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X-RAY TIMING OF THE 34 MILLISECOND BINARY PULSAR SAX J0635+0533

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ABSTRACT

Modulations detected in the observed spin period of the 34 ms X-ray pulsar SAX J0635+0533 show that the pulsar is in a binary system with a period of 11.2 ± 0.5 days, a projected orbital semimajor axis $a \sin i = 83 \pm 11$ lt-s, a mass function in the range of 3.4–7.8 $M_\odot$, and an orbital eccentricity of 0.29 ± 0.09. A combination of observations spanning 2 yr places a lower bound on the intrinsic period derivative of the pulsar of 3.8×10^{-13}. The period derivative implies a high torque on the neutron star that would require a very high mass accretion rate, in excess of $6 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$, if produced via accretion. The torque and X-ray luminosity are both within the range typical of young, rotation-powered pulsars.

Subject headings: gamma rays: observations — pulsars: general — stars: individual (2EG J0635+0521, SAX J0635+0533) — stars: neutron

1. INTRODUCTION

SAX J0635+0533 was discovered (Kaaret et al. 1999) as a hard X-ray source in the field of the gamma-ray source 2EG J0635+0521 (Thompson et al. 1995), and follow-up optical observations identified a Be star optical counterpart (Kaaret et al. 1999). Timing analysis of the discovery observations, taking into account that the pulsation period of the X-ray source may vary because of orbital motion, led to the discovery of 33.8 ms pulsations (Cusumano et al. 2000). However, the orbital parameters could not be reliably constrained because of the limited data available.

2. OBSERVATIONS AND ANALYSIS

We obtained 13 observations of SAX J0635+0533 with the *Rossi X-Ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993) during 1999 August and September. The observations were spread over 14 days with durations of 2570–3260 s and 2–5 Proportional Counter Units (PCUs; Bradt et al. 1993) operating during each observation. We barycentered the data using the position of the optical counterpart (Kaaret et al. 1999) to SAX J0635+0533 and then performed a period search employing the Z^2 or Rayleigh statistic (Buccheri et al. 1983) over a frequency interval from 29.47 to 29.56 Hz using events with energies in the range of 4.4–23.6 keV in order to optimize the signal-to-noise ratio. We found excess power with Z^2 in the range of 17–28 in seven observations. Taking into account all trial frequencies for all 13 observations, the set of powers found corresponds to a chance probability of 5×10^{-7}. The frequencies were in the range of 29.4824–29.5153 Hz. Errors on the frequency for each individual observation were obtained by examining the Z^2 versus frequency peak and finding where the Z^2 statistic decreased by 2.30 relative to the peak value.

The frequency data are shown in the upper panel of Figure 1. We fitted a Keplerian orbital profile with no intrinsic spin frequency derivative to the seven data points and obtained a reasonable fit with $\chi^2 = 3.1$ for 1 degree of freedom (dof). The derived orbital period is $11.2^{+0.5}_{-0.4}$ days, and the projected orbital semimajor axis is $a \sin i = 83^{+11}_{-8}$ lt-s, leading to a mass function of $5.0^{+2.8}_{-1.6}\ M_\odot$, consistent with that expected for a companion star mass near 10 $M_\odot$ as indicated by the companion's spectral type (Kaaret et al. 1999). The orbital eccentricity is $0.29^{+0.09}_{-0.06}$, the epoch of periastron passage is MJD $51{,}419.8^{+0.5}_{-0.9}$, and the longitude of periastron is $-4° \pm -24°$. The errors quoted correspond to $\Delta\chi^2 = 10.64$, which is equivalent to 90% confidence for six parameters. These orbital parameters should be interpreted with caution since our observations sample only slightly more than one orbital cycle. However, the coverage is adequate for estimating the maximum frequency during the epoch of the *RXTE* observations. The maximum frequency along the orbit obtained in any of the fits is 29.5168 Hz.

The lower panel of Figure 1 shows the pulsed count rate in the 4.4–23.6 keV band in observations where pulsations were detected. The pulsed rate was calculated by finding the amplitude of sinusoidal variation at the pulse frequency. This may somewhat underestimate the pulsed rate if the signal is not purely sinusoidal. For observations where pulsations were not detected, we used the ephemeris described above and searched in a frequency interval of ±0.0008 Hz around the predicted frequency. Even with the reduced number of trails, this secondary search led to no new significant detections of pulsations. The upper bounds in the lower panel of Figure 1 are 95% confidence upper bounds on the pulsed rate in the limited search range for observations in which pulsations were not detected. The pulsed flux measurements and upper limits are consistent with a constant rate near 0.10–0.11 counts s^{-1} PCU^{-1} in the 4.4–23.6 keV band.

The frequencies detected in the *RXTE* observations are all well below the frequency of 29.5364 Hz detected with *BeppoSAX*. If we interpret the change as being due to spin-down of the neutron star and compare the maximum frequency during the *RXTE* observations with that found with *BeppoSAX*, i.e., placing a lower bound on the spin-down, we find an intrinsic frequency derivative $\dot{\nu} = -3.3 \times 10^{-10}$ Hz s^{-1} or, equivalently, a period derivative $\dot{P} = 3.8 \times 10^{-13}$. The intrinsic frequency derivative is much smaller than the frequency derivative induced by orbital motion. The long temporal baseline from combining the *BeppoSAX* and *RXTE* data and the coverage of the *RXTE* data near the frequency maximum of the orbit-induced frequency variation are both crucial in obtaining a reliable lower bound on the frequency derivative.

To constrain the period derivative further, we separated the *BeppoSAX* data into intervals of 3–10 ks and searched for periodicity in each. We detected pulsations in three intervals and used these data, combined with the *RXTE* data, to perform a joint fit with the full data set for the Keplerian orbital parameters and a constant intrinsic frequency derivative. The best fit had $\chi^2 = 3.7$ for 3 dof. Fits with 59–62 orbital cycles between the *BeppoSAX* and *RXTE* observations were allowed with $\Delta\chi^2 < 12.02$, which is equivalent to 90% confidence for seven parameters. The orbital parameters are compatible with those quoted above. The best-fit $\dot{\nu} = -(3.6 \pm 0.3) \times 10^{-10}$ Hz s^{-1}. However, we note that the short span (~1 day) of the *BeppoSAX* data precludes full reconstruction of the orbit at that epoch and also that the $\dot{\nu}$ may have varied over the 2 yr interval between the *BeppoSAX* and *RXTE* observations. Thus, we suggest caution when considering this result and base our interpretation on the lower bound for $\dot{\nu}$ obtained above.

3. DISCUSSION

The lower bound on $\dot{\nu}$, and therefore the torque on the neutron star, is 30 times the largest values found from accreting neutron stars in X-ray binaries (Bildsten et al. 1997). Given the corotation radius of 180 km for the spin period of 34 ms, a mass accretion rate in excess of $6 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ would be required to produce the observed torque (Bildsten et al. 1997). This lower bound on the required average accretion rate far exceeds the expected mass capture rate of the neutron star, $\sim 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ (Illarionov & Sunyaev 1975), and is slightly larger than the highest total mass-loss rates of Be stars (Waters, Coté, & Lamers 1987; Waters et al. 1988). Thus, it is unlikely that the torque is due to accretion since it would require channeling essentially all of the mass loss from the Be star onto the neutron star. If such a high average mass accretion rate, 40 times the critical Eddington accretion rate, could be obtained, then only a small fraction could contribute to the observed luminosity. The majority of the matter would mostly likely be expelled via a "propeller" (Illarionov & Sunyaev 1975; Ghosh 1995). In this case, the characteristic spin-down time is $\nu/\dot{\nu} = 2800$ yr. However, it is unclear whether pulsations from the neutron star surface would be detectable beneath such a large mass inflow.

Conversely, the torque and X-ray luminosity of SAX J0635+0533 are both within the range typical of young, rotation-powered pulsars. The pulsed flux is consistent with being constant across all *RXTE* observations, as might be expected from a rotation-powered pulsar. In this case, the $\dot{P}$ would imply a characteristic age of $P/2\dot{P} \sim 1400$ yr and a spin-down power of $\dot{E} = 5 \times 10^{38}$ ergs s^{-1}. The orbital eccentricity is consistent with eccentricities expected for pulsar/massive star binaries but is much lower than that of any known radio pulsar/massive star binary and is in a range thought to be inaccessible in radio because of the scattering of the radio signal (Lipunov et al. 1994). There is no known synchrotron nebula in the vicinity of SAX J0635+0533 as has been observed around the Crab. However, the pulsar is likely enshrouded in the stellar wind from the companion, and this would disrupt formation of a synchrotron nebula (Illarionov & Sunyaev 1975). The shock at the interaction of the pulsar and Be star winds would also likely produce X-ray emission.

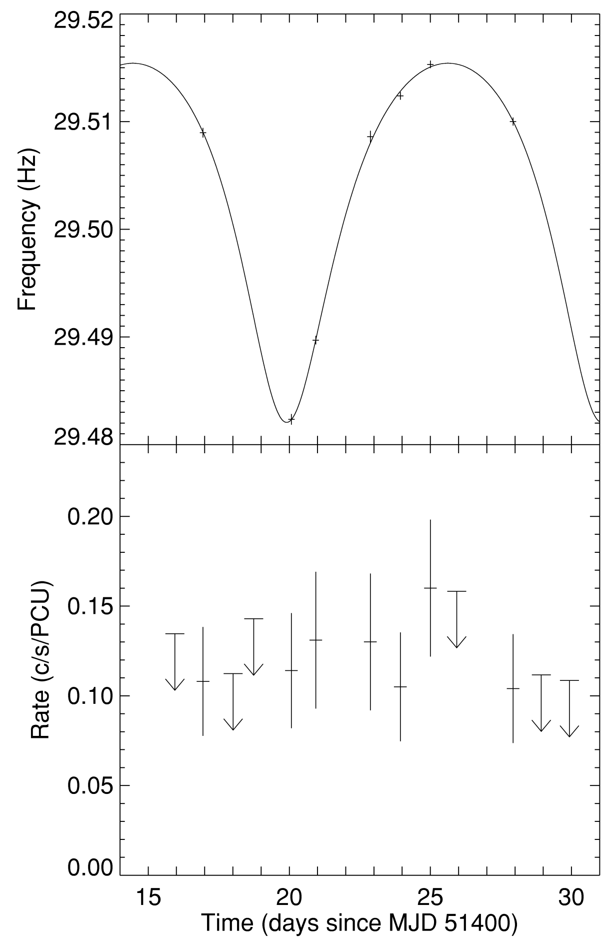

FIG. 1.—Pulsation frequency and flux vs. time for SAX J0635+0533. The upper panel shows *RXTE* frequency measurements (*crosses*) and a fitted orbital profile (*solid curve*). The lower panel shows the pulsed count rate in the 4.4–23.6 keV band.

If this interpretation is confirmed via future observations, SAX J0635+0533 would represent the first detection of a very young, highly energetic, rotation-powered pulsar in a binary system. This system has a characteristic age far younger than any known radio pulsar binary and would offer an exciting opportunity to study the infancy and early evolution of neutron star binaries, with potential implications for our understanding of neutron star natal kicks (e.g., Wex, Kalogera, & Kramer 2000) and the evolution of binary systems that merge to produce gravitational waves (e.g., Bethe & Brown 1998).

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