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DETECTION OF A ~ 78 DAY PERIOD IN THE *RXTE*, *VELA 5B*, AND *ARIEL 5* ALL-SKY MONITOR DATA OF CYGNUS X-2

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ABSTRACT

We report the detection of a 77.7 ± 1.0 day modulation in the X-ray light curve of Cygnus X-2, obtained by the all-sky monitor on board the *Rossi X-ray Timing Explorer*. The modulation has an amplitude of $\sim 40\%$. A secondary minimum is present with an amplitude of $\sim 20\%$. The hardness of the X-ray spectrum as a function of this modulation is anticorrelated with the source intensity. Reanalysis of archival data from *Vela 5B* and *Ariel 5* shows independent confirmation of this periodicity, with significant periods of 77.4 ± 0.2 and 77.7 ± 0.2 days, respectively. Using these three data sets we determine a single combined long-term ephemeris of JD $244,2209.0 \pm 4.7 + N \times (77.79 \pm 0.08)$, where phase zero is defined as the primary minimum. The occurrence of the different intensity states found in pointed observations with the *Einstein*, *EXOSAT*, and *Ginga* satellites is also consistent with this ephemeris. The 78-day periodicity is therefore a reliable clock in the system, and we tentatively associate this period with the precession of a tilted accretion disk, similar to those seen in some massive X-ray binaries and Her X-1.

Subject headings: accretion, accretion disks — stars: individual (Cygnus X-2) — stars: neutron — X-rays: stars

1. INTRODUCTION

The low-mass X-ray binary (LMXB) Cyg X-2 shows long-term variations in its X-ray intensity (Holt et al. 1976, 1979; Bonnet-Bidaud & van der Klis 1982; Branduardi-Raymont, Chiappetti, & Ercan 1984; Hirano et al. 1984; Vrtilik et al. 1986, 1988; Hasinger et al. 1990; Smale & Lochner 1992; Priedhorsky, Brandt, & Lund 1995; Kuulkers, van der Klis, & Vaughan 1996; Wijnands et al. 1997). The orbital period is 9.844 days (Cowley, Crampton, & Hutchings 1979; Crampton & Cowley 1980), which is too short to account for the reported long-term variability. Extensive searches for long-term periods in Cyg X-2 (with candidate periods of, e.g., 11.2 days [*Ariel 5*; Holt et al. 1976, 1979] and ~ 77 , ~ 51 , and ~ 45 days [*Vela 5B*; Smale & Lochner 1992]) have been hindered by the fact that Cyg X-2 is one of the class of LMXBs known as “Z” sources, by virtue of the Z-shaped track that they describe in the X-ray color-color diagram (Hasinger & van der Klis 1989). Due to the motion through the “Z,” the count rate can change within a couple of hours with a factor of 2 or more, especially when the source enters the upper limb (“horizontal branch”) or the lower limb (“flaring branch”). This stochastic, short-term variation influences the average count rate, making it harder to detect a long-term period.

We report the detection of a ~ 78 day modulation in the X-ray light curve of Cyg X-2 as obtained by the all-sky monitor on board the *Rossi X-ray Timing Explorer*, and the results of a reanalysis of data from previous experiments. A preliminary announcement appeared in Smale, Kuulkers, & Wijnands (1996).

2. OBSERVATIONS AND ANALYSIS

The all-sky monitor (ASM; Levine et al. 1996) on board the *Rossi X-ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993) scans the sky in series of ~ 90 s dwells in three energy bands, 1.5–3, 3–5, and 5–12 keV. Due to satellite motion and a 40% duty cycle (Levine et al. 1996), any given source is scanned 5–10 times per day. For a discussion of the ASM we refer to Levine et al. (1996). For our analysis we used the quick-look results provided by the *RXTE* ASM team, covering the period from 1996 February 23 to 1996 August 15.

The archival HEASARC *Vela 5B* XC and *Ariel 5* ASM data spanned the intervals from 1969 May 27 to 1979 June 18, and from 1974 October 18 to 1980 March 2, respectively. For the *Vela 5B* data, which were free of source confusion (Smale & Lochner 1992), we used only the data in the first energy channel (3–12 keV), because of its higher signal-to-noise ratio (SNR) compared to the second channel (6–12 keV). In order to improve the SNR for the first channel we used 56-hour averages of the data. The *Ariel 5* data (3–6 keV), with a time resolution of ~ 100 minutes, had a better SNR and no averaging was required. The *Ariel 5* data are contaminated with a yearly variation attributable to solar X-ray scattering or fluorescing off the Earth’s atmosphere (Priedhorsky, Terrell, & Holt 1983). This effect contributed counts for sources occulted by the Earth, which gave rise to a yearly varying count rate. We used the *Ariel 5* data that were not corrected for this effect, which resulted in a strong peak in the Lomb-Scargle periodogram of order 1 year (§ 3.2).

We used the Lomb-Scargle periodogram (Lomb 1976;

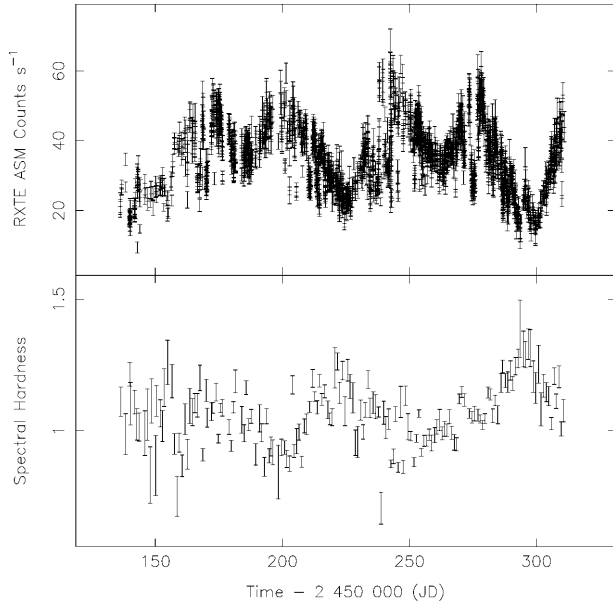


FIG. 1.—*RXTE* ASM light curve (*upper panel*) of Cyg X-2 in the energy range 1.5–12 keV and the daily averaged (5–12 keV)/(1.5–3 keV) spectral hardness curve (*lower panel*).

Scargle 1982) in order to search for periodicities. Other methods (e.g., a standard period-folding technique) were used to confirm our analysis. In order to determine the ephemeris of a periodic modulation we fitted a sinusoidal function to the data. The errors were determined using $\Delta\chi^2 = 2.7$, representing 90% confidence.

3. RESULTS

3.1. *RXTE* All-Sky Monitor Data

The 1.5–12 keV ASM light curve of Cyg X-2 (Fig. 1, *upper panel*) clearly shows a pattern that occurs twice. The count rate varies between 15 ASM counts s^{-1} and 60 ASM counts s^{-1} . In addition to this pattern there is also a degree of stochastic scattering that is probably due to the motion through the Z track and remaining systematic errors. The spectral hardness, defined as the ratio of the count rates in the 5–12 keV and 1.5–3 keV bands, is roughly anticorrelated with the variation in the 1.5–12 keV count rate (Fig. 1, *lower panel*). The daily average spectral hardness versus the daily average total count rate (Fig. 2) shows a clear decrease of the spectral hardness with increasing count rate, but also considerable intrinsic scattering, which again is probably due to motion of Cyg X-2 through the Z track and remaining systematic errors in the data. Fitting a straight line to the data, we find the following relation ($\chi^2_{\text{red}} = 0.99$ for 165 dof) between the spectral hardness (SH) and the total count rate (CR) of $SH = 1.27 \pm 0.05 - (0.0060 \pm 0.0015)CR$.

The Lomb-Scargle periodogram of the light curve (Fig. 3, *upper panel*) shows several peaks above 10 days with more than 99% confidence. The most significant peak occurs at 77.7 days, the second strongest peak occurs at 36.8 days. We do not find a significant peak near the orbital period. Fitting a sine wave to the data at the ~ 78 day period results in an ephemeris of

$$JD2450222.0 \pm 0.7 + N(77.7 \pm 1.0),$$

with phase zero defined as the primary minimum. The full amplitude of the 77.7 day modulation is 40%. A shallower

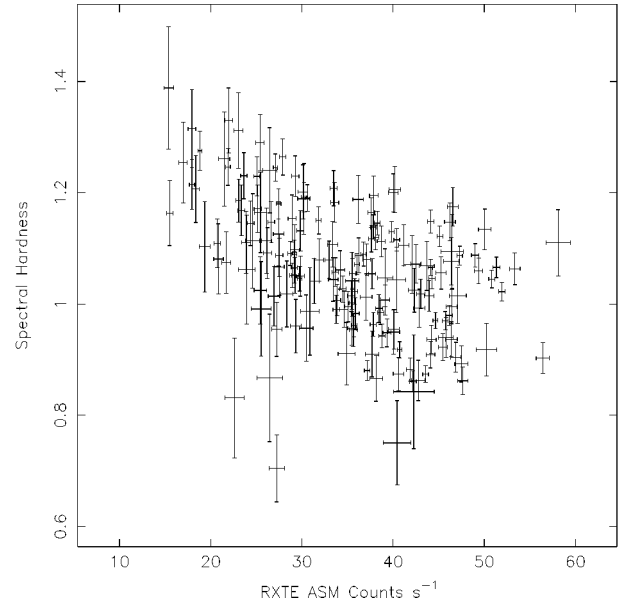


FIG. 2.—Daily average spectral hardness (Fig. 1) vs. the daily averaged count rate between 1.5 and 12 keV.

(20%) secondary minimum is observed at phase 0.5, giving rise to the peak at ~ 37 days; these features can be seen clearly in the folded light curve in Figure 4 (*upper panel*). One should keep in mind that the *RXTE* ASM folded light curve is double peaked, and therefore fitting a single sine wave is only approximately correct.

3.2. The *Ariel 5* and *Vela 5B* Data

We reanalyzed the *Vela 5B* XC data (previously discussed by Smale & Lochner 1992) and the *Ariel 5* ASM data (previously discussed by Holt et al. 1976, 1979; Vrtilik et al. 1988). The

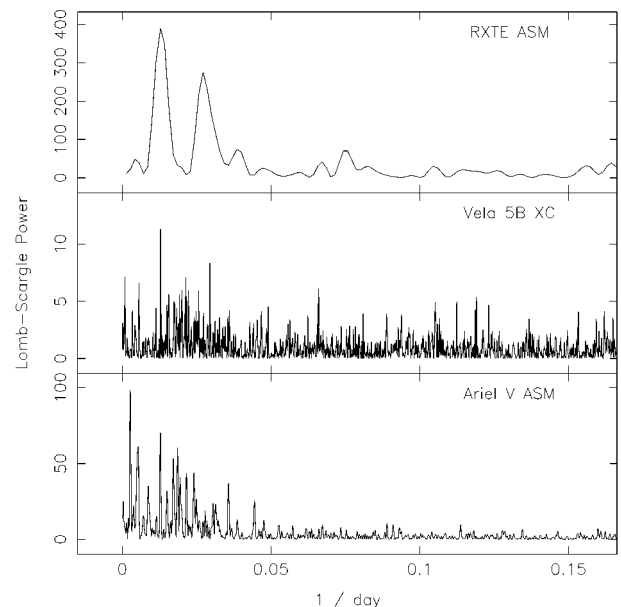


FIG. 3.—Lomb-Scargle periodogram of the *RXTE* ASM data (*upper panel*), with the highest peak at ~ 78 days, and the second highest at ~ 37 days; the *Vela 5B* XC data (*middle panel*), with the peak at ~ 77.4 days; and the *Ariel 5* ASM data (*lower panel*), with the highest peak at ~ 366 days (§ 3.2) and the second highest at ~ 77.7 days.

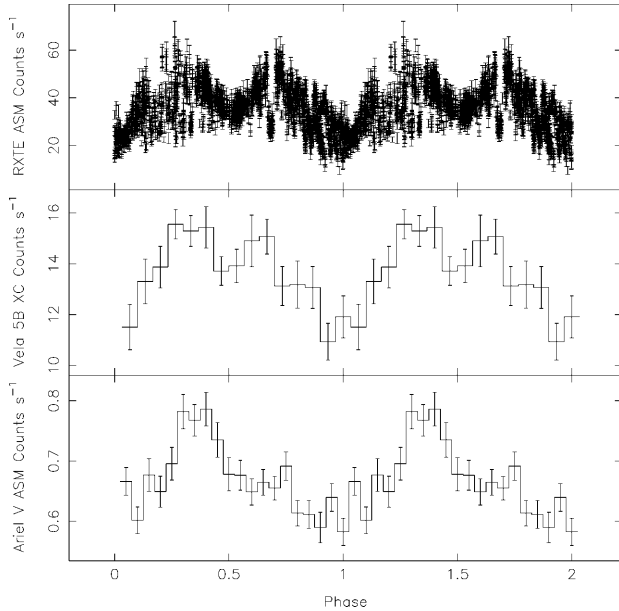


Fig. 4.—Folded light curves of Cyg X-2 of the *RXTE* ASM data (*upper panel*, with no rebinning), the *Vela 5B* XC data (*middle panel*, binned into 15 phase bins), and the *Ariel 5* ASM data (*lower panel*, binned into 20 phase bins). Two cycles are shown for clarity.

Lomb-Scargle periodogram of the *Vela 5B* data shows a peak at 77.4 days (Fig. 3, *middle panel*; see also Smale & Lochner 1992). The strongest peak in the *Ariel 5* data periodogram (Fig. 3, *lower panel*) is at 366 days, due to the yearly variation in the count rate (§ 2). The second strongest peak is at 77.7 days. Figure 4 shows the folded light curves of the *Vela 5B* (*middle panel*; see also Smale & Lochner 1992) and *Ariel 5* (*lower panel*) data. Although it is not as clear as in the folded *RXTE* ASM light curve, the folded light curve of the *Vela 5B* data is also double peaked, and the *Ariel 5* light curve shows a shoulder. Within the error bars the *Vela 5B* folded light curve is consistent with the *RXTE* folded light curve, showing two maxima with similar strength. However, the *Ariel 5* folded light curve differs significantly. The second maxima is significantly lower in strength than the primary maxima. It is not clear what the reason is for this discrepancy between the *Ariel 5* folded light curve and the *RXTE* and *Vela 5B* light curves. We determined the ephemerides of the *Vela 5B* and *Ariel 5* data. We aligned the primary minima in the *Vela 5B* and *Ariel 5* folded light curves to phase zero, resulting in the following ephemeris for the *Vela 5B* data of

$$\text{JD}2442211.4 \pm 2.0 + N(77.42 \pm 0.17),$$

and for the *Ariel 5* data of

$$\text{JD}2443373.0 \pm 1.6 + N(77.69 \pm 0.22).$$

We have derived a single overall ephemeris of

$$\text{JD}2442209.0 \pm 4.7 + N(77.79 \pm 0.08)$$

by fitting a straight line through the epochs and the cycle numbers (N) of the *Vela 5B* ($N \equiv 0$), *Ariel 5* ($N = 15$), and *RXTE* ($N = 103$) ephemerides. All ephemerides have phase zero at their primary minimum. This derivations uses the latest *RXTE* ASM data and takes into account the double-peaked nature of the folded light curves, and therefore the overall ephemeris differs slightly from the ephemeris reported by

Smale et al. (1996). It is possible that, in order to obtain the overall ephemeris, we have missed one cycle between the start of the *Vela 5B* ephemeris and the start of the *RXTE* ephemeris. Using 104 cycles in our derivation of the overall ephemeris, results in an ephemeris that is only consistent with the individual ephemerides within 3σ .

3.3. The *Einstein*, *EXOSAT*, and *Ginga* Data

The pointed observations of Cyg X-2 made by the *Einstein*, *EXOSAT*, and *Ginga* satellites revealed that the source displays roughly three intensity levels: a low, a medium, and a high level (Kuulkers et al. 1996). Using *Ginga* data, Wijnands et al. (1997) found that Cyg X-2 changes from the medium level to the high level in a continuous way. Following the method outlined by Kuulkers et al. (1996) we assign the numbers 1 to the low-level, 2 to the medium-level, and 3 to the high-level episodes. Fitting a sinusoidal function through the occurrence of the different levels, we obtain the following ephemeris

$$\text{JD}2445918.9 \pm 5.0 + N(77.66 \pm 0.36).$$

Although the 78 day period is not significantly detected using the Lomb-Scargle method (Kuulkers et al. 1996), the occurrence of the different intensity levels in the *Einstein*, *EXOSAT*, and *Ginga* data sets is consistent with the long-term periodicity we found in the *RXTE*, *Vela 5B* and *Ariel 5* data. Approximately 70% of the dates of the different intensity episodes fall within 15% of the correct phase using the overall ephemeris. The fact that the spectral hardness in the *EXOSAT* and *Ginga* data is anticorrelated with the overall intensity (Hasinger et al. 1990; Kuulkers et al. 1996; Wijnands et al. 1997) is also consistent with the *RXTE* ASM data (§ 3.1, Fig. 2).

4. DISCUSSION

We detected a 77.7 ± 1.0 days modulation in the *RXTE* ASM light curve. This confirms the period previously found in the *Vela 5B* XC data (Smale & Lochner 1992). Our reanalysis of the *Ariel 5* ASM data also shows a significant ~ 78 day period. Although only two cycles are so far observed with *RXTE*, the fact that the ~ 78 day period is independently seen in the *Vela 5B* and *Ariel 5* data, makes this long-term periodicity a reliable clock in the system. The folded *RXTE* ASM light curve is double peaked, with the minima at $\phi \sim 0$ and $\phi \sim 0.5$. There are indications that the *Vela 5B* and *Ariel 5* folded light curves are also double peaked. Combining the ephemeris found in the *RXTE* data, the *Vela 5B* data, and the *Ariel 5* data we have derived one single overall ephemeris (§ 3.2). The occurrence of the intensity states in the *Einstein*, *EXOSAT*, and *Ginga* data is consistent with this ephemeris. The *RXTE* ASM continues to produce data, and in time we will be able to improve and refine this ephemeris still further. We note that a better model for fitting the data (e.g., a template of the light curve) will improve the ephemeris.

Several models have been proposed (see Priedhorsky & Holt 1987; Schwarzenberg-Czerny 1992) to explain the long-term variations, not related to orbital variations, in high-mass X-ray binaries (e.g., Cyg X-1 and LMC X-3), and LMXBs (e.g., Her X-1), including the precession of a tilted accretion disk, neutron star precession, mass transfer feedback, and triple systems. In the model of a precessing accretion disk the observed variations would arise from the changing aspect of the disk, and the obscuration of the inner disk region and of

the central source. There are no detailed physical models describing how such a tilted disk could be created, though possible mechanisms include slaving of the disk to the companion star, tidal, magnetic, or radiation pressure torques in the system (Priedhorsky & Holt 1987). Schandl & Meyer (1994) proposed that coronal winds are producing the tilted shape of the accretion disk in Her X-1.

The most likely interpretation (Priedhorsky & Holt 1987) for the long-term variations in other LMXBs than Cyg X-2 (e.g., 4U 1820–30, the Rapid Burster, 4U 1915–05, Aql X-1, excluding Her X-1) is a variation in the mass accretion rate (\dot{M}) onto the compact object. Several arguments (Priedhorsky & Holt 1987) are in favor of this interpretation. The burst activity of 4U 1820–30 and the Rapid Burster is correlated with the long-term variation, the optical intensity of Aql X-1 is strongly correlated with the X-ray intensity and the ratio of the long period (P_{long}) to the orbital period (P_{orb}) is of the order of 10^3 to 10^4 , whereas the high-mass systems, $P_{\text{long}}/P_{\text{orb}}$ are in the range of 10 to 50. The high ratio for the LMXBs makes it unlikely that those variations are due too a precessing accretion disk. However, these arguments that changes in \dot{M} cause the long-term variations do not apply to the 78-day variation in Cyg X-2. The burst activity of Cyg X-2 is not correlated with the overall intensity (Kuulkers, van der Klis,

& van Paradijs 1995; Wijnands et al. 1997), and $P_{\text{long}}/P_{\text{orb}}$ is ~ 8 , indicating that Cyg X-2 is more similar to the high-mass systems than the low-mass systems. Kuulkers et al. (1996) also concluded that the different overall intensity levels found in the *EXOSAT* data cannot be caused by changes in \dot{M} . In both the high and the medium level (but not the low level) Z-shaped tracks are observed, indicating that the difference in overall intensity is not caused by variations in \dot{M} . Instead, the motion through the Z track is thought to be caused by changes in \dot{M} (see Hasinger & van der Klis 1989). Therefore, we tentatively associate the 78 day period found in the light curves of Cyg X-2 with the precession of the accretion disk in the system.

This paper utilizes quick-look results made publicly available by the ASM/*RXTE* Team, including members at MIT and NASA/GSFC, and also data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/GSFC. This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277. E. K. acknowledges receipt of an ESA fellowship. We thank Michiel van der Klis for helpful discussions and comments on a previous version of this letter.

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