the BATSE frequency curve in events 5, 7 and 9. According to this picture, one would expect an increase in X-ray luminosity at periastron. Although this is only marginally indicated in the BATSE pulsed flux light curve, it should be pointed out that total flux data from the ASM/RXTE for the epoch MJD 50088 to 51044 does not correlate significantly with the BATSE pulsed flux, indicating that the pulsed flux may not be a good tracer of the accretion luminosity in this system. Furthermore, the periodic $\sim 5\mu$Hz excursions in the residual frequency would lead to very low-significance variations in the X-ray flux measured by the ASM [14].

An alternative interpretation for the observed modulation would be the presence of oscillation modes in the red giant star. However, the stability of the infrared magnitudes of V2116 Oph [5] preclude it from being a long-period variable, since these stars undergo regular $\gtrsim 1$ mag variations in the infrared [16].

We conclude by pointing out that, given the 304-day orbital period and the spectral and luminosity characteristics of V2116 Oph, it can be shown that the companion in this system is probably not filling its Roche lobe and the accretion disk forms from the slow, dense stellar wind of the red giant [14]. A more thorough covering of the X-ray luminosity of the system, with high sensitivity and spanning several cycles, will be very important to test the elliptical model for GX 1+4.

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SAX J0635+0533: Detection of 33.8 ms X-ray pulsations

Giancarlo Cusumano*, Maria C. Maccarone*, Luciano Nicastro*, Bruno Sacco* and Phil Kaaret†

*Istituto di Fisica Cosmica con Applicazioni all'Informatica, CNR, Palermo 90146, Italy
†Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

Abstract. We have detected 33.8 ms pulsations from SAX J0635+0533, a newly discovered Be/X-ray binary suggested as a possible counterpart to the gamma-ray source 2EG J0635+0521. We interpret the periodicity as the spin period of a neutron star in a binary system with a Be companion.

INTRODUCTION

The X-ray source SAX J0635+0533 was discovered by Kaaret et al. (1999) thanks to a *Beppo*SAX observation within the error box of the unidentified Galactic gamma-ray source 2EG J0635+0521 [1], a candidate gamma-ray pulsar as suggested by its hard gamma-ray spectrum [2]. The X-ray source is characterized by quite hard X-ray emission detected up to 40 keV [3]. Its energy spectrum is consistent with a power-law model with a photon index of 1.5, an absorption column density of 2.0×10^{22} cm^{-2}, and a flux of 1.2×10^{-11} erg cm^{-2} s^{-1} in the 2 – 10 keV energy band. A search for pulsed emission over a period range from 0.030 s to 1000 s did not detect any pulsed signal. Due to the large error box of the gamma-ray source, the identification of SAX J0635+0533 with 2EG J0635+0521 is not definitive: such an identification could only be made through pulsed detection in both X-ray and gamma-ray emission or a much improved gamma-ray position. Follow up optical observations [3] suggest as a counterpart of SAX J0635+0533 a Be star with a V-magnitude of 12.8, located within the 1′ X-ray source error box. The estimated distance is in the range 2.5 – 5 kpc.

We revisited the *Beppo*SAX observation of SAX J0635+0533, available from the public archive (obs code #30326001). In our analysis, we use only data coming from the two NFI imaging instruments, namely the Low Energy Concentrator Spectrometer (LECS) operating in the energy range 0.1–10 keV [4] and the Medium Energy Concentrator Spectrometer (MECS) operating in the energy range 1.3–10 keV [5]. In this letter we present new timing results. Our analysis has revealed a 33.8 ms pulsation of the X-ray source.

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TIMING ANALYSIS

The SAX J0635+0533 light-curve (1000 s bin size) for the MECS is shown in Fig. 1 (gaps are present due to non-observing time intervals during South Atlantic Anomaly and Earth occultation). Fig. 1 shows that the emission of SAX J0635+0533 is variable up to a factor of 10.

In order to search for periodicity, the arrival times of all selected events have been converted to the Solar System Baricentric Frame. The Z_1^2 test [6] on the fundamental harmonics with the maximum resolution ($\delta f = 1/72\,714$ Hz) applied to the MECS baricentered arrival times does not reveal significant deviations from a statistically flat distribution up to 50 Hz.

If SAX J0635−0533 is a binary pulsar of rotational spin period P_s and orbital period P_o, the observed P_s is modulated by the orbital motion. Thus, a direct search for a coherent oscillation at P_s can be successful only if the modulation amplitude is small over the time interval ΔT in which the search is performed. This condition is satisfied if $\Delta T \ll P_o$. To reduce the effect of a possible orbital motion in the periodicity search, we divide the whole data span into M subintervals, calculating the Z_1^2 statistics for each trial period in each subinterval, and then adding together the M statistics for each trial period. This procedure results in a less noisy spectrum. We selected time slices corresponding to intervals of continuous observation taken between two Earth occultation periods. The total number of these slices is $M = 13$, each one lasting ~ 2300 s. We adopted a frequency step

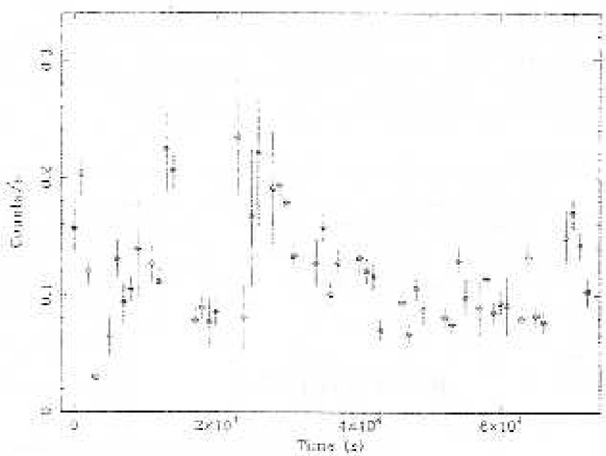

FIGURE 1. The MECS light curve of SAX J0635+0533.

$\delta f = 2 \times 10^{-4}$ Hz, spanning 50 Hz of search range with 250 000 trial frequencies.

Fig. 2 shows the power spectrum obtained with the MECS and LECS data in the $Z_1^2(\nu = 26)$ statistics as a function of frequency, where an evident excess appears at $f_0 = 29.5364 \pm 0.0001$ Hz. The value of $Z_1^2(\nu = 26)$ at this frequency is equal to 99.6. Because the $Z_1^2(\nu = 26)$ follows the χ^2 statistics with 26 degrees of freedom, the single trial chance occurrence probability to have an excess greater than 99 is 2×10^{-10}. Taking into account the number of trial frequencies used, the probability is 5×10^{-5}, corresponding to 4 standard deviations of the Gauss statistics.

From the $Z_1^2(\nu = 26)$ value we can estimate the pulsed fraction. For N_p pulsed counts over N_t total counts, $Z_1^2(\nu = 26) = 2\alpha N_p^2/N_t - \nu$, where α is a shape constant. In our case, $\alpha = 0.25$ (sinusoidal shape), and the pulsed fraction is then about 0.2.

DISCUSSION

The coherence of the detected periodicity is high, $Q = f/\delta f \sim 10^5$. The high coherence induces us to interpret this periodicity as a neutron star spin period. Timing analysis results indicate that the neutron star could orbit around a companion star.

The X-ray emission may be powered either by accretion or by spin-down of the neutron star. We consider these possibilities in turn.

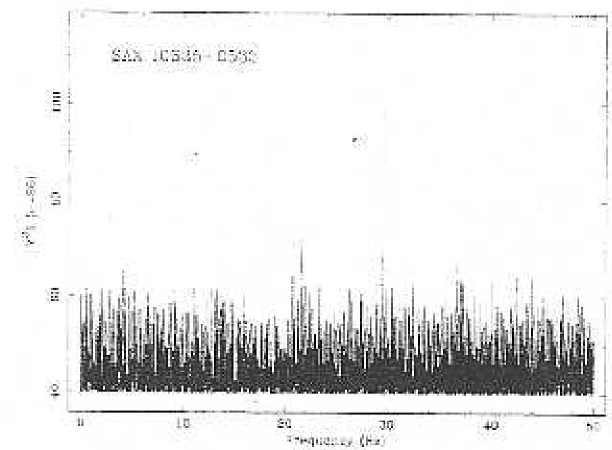

FIGURE 2. The $Z_1^2(\nu = 26)$ statistic as a function of frequency for MECS+LECS events.

The SAX J0635−0533 system may consist of a rotation-powered pulsar orbiting the Be star. In this case, the X-ray emission could be magnetospheric emission similar to the power-law component in the X-ray emission of known X-ray/gamma-ray pulsars. The pulsation frequency we have found and the X-ray luminosity of the source are similar to those of the known X-ray/gamma-ray pulsars, but high X-ray variability of SAX J0635+0533 on time scales of 1000 s is unlike the steady X-ray emission seen from isolated pulsars. However, it could be produced by variable X-ray absorption caused by matter in the binary system or a wind from the Be star.

An alternative, but still rotation-powered, scenario is that SAX J0635+0533 is similar to the Be radio pulsar PSR J1259-63. These two sources have similar spin frequencies and similar X-ray spectra [7]. In this case, the X-ray emission of SAX J0635+0533 should arise from a shock interaction of the energetic particles from the pulsar with the wind from the Be star. However, the upper bound, 8%, on the X-ray pulsed fraction from PSR J1259-63 in the 2-10 keV band (Kaspi et al. 1995) is well below the value estimate for SAX J0635+0533 in the same energy band.

The X-ray emission from SAX J0635+0533 may be powered by accretion. Strong X-ray variability would naturally occur in such a system. Following this interpretation we can infer the magnetic field strength of the neutron star. For accretion to proceed, the centrifugal force on the accreting matter co-rotating in the magnetosphere must be less than the local gravitational force [9]. Assuming a bolometric luminosity of 1.2×10^{35} erg s^{-1} (0.1–40 keV) estimated from spectra results given in Kaaret et al. (1999) for a 5 kpc distance, and a neutron star mass of 1.4 $M_{\odot}$ and radius of 10 km, we can set an upper limit on the magnetic field strength of 2×10^{9} G. This is a factor 10^{3} lower than those measured in typical accreting X-ray pulsars, but similar to the fields inferred for the 2.49 ms low-mass X-ray binary SAX J1808.4−3658 [10] and for millisecond radio pulsars. The X-ray luminosity of SAX J0635+0533 is a factor of 10 below that of most Be/X-ray binaries or the peak luminosity of SAX J1808.4−3658, but may simply indicate a low mass accretion rate.

A definitive association of SAX J0635+0533 with the EGRET source requires detection of a periodicity in gamma-rays at the pulsar spin period. Due to the long integration time required to obtain a detectable gamma-ray signal, only a priori knowledge of the binary parameters would permit a sensitive search for periodicity in gamma-rays. This can be obtained with additional X-ray observations of SAX J0635+0533.

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