

Discovery of a 1247 s pulsar in the Be X-ray binary SAX J2239.3+6116

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Abstract. A search for pulsations from the Be X-ray binary SAX J2239.3+6116, through observations with the Narrow Field Instruments on BeppoSAX and the Proportional Counter Array on RXTE, yielded the clear presence of a 1247 s coherent oscillation. Given the fairly high X-ray luminosity on previous occasions (up to a few times 10^{36} erg s⁻¹ in 2 to 28 keV), the oscillation must be due to the spin of a neutron star. Assuming that the 262 day recurrence time is the orbital period, SAX J2239.3+6116 has both the longest orbital period and the longest pulse period of 24 Be X-ray binaries with measured orbital periods.

Key words. stars: neutron – pulsars: SAX J2239.3+6116– X-rays: binaries

1. Introduction

SAX J2239.3+6116 was discovered as a moderately bright X-ray transient through serendipitous observations with the Wide Field Cameras (WFCs) on BeppoSAX in 1997 and 1999 (In 't Zand et al. 2000). A subsequent archival search of data from the All-Sky Monitor (ASM) on RXTE showed four unambiguous outbursts from the same source, one of which is simultaneous with a WFC detection. The five outbursts thus observed occurred with regular intervals of 262 ± 5 d. The highest X-ray flux ever measured was sampled with the WFCs at 1×10^{-9} erg cm⁻² s⁻¹ (2–28 keV). A 20 msec exposure with the Narrow Field Instruments on BeppoSAX in 1998 resulted in a more accurate X-ray position. Optical follow-up observations of this error box revealed a candidate optical counterpart: a Be star at an estimated distance of 4.4 kpc. The combination of periodicity, peak flux and optical counterpart prompted In 't Zand et al. (2000) to classify SAX J2239.3+6116 as a Be X-ray binary (BeXB) with an orbital period of 262 d. Pulsations, a common attribute of a BeXB, were not found but the limits were not very constraining, simply because no sensitive X-ray measurements had been obtained during an outburst.

High-mass X-ray binaries (combining the catalog of Liu et al. 2000 with more recent results) include

24 BeXBs with measured orbital periods P_o . Interestingly, SAX J2239.3+6116 is the case with the longest P_o , followed by X Per (250.3 d; Delgado-Martí et al. 2001) and GS 1843-024 (242.18 d; Finger et al. 1999). It is expected, based on the P_o/P_p correlation found in the “Corbet” diagram (Fig. 6), that if SAX J2239.3+6116 contains a pulsar it should have a pulse period near 10^3 s. A non-detection would bring a black hole hypothesis into serious consideration (like for 4U 1700-377, see Brown et al. 1996).

We set out to search for the X-ray pulsar with sensitive measurements, at times when the transient is active. The first opportunity to do so was presented by the fifth BeppoSAX Announcement of Opportunity in which we applied for target-of-opportunity observations at the earliest occurring outburst.

2. Observations, light curve and spectrum

The ephemeris as determined from the ASM data predicted an outburst on July 7, 2001 (MJD 52098), with an uncertainty of approximately 10 days. Since the anticipated peak flux was too low for ASM observations to be able to trigger the BeppoSAX observation, public snapshot observations were initiated with the sensitive Proportional Counter Array (PCA) on RXTE on June 30, 2001. The PCA (e.g., Jahoda et al. 1996) consists of five non-imaging Proportional Counter Units (PCUs) with collimators that limit the field of view to 1° full-width at half maximum (FWHM). The collecting area is 6500 cm² and

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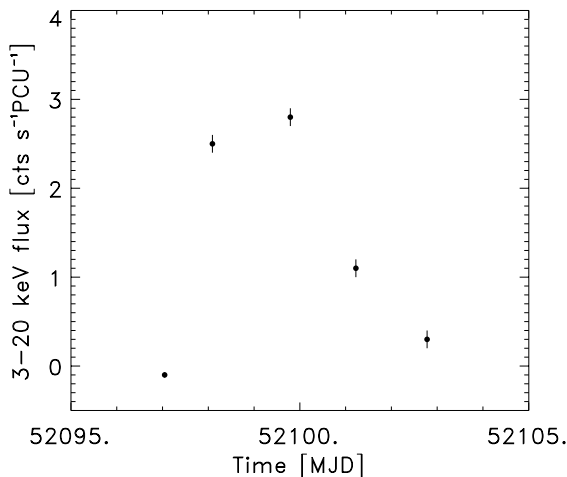


Fig. 1. Light curve generated from the 5th through 9th PCA measurement. 1 cts s⁻¹ PCU⁻¹ is equivalent to 0.5 mCrab or 0.9×10^{-11} erg cm⁻² s⁻¹.

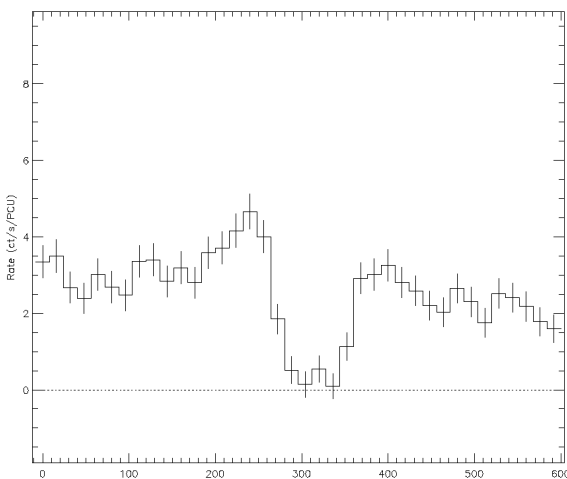


Fig. 2. Background-subtracted light curve from the 6th PCA observation. The dotted line refers to the zero-flux level.

the bandpass 2 to 60 keV. The snapshot observations were performed roughly every two days. Nine measurements were carried out in total with exposure times between 0.78 and 2.10 ksec, some with 5 PCUs operating, and some with only 2 PCUs. The last one was on July 12. Figure 1 shows the light curve generated from part of these data. SAX J2239.3+6116 was first detected in the sixth snapshot observation on July 8th. In Fig. 2 we show the light curve of this 6th observation with 16 s time resolution. The light curve shows considerable variability without a clear periodicity. Most notably, there is a 80 s long dip during which the flux drops to near zero. The mid-time of the dip is MJD 52098.09305 ± 0.00012. For the 7th and 8th observation there was also similar variability although less definitive because fewer detectors were on.

The PCA detection triggered our TOO with the BeppoSAX Narrow Field Instruments (NFI). The NFI consist of 4 devices. The Low-Energy and Medium-Energy Concentrator Spectrometers (LECS and MECS) are imaging devices in the 0.1 to 10 keV band

(Parmar et al. 1997; Boella et al. 1997b). SAX J2239.3+6116 was not unambiguously detected in the other two devices, consistent with their sensitivities. The observation was carried out between July 12.803 and 13.851 UT (MJD 52102.803 through 52103.851). The net exposure times are 40 039 s for the MECS and 17 952 for the LECS. We analyzed the data in a standard manner, by accumulating photons within 4' (MECS) or 8' (LECS) from the source centroid. We applied a background correction by employing long-duration data from high latitude fields, grouped energy channels such that at least 20 photons are present in each bin, and used standard response matrices. The validity of the background model was verified through a comparison of both data sets (i.e., the high latitude and the source data sets) for photons further than 5' and 10' from the source centroid for the MECS and LECS respectively. The MECS detected 1610 ± 43 photons from SAX J2239.3+6116 and the LECS 149 ± 24 . For the spectral analysis, the bandpasses were restricted to the photon-rich and well-calibrated ranges of 1.0–4.0 keV for the LECS and 1.6–10.5 keV for the MECS. The data could be fitted satisfactorily with a simple absorbed power law model ($\chi^2_\nu = 1.19$ for $\nu = 49$ degrees of freedom). The photon index is 1.6 ± 0.2 , the absorbing column density $N_{\text{H}} = (3 \pm 1) \times 10^{22}$ cm⁻², and the average 2 to 10 keV flux 3.8×10^{-12} erg cm⁻² s⁻¹ (4.7×10^{-12} erg cm⁻² s⁻¹ unabsorbed). Over the course of the observation the source showed a decreasing trend with a flux reduction of $20 \pm 5\%$.

Observation 6 of the PCA gives a spectrum for which the 2.5–30 keV range can be fit acceptably with a power law or a power law with a high energy cut-off. If the column density is fixed at the value seen with the LECS and MECS, the power law photon index when the source was seven times brighter was 1.1 ± 0.2 , with a high energy cut-off beginning at 6.3 ± 0.9 keV and e-folding energy of 7 ± 1 keV. The 2–10 keV flux is 2.3×10^{-11} erg cm⁻² s⁻¹. The spectral shape is typical for an accretion-powered pulsar (e.g., White et al. 1983; Mihara 1995; Dal Fiume et al. 2000).

3. Detection of oscillations

Figure 3 shows the Fourier power density spectrum of all MECS photons (i.e., without background subtraction), both from within the source point-spread function and outside. A clear peak is present at 0.80 mHz, with side-lobes separated by 0.18 mHz from the main peak due to aliasing through occultations by the Earth during each BeppoSAX orbit and passages through the South-Atlantic Geomagnetic Anomaly. As a check on the reality of the oscillation, we confirmed that the non-source photons of the same observation show no power at the relevant frequency. A periodogram of the same data for the source photons, see Fig. 4, gives the most accurate measurement of the period: 1247.2 ± 0.7 s. We identify this as a pulsar signal.

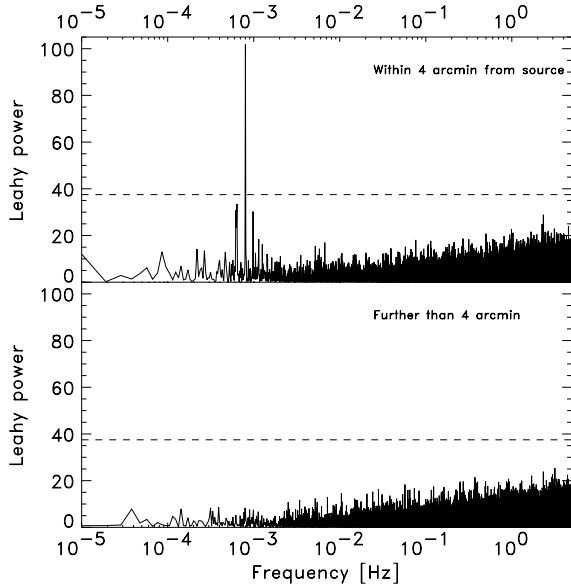


Fig. 3. Fourier power density spectrum from all 1855 MECS-detected photons within 4' from the source (top) and from the remaining 9848 photons (bottom). The power is defined following Leahy et al. (1983). The dashed lines represent the 99%-confidence detection levels.

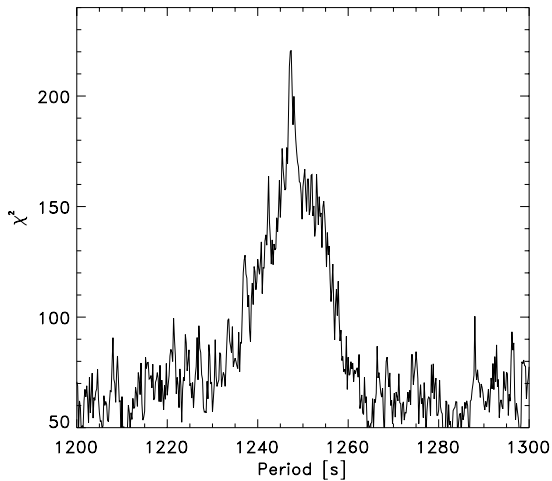


Fig. 4. Periodogram of source photons (same data as used for spectrum presented in the top panel of Fig. 3). A phase resolution of 64 was employed.

Figure 5 shows the light curve folded with this period. There is a broad peak and the modulation depth is $60 \pm 10\%$. A conspicuous feature is a dip at phase 0.65. The epoch of this dip is $\text{MJD } 52102.81318 \pm 0.00045$. The PCA data show a dip of similar duration but larger depth (Fig. 2). The time difference between both dips is 326.988 ± 0.036 pulse cycles which is consistent with both dips having identical pulse phases. PCA observations 7 and 8 show similar dips at similar phases but with different depths. Assuming the dips are phase locked, we can refine the pulse period to 1247.15 ± 0.14 s. Features like this dip are not uncommon in pulse profiles of accretion-powered X-ray pulsars, particularly at energies below 10 keV (for

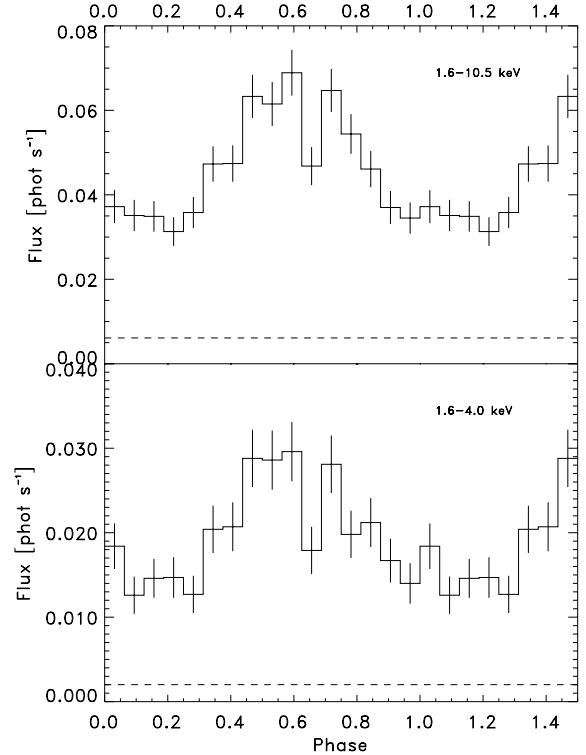


Fig. 5. Light curve in two bands, folded at the period of 1247.2 s. Phase is defined to be zero for the start of the observation. The dashed lines show the background levels.

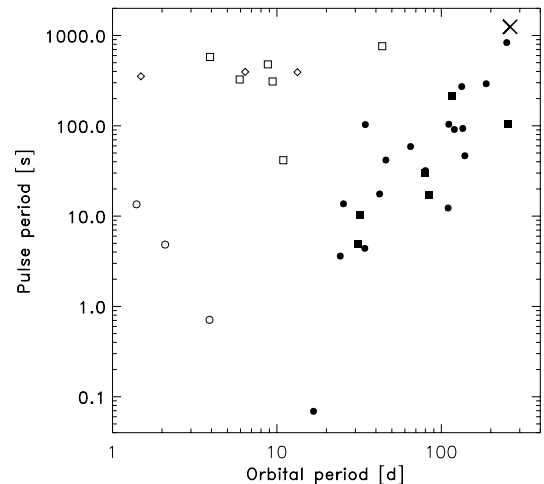


Fig. 6. Corbet diagram, updated with SAX J2239.3+6116 (cross). Open symbols are supergiant systems, filled symbols Be systems. For the Be systems, the circles indicate optically identified cases and squares those that are not. The open squares refer to optically identified Roche-lobe underfilling supergiants and the open circles to Roche-lobe filling giants. The diamonds refer to systems without optical counterpart.

recent overviews of pulse profiles, see Mihara 1995 or Bildsten et al. 1997).

4. Discussion

The ASM data between January 1996 and July 2001 encompass eight predicted times of outbursts, but only the

first four are readily detectable above a threshold of about 1 mCrab. The 262 d orbital period was basically determined from those four ASM detections (In 't Zand et al. 2000). The fifth outburst detected with WFC is consistent with that periodicity. Given the lack of clear outbursts afterwards, one might perhaps wonder whether the 262 d periodicity is well defined and can be identified with the orbital period. Quasi-periods of similar magnitude and variable peak flux have been found in other X-ray binaries without being associated to the orbit (e.g., in Terzan 6, see In 't Zand et al. 1999). We argue that the periodicity in SAX J2239.3+6116 is indeed the orbital period, because the coherence of the periodicity is rather high and because orbital periods of this magnitude are expected for BeXBs and the optical Be-star identification is rather secure (the estimated chance probability is less than 10^{-4} which is low for such a high-flux source, see also In 't Zand et al. 2000). The fact that the outbursts have become harder to see in the ASM data is very likely due to them becoming significantly shorter: the average duration of the first four outbursts was about 1 month, while the July 2001 outburst appears to have lasted just a few days. The orbital period using the timing of the July 2001 outburst reveals a refined value of $P_o = 262.6 \pm 0.7$ which is close to what was measured previously but more precise.

Could the compact object be a white dwarf rather than a neutron star? The distance of 4.4 kpc (In 't Zand et al. 2000) implies that the maximum 2–28 keV luminosity ever measured was 2.3×10^{36} erg s $^{-1}$. This is 3 orders of magnitude above what is normal for non-synchronously rotating magnetic white dwarfs accreting from a companion star (e.g., Eracleous et al. 1991; Patterson 1994). A number of white dwarf systems have been observed with $\sim 10^{36}$ erg s $^{-1}$ luminosities or higher, but those have supersoft spectra (with kT of order a few tens of eV; e.g., Gänsicke et al. 2000). SAX J2239.3+6116 did not, and we dismiss the white dwarf scenario.

The variably-peaked (1.5 mCrab for the July 2001 outburst and 20 mCrab for the May 1997 outburst¹) and periodic outburst behavior are typical for Type I BeXB outbursts (e.g., Stella et al. 1986; Bildsten et al. 1997) which are explained as due to increased mass accretion rates by the compact object when, during periastron in an eccentric orbit, it passes through denser parts of the companion wind without forming an accretion disk.

The values of spin period and orbital period for accretion-powered pulsars with high-mass companion stars have been shown to qualitatively reflect the nature of the stellar wind and the history of the neutron-star's interaction with it (Corbet 1984; Waters & van Kerkwijk 1989). Figure 6 shows the position of SAX J2239.3+6116 in the $P_p - P_o$ diagram for the periods 124 s and 262 d. It would be at the long period end of the distribution of pulsars with Be star companions, where that distribution

meets the distribution of supergiants. Since this system has faint X-ray outbursts for only a part of a long orbital period, determination of orbital parameters through Doppler shifts of the spin period will be difficult. Pulse period changes are easier to measure. Given the accuracy obtained for the July 2001 outburst, spin-up time scales of less than 10^3 yr are measurable between two outbursts. This would cover time scales seen in some systems which can be as short as 10 to 100 yr (Bildsten et al. 1997).

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¹ One should keep in mind that peak fluxes may be biased because of sparse sampling.