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DETECTION OF 33.8 MILLISECOND X-RAY PULSATIONS IN SAX J0635+0533

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ABSTRACT

We revisited the *BeppoSAX* observation of SAX J0635+0533, which was suggested as a possible counterpart to the gamma-ray source 2EG J0635+0521. We have discovered a 33.8 ms pulsation from the source and derived an improved position, consistent with the location of the Be star proposed as a binary companion. We interpret the periodicity as the spin period of a neutron star in a binary system with a Be companion.

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

1. INTRODUCTION

The X-ray source SAX J0635+0533 was discovered by Kaaret et al. (1999) thanks to a *BeppoSAX* observation within the error box of the unidentified galactic gamma-ray source 2EG J0635+0521 (Thompson et al. 1995), a candidate gamma-ray pulsar as suggested by its hard gamma-ray spectrum (Merck et al. 1996). The X-ray source is characterized by quite hard X-ray emission detected up to 40 keV (Kaaret et al. 1999). 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} ergs cm^{-2} s^{-1} in the 2–10 keV energy band. A search for pulsed emission over a period range from 0.030 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 (Kaaret et al. 1999) 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 of 2.5–5 kpc. The total galactic 21 cm column density along the optical counterpart direction is 7×10^{21} cm^{-2} (Stark et al. 1992), in agreement with an estimation derived from the extinction of the optical spectrum. Kaaret et al. (1999) assert that the larger column density for SAX J0635+0533, estimated from the X-ray spectrum, implies the presence of circumstellar gas around the X-ray source. Moreover, taking into account the positional consistency between the X-ray and the gamma-ray sources as well as the hard X-ray spectrum, the strong X-ray absorption, and the optical association with the Be star, they suggest that SAX J0635+0533 is an X-ray binary emitting gamma rays.

We revisited the *BeppoSAX* observation of SAX J0635+0533, available from the public archive (observation code 30326001). In this Letter, we present new imaging and timing results. Our analysis has revealed a 33.8 ms pulsation of the X-ray source. In § 2, we describe the observation and data reduction. In § 3, we report the data analysis procedures and results. We conclude with a discussion of the results in § 4.

2. OBSERVATION AND DATA REDUCTION

The field that includes the serendipitous source SAX J0635+0533 was observed on 1997 October 23–24 by the Narrow Field Instruments (NFIs) on board *BeppoSAX* (Boella et al. 1997a). 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 of 0.1–10 keV (Parmar et al. 1997) and the Medium-Energy Concentrator Spectrometer (MECS) operating in the energy range of 1.3–10 keV (Boella et al. 1997b). At the observation epoch, only two of the three MECS detector units were operating.

LECS and MECS raw data have been reduced in cleaned photon list files by using the SAXDAS version 2.0 software package and adopting standard selection criteria.[1] The source was located ∼3′ off-axis. The total duration of the observation is 72,714 s, and the net exposure is 14,043 and 34,597 s for LECS and MECS, respectively. The different exposures are due to the fact that the LECS was only operated during satellite nighttime.

3. DATA ANALYSIS

In our analysis, we include only events within a 3′.7 radius around the source position; this radius optimizes the signal-to-noise ratio for SAX J0635+0533 and contains ∼80% of the source signal for both LECS and MECS. Due to the fact that the source is strongly absorbed, we further improve the signal-to-noise ratio by using the energy range of 1.8–10 keV for both the instruments. The resulting number of selected events is then 479 for LECS and 3658 for MECS. We estimate that less than 1% of these events is due to the diffuse and instrumental background.

3.1. *Spatial Analysis*

The position of SAX J0635+0533 has been reevaluated by considering MECS data accumulated under specific constraints of the spacecraft; in particular, only data referring to the Z star tracker (the one aligned with the NFIs) in use have been taken

[1] See http://www.sdc.asi.it/software/saxdas, which is maintained by F. Fiore and A. Matteuzzi.

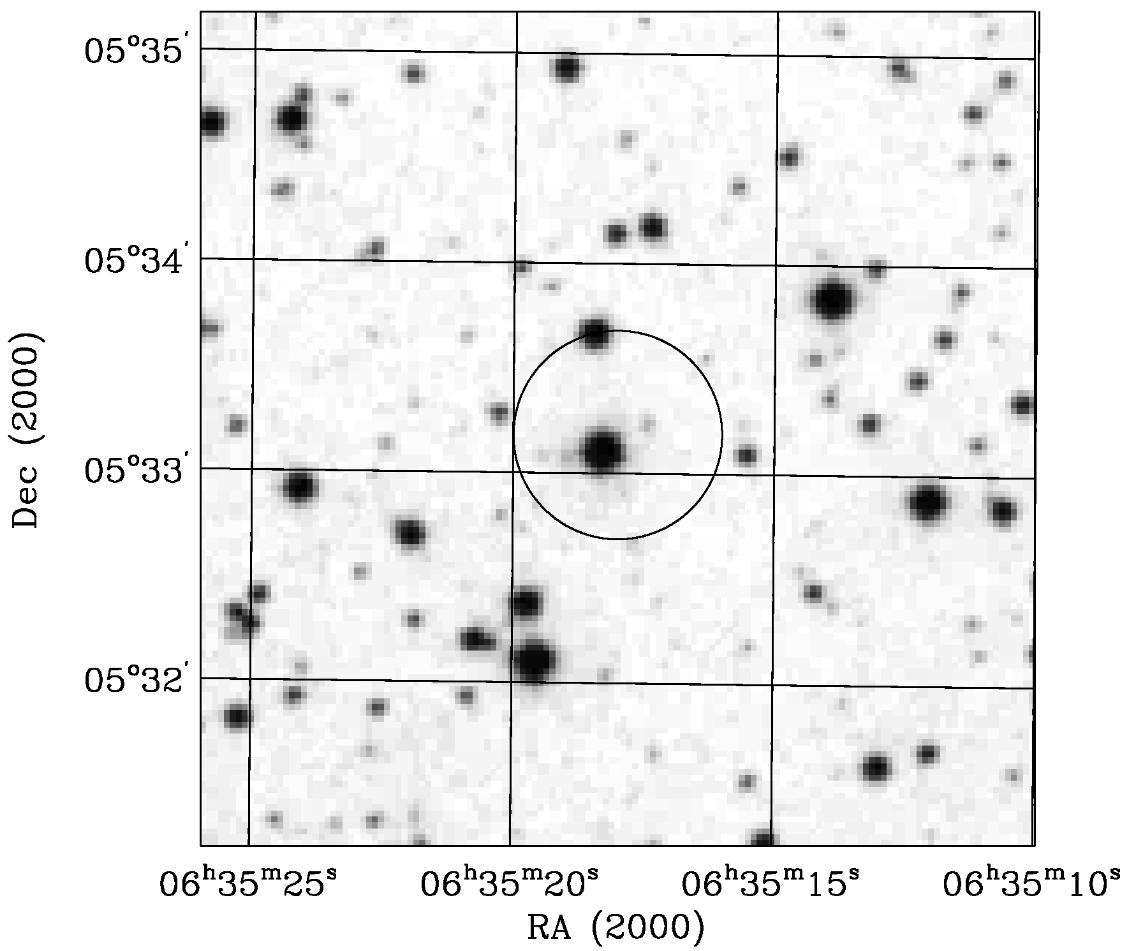

FIG. 1.—Finding chart for SAX J0635+0533 from the Digitized Sky Survey in a field of 4′ × 4′. The X-ray error circle has a radius of 30″ (see text).

into account. This allows us to reduce the attitude reconstruction error to ~30″ (90% confidence level).[2]

After suitable smoothing of the screened data and then by using a Gaussian-centering procedure, the position has been found at R.A. = $06^h35^m18^s$, decl. = 05°33′11″ (J2000) with no significant statistical error. The error box is only determined by the attitude reconstruction error. The Be star (Kaaret et al. 1999) is within 30″ of the SAX J0635+0533 error box and 6″.8 distant from its center.

Figure 1 shows a finding chart for SAX J0635+0533 from the Digitized Sky Survey in a field of 4′ × 4′. Within the reduced X-ray source error circle, only two of the seven stars referred to in Kaaret et al. (1999) are now present. The Be star is the brightest one that is positioned close to the center of the X-ray source error circle.

[2] See http://www.sdc.asi.it/software/cookbook/attitude.html, which is maintained by F. Fiore.

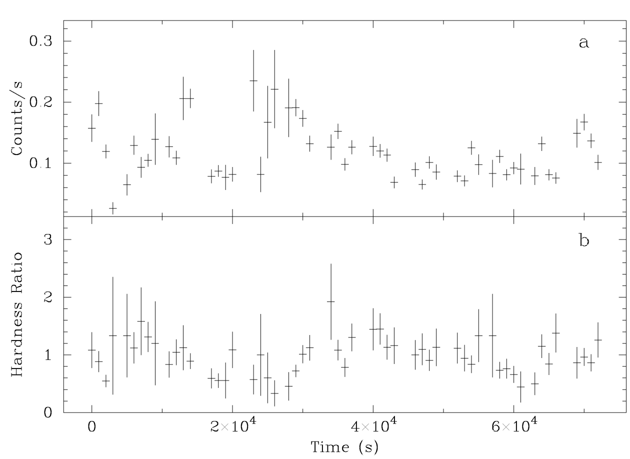

FIG. 2.—(*a*) MECS light curve of SAX J0635+0533. (*b*) Hardness ratio vs. time between 4–10 and 1.8–4 keV energy bands.

3.2. *Temporal Analysis*

The SAX J0635+0533 light curve (1000 s bin size) for the MECS is shown in Figure 2*a* (gaps are present because of the nonobserving time intervals during South Atlantic Anomaly and Earth occultation). Figure 2*a* shows that the emission of SAX J0635+0533 is variable up to a factor of 10. Figure 2*b* shows the hardness ratio between 4–10 and 1.8–4 keV bands. The relative contributions of these two energy bands are not constant, but no strong correlation with respect to the total intensity is evident.

In order to search for periodicity, the arrival times of all selected events have been converted to the solar system barycentric frame, using the BARICONV code.[3] The Z_1^2 test (Buccheri et al. 1983) on the fundamental harmonics with the maximum resolution (δf = 1/72714 Hz) applied to the MECS bary-

[3] See http://www.sdc.asi.it/software/saxdas/baryconv.html, which is maintained by U. Lammers.

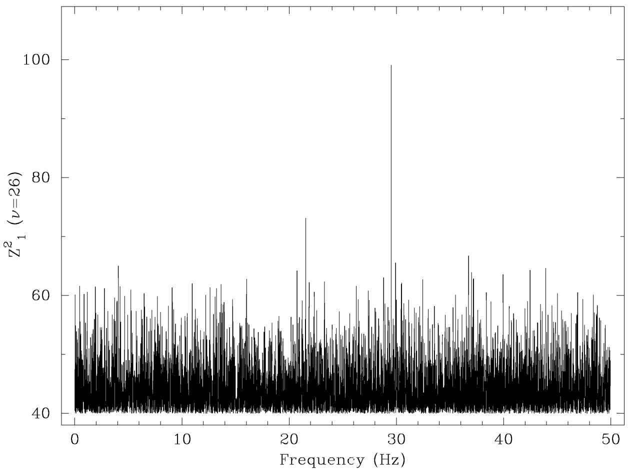

FIG. 3.—The $Z_1^2(\nu = 26)$ plot for MECS + LECS events

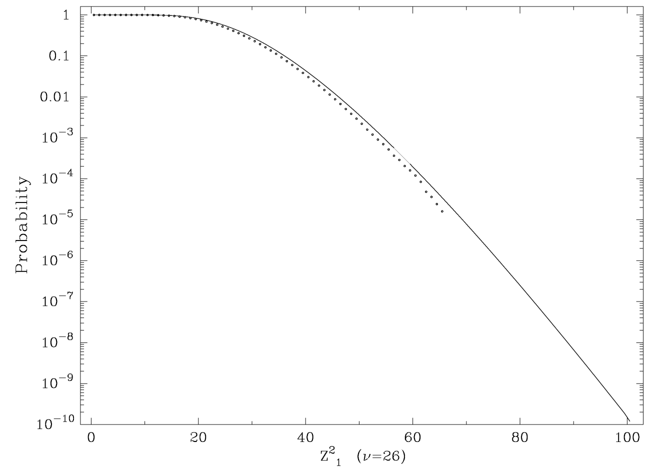

FIG. 4.—The chance-occurrence probability to find values greater than $Z_1^2(\nu = 26)$ (*solid line*) compared with the measured integral distribution (*dots*).

centered 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-independent statistics: the sum results in a statistic with $2M$ degrees of freedom (Bendat & Piersol 1971), which we refer to as the $Z_1^2(\nu = 2M)$ statistics. This procedure results in a less noisy spectrum. Because the power depends on the square of the pulsed signal, its strength decreases with M, and only sufficiently strong signals can be detected. 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 ∼3300 s. We adopted a frequency step $\delta f = 2 \times 10^{-4}$ Hz spanning 50 Hz of search range with 250,000 trial frequencies.

Figure 3 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 of having an excess greater than 99 is 2×10^{-10}, as shown in Figure 4. Taking into account the number of trial frequencies used, the probability is 5×10^{-5}, corresponding to 4 σ of the Gauss statistics. When we use only MECS data, the $Z_1^2(\nu = 26)$ value decreases to 91, in agreement with the reduction of the source counts. We also tested the power at half and double values of the detected frequency f_0: no signal is present at $f = f_0/2$ or at $f = 2f_0$. In order to check for the persistence of the periodicity in the whole observation, we also binned the maximum-resolution spectrum of the entire data set by a factor of 13. We obtain a high $Z_1^2(\nu = 26) > 104$, at a frequency equaling 29.5364 Hz, indicating that the previous high-power value does not come from one or few selected time intervals.

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.

We also performed a periodicity search over the full observation, including the first and second derivative of the frequency ($\dot f$ and $\ddot f$, respectively) at the maximum-resolution step. The search was performed within the interval $\Delta f = 2 \times 10^{-4}$ Hz centered on the detected value f_0. The value ranges for $\dot f$ and $\ddot f$ were chosen consequently. We obtained a maximum in the power spectrum [$Z_1^2(\nu = 2) = 52$] for $f = 29.53643 \pm 0.00001$ Hz, $\dot f = (-3.1 \pm 0.2) \times 10^{-9}$ Hz s^{-1}, and $\ddot f = (1.1 \pm 0.1) \times 10^{-14}$ Hz s^{-2}, where the errors refer to the parameter resolution. Assuming a circular orbit, the second-order polynomial expansion of the frequency versus time relation is locally compatible with an orbital period of $P_o \sim 18$ days and a semimajor projected axis of $a_p \sin i \sim 63$ lt-s. However, we stress that the interval of observation is much shorter than the derived orbital period and that the parabolic fit may not be a good representation if the orbit is eccentric. Thus, these results should be taken only as a possible indication of the orbital parameters and not as a firm detection of orbital motion. Figure 5 shows the pulse profile folding the data, taking into account the frequency derivative terms. Note that if the orbit is eccentric, the real pulse profile could be narrower.

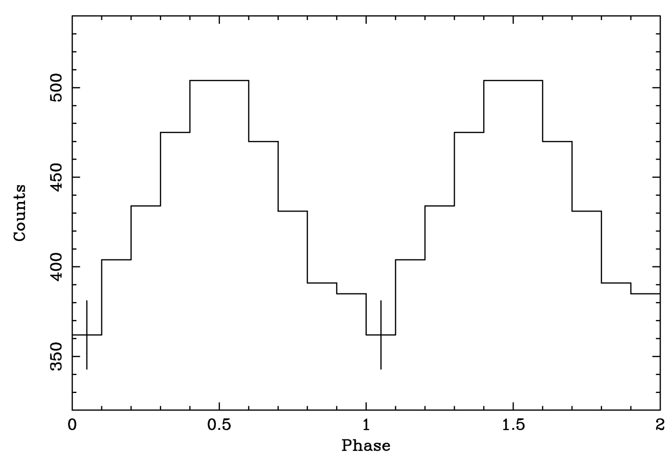

FIG. 5.—Pulse profile obtained taking into account $\dot f$ and $\ddot f$. Two cycles are shown for clarity. The superposed error bar corresponds to 1 σ.

4. DISCUSSION

The coherence of the detected periodicity is high, $Q = f/\delta f \sim 10^5$. This value is much greater than those observed in quasi-periodic oscillations, which are often detected in the X-ray emission of X-ray binaries (van der Klis et al. 1996). The high coherence induces us to interpret this periodicity as a neutron star spin period.

The association between SAX J0635+0533 and the Be star has been reinforced thanks to a reduced error circle of the X-ray position coordinates. Timing analysis results indicate that the neutron star could orbit around a companion star. The tentative orbital parameters are consistent for an orbital inclination of less than 25° with a primary mass greater than 10 $M_\odot$, as expected for a Be star.

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

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. The high X-ray variability of SAX J0635+0533 on timescales 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 (Nicastro et al. 1998). 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 corotating in the magnetosphere must be less than the local gravitational force (Illarionov & Sunyaev 1975; Stella, White, & Rosner 1986). Assuming a bolometric luminosity of 1.2×10^{35} ergs s^{-1} (0.1–40 keV) estimated from spectra results given in Kaaret et al. (1999) for a 5 kpc distance, 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 of 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 (Wijnnands & van der Klis 1998) 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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