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A low luminosity state in the massive X-ray binary SAX J0635+0533

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ABSTRACT

The X-ray pulsar SAX J0635+0533 was repeatedly observed with the XMM-Newton satellite in 2003–2004. The precise localization provided by these observations confirms the association of SAX J0635+0533 with a Be star. The source was found, for the first time, in a low-intensity state, a factor ~30 lower than that seen in all previous observations. The spectrum, well fitted by an absorbed power law with photon index ~1.7 and $N_{\rm H} = 1.2 \times 10^{22}$ cm^{-2}, was compatible with that of the high state. The low flux did not allow the detection of the pulsations at 33.8 ms seen in BeppoSAX and RXTE data. In view of the low luminosity observed in 2003–2004, we reconsider the peculiarities of this source in both the accretion and rotation-powered scenarios.

Key words. X-rays: individuals: SAX J0635+0533 – X-rays: binaries

1. Introduction

The X-ray source SAX J0635+0533 was discovered with BeppoSAX in October 1997 (Kaaret et al. 1999) during a search for counterparts of unidentified gamma-ray sources (Thompson et al. 1995). Its 2–10 keV flux of 1.2×10^{-11} erg cm^{-2} s^{-1}, hard power-law spectrum (photon index ~1.5) extending to 40 keV, and positional coincidence with a $V = 12.8$ star of Be spectral type, immediately suggested classifying SAX J0635+0533 as an accreting high-mass X-ray binary. The subsequent discovery of X-ray pulsations at 33.8 ms (Cusumano et al. 2000) in the BeppoSAX data makes this object quite peculiar and raises some problems for the accretion scenario. In fact, if the X-ray emission is powered by accretion on the neutron star surface, the magnetic field in SAX J0635+0533 must be about three orders of magnitude less than expected in a typical high-mass X-ray binary to avoid the propeller effect (see, e.g., Campana et al. 1995).

The pulse frequencies measured with RXTE in 1999, about two years after the source discovery, indicated an orbital modulation with a period of about 11 days and set a lower limit on the long-term spin-down $\dot{P} > 3.8 \times 10^{-13}$ s s^{-1} (Kaaret et al. 2000). Such a high $\dot{P}$ in a rapidly spinning neutron star implies a large rotational energy loss, $\dot{E}_{\rm rot} = 10^{45}\, 4\pi^2\, \dot{P}/P^3 = 4 \times 10^{38}$ erg s^{-1}, capable of powering the observed X-ray luminosity without the need of invoking mass accretion. In this interpretation, SAX J0635+0533 would resemble other binary systems composed of a fast pulsar orbiting a massive star, such as PSR B1259–63 (Johnston et al. 1992), in which the X-ray emission is thought to originate in the shock between the pulsar's relativistic wind and that of the companion star. The failure to detect radio pulsations from SAX J0635+0533 (Nicastro et al. 2000) does not rule out this scenario, since beaming and/or absorption effects might render the radio emission unobservable.

Here we report the results of XMM-Newton observations, carried out in 2003–2004, during which SAX J0635+0533 was detected at a very low flux level, the lowest ever seen from this source.

2. Observations and data analysis

SAX J0635+0533 was observed by *XMM-Newton* with ten different pointings between 2003 September 11 and 2004 April 14. The three *EPIC* focal plane cameras (Turner et al. 2001; Strüder et al. 2001) were active during these pointings. The two *MOS* cameras were operated in the standard full frame mode (time resolution 2.6 s), in order to cover the whole 30′ field-of-view. The pn camera was operated in timing mode, providing a time resolution of 30 μs, but without imaging information. The thin filter was used for each observation and focal plane camera.

For each pointing, we retrieved the *pps* files from the *XMM-Newton* archive produced by pipeline processing system, which is operated by the Survey Science Center. Since only timing-mode data were obtained with the pn camera, we concentrated on the *MOS* data to study the source properties. The faintness of SAX J0635+0533 during these observations made it impossible to see the 33.8 ms pulsations in the pn camera data. For each observation, we looked for possible periods of high instrumental background caused by flares of soft protons with energies less than a few hundred keV. To this aim, we selected only single and double events (PATTERN ≤ 4) with energies greater than 10 keV and recorded in the peripheral CCDs. Then, we set a countrate threshold for good time intervals (GTI) at 0.5 cts s^{-1}. By selecting only events within GTIs, we finally obtained a "clean" event list for each *MOS* data set. The dates and effective exposure times (after soft-proton rejection) of the observations are listed in Table 1.

After merging the event lists of the two *MOS* cameras, we accumulated an image of the field-of-view comprising all the observations. This clearly showed a source, with a count rate of $(4.3 \pm 0.3) \times 10^{-3}$ counts s^{-1} in each camera, at the coordinates RA = 06$^{\rm h}$35$^{\rm m}$18.3$^{\rm s}$, Dec = +05°33′06.3″ (J2000). This position was obtained after the astrometric correction of the X-ray coordinates of the detected sources, based on the positions of five optical counterparts found in the Guide Star Catalog (Lasker et al. 2008). The final uncertainty on the source position is 1″ at 90% c.l. (including statistical and systematic errors). The *XMM-Newton* localization confirms the association with the star

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Table 1. Flux and luminosity values of SAX J0635+0533 in the individual observations.

Start Observation date – UT	Net exposure (ks)	Absorbed flux (0.2–12 keV) ($erg\,cm^{-2}\,s^{-1}$)	Luminosity[a] ($erg\,s^{-1}$)	Hardness Ratio[b]
2003-09-11 13:22:41	8.1	$<6.1\times10^{-14}$	$<3.03\times10^{32}$	–
2003-09-15 18:47:20	5.1	$<7.8\times10^{-14}$	$<3.88\times10^{32}$	–
2003-09-18 13:17:46	6.8	$<2.2\times10^{-13}$	$<11.1\times10^{32}$	–
2003-09-21 09:53:21	3.7	$(1.7\pm0.5)\times10^{-13}$	$(8.5\pm0.5)\times10^{32}$	0.17 ± 0.18
2003-09-25 12:45:02	5.0	$(5.5\pm0.7)\times10^{-13}$	$(27.6\pm3.4)\times10^{32}$	0.48 ± 0.08
2003-10-08 07:29:55	2.8	$(3.7\pm0.6)\times10^{-13}$	$(18.6\pm2.4)\times10^{32}$	0.29 ± 0.13
2003-10-13 15:30:19	4.6	$(9.0\pm3.3)\times10^{-14}$	$(4.5\pm1.6)\times10^{32}$	-0.28 ± 0.21
2003-10-15 22:34:19	5.9	$(3.2\pm1.3)\times10^{-14}$	$(1.6\pm0.7)\times10^{32}$	-0.06 ± 0.15
2004-03-13 11:44:58	2.7	$(4.0\pm0.7)\times10^{-13}$	$(20.7\pm3.3)\times10^{32}$	0.30 ± 0.11
2004-04-14 08:04:48	4.5	$<1.6\times10^{-13}$	$<8.0\times10^{32}$	–

[a] In the energy range 0.2–12 keV, corrected for the absorption, and assuming a distance of 5 kpc.
[b] Ratio between the source count rates in the hard (H = 2–12 keV) and soft (S = 0.2–2 keV) energy ranges, defined as $(H-S)/(H+S)$.

proposed by Kaaret et al. (1999) on the basis of an estimated 4% probability of finding by chance a Be star in the 30″ radius error circle determined with BeppoSAX (see Fig. 1).

We extracted the source spectra by selecting events in a circular region with a small radius (10″) in order to minimize the background contribution. The background spectra for the two *MOS* cameras were accumulated from large circular areas with no sources and radii of 100″. We generated ad hoc redistribution matrices and ancillary files using the *SAS* tasks `rmfgen` and `arfgen`, respectively. To ensure the applicability of the χ^2 statistics, all spectra were rebinned with a minimum of 30 counts per bin and fitted in the energy range 0.3–10 keV using *XSPEC* 11.3.2. We checked that separate fits of the two spectra gave consistent results, therefore we analyzed them simultaneously, in order to increase the count statistics, imposing common spectral parameters for the two spectra and introducing a free relative normalization factor between them, to account for possible differences in the instrument cross-calibration. We found a 1.02 cross-normalization factor between the *MOS2* and the *MOS1* camera.

A good fit was obtained with an absorbed powerlaw (Fig. 2), yielding a hydrogen column density $N_H = (1.17^{+0.49}_{-0.35}) \times 10^{22}$ cm^{-2} and a photon index $\Gamma = 1.74^{+0.43}_{-0.31}$. The absorbed flux in the energy range 0.2–12 keV is $f_X \sim 1.45 \times 10^{-13}$ erg cm^{-2} s^{-1}, while the corresponding unabsorbed flux is $\sim 2.55 \times 10^{-13}$ erg cm^{-2} s^{-1}. Acceptable fits were also obtained with a thermal bremsstrahlung (kT = 9.2 keV) and with a blackbody ($kT \sim 1$ keV).

To study the source variability, we analyzed the ten datasets separately. For each of them we performed a detailed source detection in five energy bands (0.2–0.5, 0.5–1, 1–2, 2–4.5, and 4.5–12 keV), applying the same procedure and parameters as used by the *XMM-Newton SSC* to produce the *XMM-Newton* serendipitous source catalog (Watson et al. 2009). The source detection was performed simultaneously on both *MOS* data sets and using the corresponding exposure maps, which account for spatial quantum efficiency variations, mirror vignetting, and effective field of view. The threshold value for the detection likelihood was set to 5 for the *likemin* parameter of the *SAS* task `eboxdetect` and to 6 for the *mlmin* parameter of the *SAS* tasks `emldetect` and `esensmap`. We emphasize that these values imply a rather loose constraint on the source significance in order to be detected; they allow detection of even very weak sources, with a low (i.e. ≃3) signal-to-noise ratio. In this way we aim to check that SAX J0635+0533 is even only marginally detected in any observation. On the other hand, in our detection procedure we used "ad hoc" *energy conversion factors* (*ECF*) to convert the measured count rates of the detected sources (both in each of the five energy bands and in the total 0.2–12 keV band) into the corresponding energy flux. They were derived with the best-fit power-law model of the source average spectra.

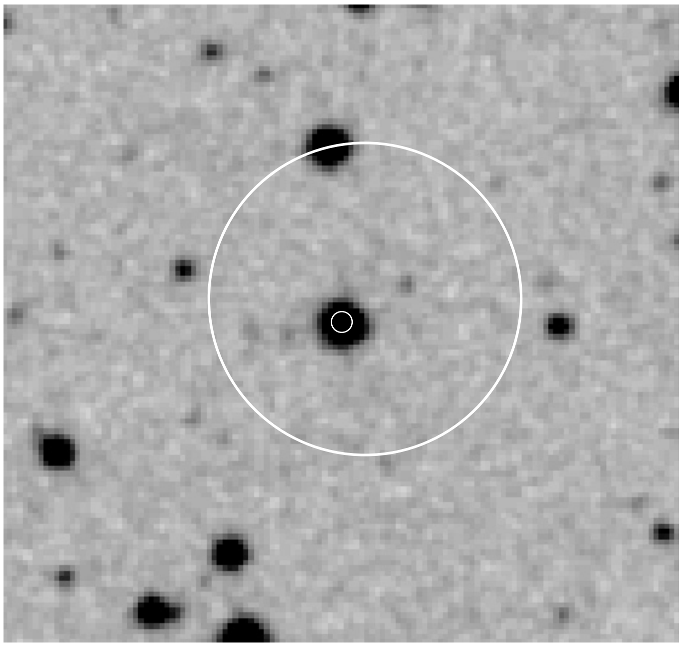

Fig. 1. Optical image of a 2′×2′ field around the position of SAX J0635+0533 from the Digitized Sky Survey (*B* filter). The large circle is the BeppoSAX error region with a radius of 30″ (Cusumano et al. 2000). The small circle (2″ radius) is the *XMM-Newton* position. North is to the top, east to the left.

Based on this analysis, we find that SAX J0635+0533 was detected only in six observations, as reported in Table 1. The upper limits on the count rate (at the confidence level corresponding to a detection likelihood L = 6) are obtained from the sensitivity maps at the source position.

The long-term light curve of SAX J0635+0533 is plotted in Fig. 3. In September-October 2003 the source flux varied by at least a factor 10. Although the observations are not continuous,

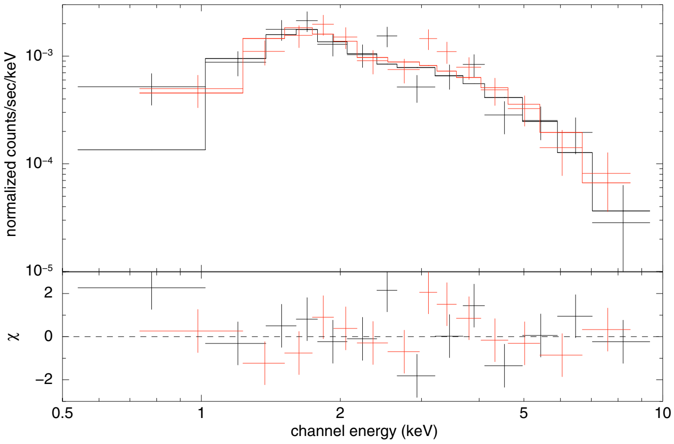

Fig. 2. *Top panel*: average spectrum of SAX J0635+0533 with the best-fit power-law model. The spectra of the *MOS1* and *MOS2* cameras are shown in black and red, respectively. *Bottom panel*: data-model residuals, in units of σ.

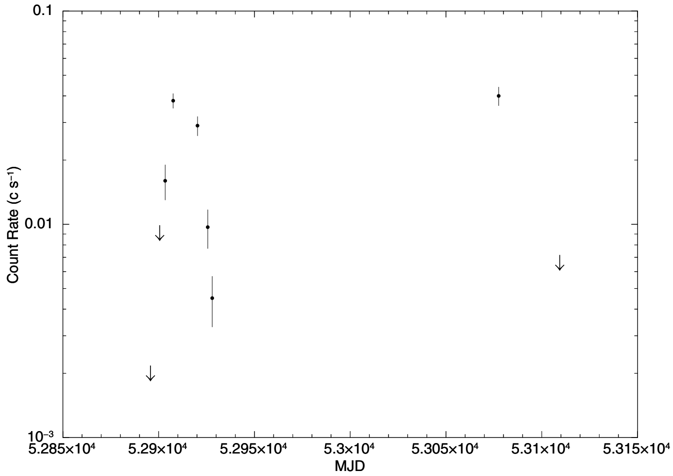

Fig. 3. Light curve of SAX J0635+0533. The count rates refer to the 0.2–12 keV energy range and to the sum of 2 MOS. The data of the first two observations have been merged. The upper limits (obtained with a threshold in detection likelihood $L = 6$) correspond to a $\sim 3\sigma$ confidence level.

they suggest an outburst lasting about three weeks, with a rise time of only a few days to a maximum flux of $\sim 5 \times 10^{-13}$ erg cm^{-2} s^{-1}, followed by a similarly rapid decay. A similar flux level was observed again six months later. Comparing the hardness ratios measured in the different observations, we found some evidence of a slight spectral hardening correlated with the source intensity (Table 1, Fig. 4).

3. Discussion

The maximum flux we observed for SAX J0635+0533, 4.2×10^{-13} erg cm^{-2} s^{-1} in the 2–10 keV range, is a factor >30 smaller than that measured at the time of the BeppoSAX discovery in 1997 (1.2×10^{-11} erg cm^{-2} s^{-1}, Kaaret et al. 1999). To our knowledge, this is the lowest flux ever reported for SAX J0635+0533. The upper limits of the *XMM-Newton* pointings of September 2003 imply an even smaller flux.

The distance of SAX J0635+0533 is not well constrained. The range 2.5–5 kpc was estimated by Kaaret et al. (1999) from the properties of the proposed optical counterpart. We also note

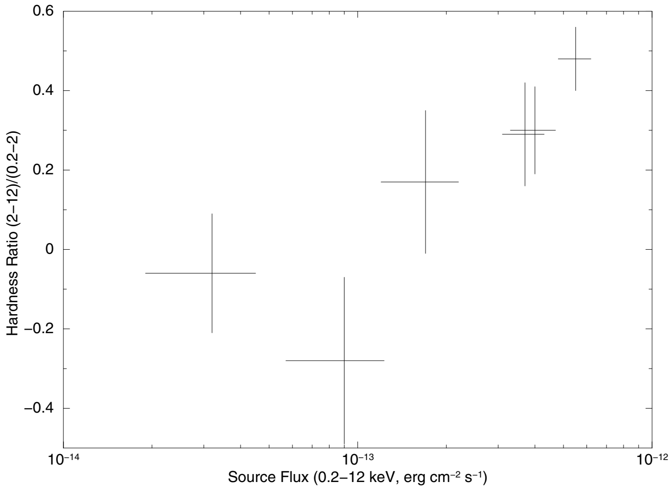

Fig. 4. Hardness ratio versus source flux. The hardness ratio is defined as $(H - S)/(H + S)$, where H and S are the source count rates in the hard (H = 2–12 keV) and soft (S = 0.2–2 keV) energy ranges.

that a distance far in excess 5 kpc is unlikely, considering the location of SAX J0635+0533 in the Galactic anti-center direction. In the following discussion, where we consider the two alternative possibilities for the origin of the observed X-ray emission, we conservatively normalize the relevant quantities to a distance d_5 of 5 kpc.

3.1. Accretion-powered X-ray emission

Neutron stars accreting from Be star companions constitute the large majority of the high-mass X-ray binary systems present in the Galaxy. Also in view of our improved localization of SAX J0635+0533, it is natural to first discuss this possibility.

Already at the time of its discovery, it was noticed that the luminosity of SAX J0635+0533 was relatively low compared to classical Be/neutron star systems. The persistent sources of this class have X-ray luminosity of 10^{36}–10^{37} erg s^{-1}. This is also the luminosity typically reached during the outbursts of transient Be/neutron stars systems, which comprise the majority of this population. With the advent of more sensitive observations, a number of persistent Be binaries with lower luminosity, $\sim 10^{34}$ erg s^{-1}, have also been discovered (see, e.g. Reig & Roche 1999; La Palombara & Mereghetti 2006, 2007). Our observations indicate for SAX J0635+0533 an average luminosity, a few 10^{33} d_5^2 erg s^{-1}, much lower than these values, and provide an upper limit as low as 3×10^{32} d_5^2 erg s^{-1} in mid September 2003. If we further consider that the source could well be closer than 5 kpc, we are faced with an even lower luminosity.

The new data clearly indicate that SAX J0635+0533 is a transient source, but it differs from the other Be systems for its low luminosity both during the "high state" and in "quiescence". The non detection in September 2003 allows us to set an upper limit on the mass accretion rate of 1.5×10^{12} g s^{-1}. This limit applies assuming that the accretion flow proceeds down to the neutron star surface, which is very unlikely if the neutron star is indeed rotating at 33.8 ms. In the presence of the neutron star magnetic field, different scenarios preventing or reducing the accretion rate onto the neutron star surface can occur (see, for example, Campana et al. 1998). For such a short spin period and low luminosity, the direct accretion regime, in which the magnetospheric radius is smaller than the corotation radius, hence the magnetic centrifugal barrier is open, requires a magnetic field less than $\sim 10^8$ G. This field is at least three orders of magnitude lower than expected in a young neutron star with a Be companion. In fact, all other accreting pulsars of this class have much longer spin periods. The only exception is the recurrent transient A 0538–66, which rotates at 69 ms (Skinner et al. 1982). The pulsations in this systems were only detected during a bright outburst reaching a luminosity of $\sim 10^{39}$ erg s^{-1} (Skinner et al. 1982), implying a magnetic field of $\sim 10^{11}$ G. Although below average, such a field is not implausible. Furthermore it is consistent with interpretation of the unpulsed quiescent luminosity of A 0538–66 (several 10^{33} erg s^{-1}) because accretion halted at the centrifugal barrier (Campana et al. 1995).

If SAX J0635+0533 has a typical magnetic field, the low luminosity observed with XMM-Newton could come from mass accretion stopped at the magnetospheric radius. Assuming for simplicity spherically symmetric accretion, along with a neutron star with mass 1.4 $M_\odot$ and radius 10^6 cm, gives in this case an X-ray luminosity of $\sim 2 \times 10^{32}\ B_{12}^{-4/7}\ \dot{M}_{15}^{9/7}$ erg s^{-1} (B_{12} is the magnetic field in units of 10^{12} G and $\dot{M}_{15}$ the accretion rate in units of 10^{15} g s^{-1}; see, e.g., Campana et al. 1998). However, the higher luminosity state observed in the past with BeppoSAX and RossiXTE cannot be explained in the same way due to the pulsations with a relatively high pulsed fraction, which are not expected when the magnetic centrifugal barrier operates.

In conclusion, the difficulties already pointed out in interpreting SAX J0635+0533 as a typical accretion powered Be binary (Kaaret et al. 2000; Nicastro et al. 2000) are reinforced by the low luminosity reported here. Of course, the properties of this system would fit in this scenario better if the fast periodicity were disproved by further observations.

3.2. Rotation-powered X-ray emission

The alternative interpretation of SAX J0635+0533 is that of a rotation-powered neutron star, whose X-ray emission derives from the shock between the relativistic pulsar wind and the companion's wind. The large luminosity difference between our data and the previous observations could stem from varying shock conditions in a very eccentric orbit. However, also in this scenario this source would present some peculiar properties, compared to the (admittedly few) other systems of this kind. The large variations seen in September 2003 are difficult to explain if the source was far from periastron, where no big changes in the shock properties are expected. Rotation-powered pulsars in interacting binaries, such as the already-mentioned PSR B1259–63 (Chernyakova et al. 2006, 2009) or the "black widow" pulsar PSR B1957+20 (Huang & Becker 2007), have X-ray efficiencies in the range 10^{-4}–10^{-2}. On the other hand, the $\dot{P}$ reported by Kaaret et al. (2000), corresponding to a rotational energy loss $\dot{E}_{\rm rot}$ greater than a few 10^{38} erg s^{-1}, implies a much lower efficiency for SAX J0635+0533.

4. Conclusions

Despite SAX J0635+0533 being found by *XMM-Newton* in a very low-luminosity state, thanks to the good sensitivity of the EPIC instrument, we could derive a precise localization that confirms the proposed Be optical counterpart of this source. We observed large flux variability when the source was detected in September/October 2003 and derived a stringent upper limit of $3 \times 10^{32}\ d_5^2$ erg s^{-1} for its luminosity when the source was not detected.

The spectral and flux properties of SAX J0635+0533 are consistent with a variable neutron-star binary powered by accretion from the Be companion or by the loss of rotational energy. Both interpretations imply some peculiarities with respect to other known sources. These result from the very short spin period and possibly high period derivative reported for SAX J0635+0533, which unfortunately we could not confirm owing to the source faintness during our observations.

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