Hilditch, R. W., & Pollacco, D. L. 1993, MNRAS, 265, 1042
Bildsten, L., et al. 1997, ApJS, 133, 367
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Brookshaw, L., & Tavani, M. 1993, ApJ, 410, 719
Corbet, R. H. D. 1986, MNRAS, 220, 1047
Crampton, D., Hutchings, J., & Cowley, A. 1985, ApJ, 299, 839
Ebisawa, K. 1997, BAAS, 191, 110.07
Feldmeier, A., Anzer, U., Boerner, G., & Nagase, F. 1996, A&A, 311, 793
Finley, J. P., Belloni, T., & Cassinelli, J. P. 1992, A&A, 262, L25
Finley, J., Taylor, M., & Belloni, T. 1994, ApJ, 429, 356

Finley, J., et al. 1999, in preparation

Guarnieri, A., Bartolini, C., Teodorani, M., Silingardi, R., & Piccioni, A. 1994, in AIP Conf. Proc. 308, The Evolution of X-Ray Binaries, ed. S. S. Holt & C. S. Day (New York: AIP), 351

Kaper, L., Hammerschlag-Hensberge, G., & Zuiderwijk, E. J. 1994, A&A, 289, 846

Koenigsberger, G., Swank, J. H., Szymkowiak, A. E., & White, N. E. 1983, ApJ, 268, 782

Levine, A. M., Bradt, N., Cui, W., Jernigan, J. G., Morgan, E. H., Remillard, R., Shirey, R. E., & Smith, D. A. 1996, ApJ, 469, L33

Lomb, N. R. 1976, Ap&SS, 39, 447

Nagase, F. 1989, PASJ, 41, 1

Parmar, A. N., White, N. E., & Stella, L. 1989, ApJ, 338, 359

Patterson, J. 1994, PASP, 106, 209

Reig, P., Chakrabarty, D., Coe, M. J., Fabregat, J., Negueruela, I., Prince, T. A., Roche, P., & Steele, I. A. 1996, A&A, 311, 879

Remillard, R. A., & Levine, A. M. 1997, in Proc. All-Sky X-Ray Observations in the Next Decade (Saitama: RIKEN), 29

Rubin, B. C., Finger, M. H., Scott, D. M., & Wilson, R. B. 1997, ApJ, 488, 413

Scargle, J. H. 1982, ApJ, 263, 835

Smale, A. P., & Charles, P. A. 1989, MNRAS, 238, 595

Taylor, M., Finley, J. P., Kurt, C., & Koenigsberger, G. 1995, AJ, 109, 396

Taylor, J., Manchester, R. N., & Lyne, A. G. 1993, ApJS, 88, 529

van Kerkwijk, M., & Waters, R. 1989, in Proc. 23d ESLAB Symposium ESA SP-296 (Noordwijk: ESA), 473

Waters, L. B. F. M., & van Kerkwijk, M. H. 1989, A&A, 223, 196

Yamauchi, S., Asaoka, I., Kawada, M., Koyama, K., & Tawara, Y. 1990, PASJ, 42, L53