Astron. Astrophys. 362, L5–L8 (2000)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Radio observations of the 33.8 ms X-ray pulsar SAX J0635+0533

L. Nicastro[1], **B.M. Gaensler**[2⋆], **and M.A. McLaughlin**[3]

[1] Istituto di Fisica Cosmica con Applicazioni all'Informatica, CNR, Via U. La Malfa 153, 90146 Palermo, Italy
[2] Massachusetts Institute of Technology, Center for Space Research, Cambridge, MA 02139, USA
[3] Cornell University, Astronomy Department, Ithaca, NY 14850, USA

Received 27 July 2000 / Accepted 18 September 2000

Abstract. The hard X-ray source SAX J0635+0533 shows pulsations at a period of 33.8 ms and is thought to be associated with a bright Be star. We here report on radio observations towards this source with the VLA and Arecibo radiotelescopes. With the VLA we do not detect any radio flux at the Be-star position, but one 4.7 mJy (at a radio frequency of 1.4 GHz) source lies just on the border of the $30''$ X-ray error circle. Periodicity searches at 430 MHz performed with the Arecibo telescope failed to detect any pulsation. We argue that the 4.7 mJy source is not the radio counterpart of SAX J0635+0533. Most likely SAX J0635+0533 is a rather "non-standard" Be-star/neutron-star X-ray binary pulsar, probably with a relatively short orbital period. It could still be a radio emitting pulsar but with an emission beam not pointing toward the Earth.

Key words: stars: individual: SAX J0635+0533 – stars: neutron – stars: pulsars: general – radio continuum: stars – X-rays: stars

1. Introduction

A BeppoSAX observation of the field centered on the unidentified EGRET source 2EG J0635+0521 led to the discovery of a hard X-ray source, proposed to be associated with a bright ($R \simeq 12$) Be-star located within the $1'$ X-ray error circle (Kaaret et al. 1999). Optical spectra showed it is at a distance of 2.5–5 kpc, with an $E(B-V)$ derived neutral hydrogen column density of 6×10^{21} cm^{-2} (in agreement with the Galactic 21-cm column density toward the source). The X-ray photon spectrum was fitted with a power law of spectral index -1.5 and column density $N_{\rm H} \simeq 2 \times 10^{22}$ cm^{-2}. The derived 2–10 keV X-ray luminosity is $L_X \simeq 23 \times 10^{33} (d_{\rm kpc}/4)^2$ erg s^{-1}. The extra absorption, with respect to the value obtained through the optical data, suggests that local extra gas must be present. This interpretation agrees with the Be-star association and led Kaaret et al. (1999) to the conclusion that the system is a (probably gamma-ray emitting) high mass X-ray binary.

A reduced X-ray error circle of $30''$, including the Be-star, resulted from the re-analysis of the BeppoSAX data by Cusumano et al. (2000), but the most relevant result was the discovery of coherent pulsed emission at a period of 33.8 ms with a significance level of 4σ. Unfortunately the available X-ray data did not allow them to derive the system orbital parameters. However, the derived X-ray luminosity ($7.7 \times 10^{34} (d_{\rm kpc}/4)^2$ erg s^{-1} in 0.1–40 keV) and magnetic field strength ($\lesssim 10^9$ G), derived from assuming the pulsar is powered by accretion, are not typical of Be/X-ray binaries (which have higher luminosities and magnetic fields).

In an accretion scenario, any radio emission is expected to be quenched within the high density environment. In a non-accretion (rotation-powered) scenario, high-energy emission can be produced either by shock acceleration or by a magnetospheric process. In this case the source could also show variable and/or periodic radio emission. Detection of radio pulses with the same period of the X-ray emission would lead to an unambiguous interpretation in this sense.

Here we present the results of observations made with the VLA at 1.4 and 4.8 GHz and pulse searches performed using the Arecibo radiotelescope at 430 MHz.

2. Observations ad data reduction

The SAX J0635+0533 field was observed on 2000 April 25 with the Very Large Array in its C configuration at 1.465 and 4.86 GHz; bandwidths were 22 and 100 MHz, respectively. A gain calibrator source (4C 10.20) was observed at each frequency switch (six in total) and 3C286 (flux densities of 6.8 and 3.3 Jy at 1.4 and 4.8 GHz respectively) was used as the primary calibrator. The total net observing time was ~ 80 and ~ 110 minutes at 1.4 and 4.8 GHz respectively. All four Stokes parameters were recorded. One of the 27 antennas could not be used because of technical reasons. Data were processed in the `MIRIAD` package. After appropriate editing and calibrating, images were formed using uniform weighting and deconvolved using `CLEAN`. The synthesized beam is $11'' \times 11''$ (1.4 GHz) and $3\rlap{.}''5 \times 3\rlap{.}''5$ (4.8 GHz). The resulting images have sensitivities of 120 and 20 μJy at 1.4 and 4.8 GHz, respectively, yielding 5σ detection limits of

Send offprint requests to: nicastro@ifcai.pa.cnr.it
⋆ Hubble Fellow

Table 1. 4.8 GHz positions and fluxes of sources within the $60''$ X-ray error circle of SAX J0635+0533.

Source	RA	Dec	$F^*_{4.8\ \mathrm{GHz}}$ (mJy)
A	$06^\mathrm{h}\,35^\mathrm{m}\,21\overset{\mathrm{s}}{.}64$	$+05^\circ\,33'\,19\farcs6$	0.79 ± 0.03
B	$06^\mathrm{h}\,35^\mathrm{m}\,20\overset{\mathrm{s}}{.}64$	$+05^\circ\,33'\,26\farcs4$	0.20 ± 0.03
C	$06^\mathrm{h}\,35^\mathrm{m}\,16\overset{\mathrm{s}}{.}94$	$+05^\circ\,33'\,37\farcs7$	1.98 ± 0.04

* Errors are 1σ level. Coordinates are equinox 2000.

0.6 and 0.1 mJy. In the polarisation images (Stokes Q and U) these limits are of 0.45 (1.4 GHz) and 0.12 mJy (4.8 GHz).

If we adopt the 90% confidence level $30''$ X-ray error radius circle, we have only one source detected on its border while three sources are detected within the $1'$ X-ray error circle quoted by Kaaret et al. (1999) (see Fig. 1). The 4.8 GHz positions and fluxes of these sources are given in Table 1. At 1.4 GHz, only source C is detected with a flux of 4.72 ± 0.15 (1σ) mJy. Assuming the flux spectrum can be described by a power law $S \propto \nu^\alpha$, we find $\alpha = -0.72$ between 1.4 and 4.8 GHz. We do not detect polarisation from any of these sources.

We checked for time variability of source C at 1.4 and 4.8 GHz by accumulating 6 images for the 6 interleaved observations. The source is constant within 25% of its average flux. We also produced the time series of 12 other field sources with 1.4 GHz fluxes in the range 2–10 mJy. They all show similar flux variations, probably due to calibration and deconvolution uncertainties. No optical counterpart to source C is visible in the POSS-II[1] survey plates at a limiting magnitude of ~ 21 (R) and ~ 20 (B).

We also carried out a search for radio pulsations at 430 MHz on 2000 January 20 using the Arecibo telescope. The source was observed for 15 minutes with a 10-MHz bandwidth and a sampling time of 0.1 μs using the AOFTM (Arecibo Observatory Fourier Transform Machine). The expected rms of these observations was 30 μJy so that a 10σ detection corresponds to 0.3 mJy. The periodicity search in a wide period range, covering the published 33.8 ms and its harmonics, did not result in any convincing candidates above a 7σ threshold. We did not detect any isolated dispersed pulses.

3. Discussion

3.1. The nature of source C

At 4.8 GHz we detect three sources in the $60''$ X-ray error circle quoted by Kaaret et al. (1999); only source C is within the reduced $30''$ error-circle by Cusumano et al. (2000) (Fig. 1). The steadiness of the flux of source A and its non-detection at 1.4 GHz, suggesting an inverted spectrum, are not expected for an isolated neutron star. While source B is too weak for any detailed

[1] The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation, the National Aeronautics and Space Administration, the National Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation.

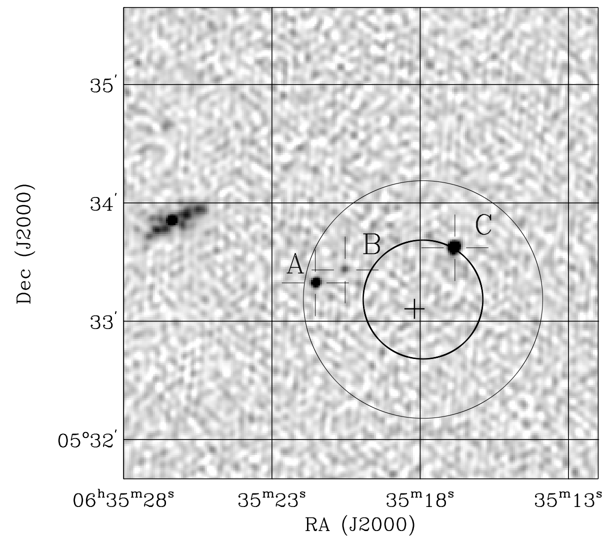

Fig. 1. 4.8 GHz VLA image of the region around SAX J0635+0533. The $30''$ and $60''$ X-ray error circles (Kaaret et al. 1999; Cusumano et al. 2000) and the position of the putative Be-star counterpart (+) are marked along with the 3 sources cited in the text.

analysis, we can constrain its spectral index to be flatter than -0.9. For source C, we estimate that the chance probability to have a 1.4 GHz radio source of flux greater than 4.7 mJy within a $30''$ error circle is 0.65% (2.7σ) (Windhorst et al. 1984). This value would suggest a putative association but, on the other hand, it remains the only argument in favor. In fact the lack of time variability, polarisation and pulsation and the flat spectral index (-0.72 ± 0.05 between 1.4 and 4.8 GHz), suggest an extragalctic origin.

3.2. The nature of the Be/X-ray pulsar

We then accept the association of SAX J0635+0533 with the Be-star. In this case the X-ray emission can be either accretion powered or rotation powered (i.e. magnetospheric). The observed X-ray properties (and the gamma-ray properties if one believes the association with 2EG J0635+0521) do not exclude this latter hypothesis. We know that PSR B1259−63 (a Be-star/neutron star system with a pulse period of 47 ms), shows magnetospheric pulsed (away from periastron) and continuum (near periastron) radio emission (see e.g. Johnston et al. 1996; Johnston et al. 1999), as well as variable unpulsed X-ray emission (Kaspi et al. 1995; Nicastro et al. 1998) along its ~ 3.5 years orbit. This emission is thought to originate in a discontinuity shock between the relativistic pulsar wind and the Be-star wind (Tavani & Arons 1997). This same mechanism could account for the X-ray emission in SAX J0635+0533. The lack of radio flux could be due to scattering of the photons in a high density Be-star wind, implying a short orbital period. This hypothesis is supported by the high value of N_H.

But if the radio emission is not quenched (at our flux limits) by the local environment, then we must find another explanation for our non-detections. If we make the reasonable assumption we are dealing with a young ($\tau \lesssim 10^5$ years) isolated rotation-powered pulsar, we then can estimate the energy loss rate, $\dot{E}$, from the X-ray conversion efficiency. Extrapolating the flux in the 0.1–2.4 keV ROSAT band and assuming an efficiency of 0.1% (Becker & Trümper 1997), we obtain an $\dot{E} \sim 1.5 \times 10^{37}$ erg s^{-1}. Frail & Moffett (1993) found as average luminosity of young pulsars a value $L_{1.4\ \mathrm{GHz}} \simeq 30$ mJy kpc^2 and $L_{400\ \mathrm{MHz}} \simeq 300$ mJy kpc^2. They also calculate a beaming fraction for such pulsars $f = 61\% \pm 13\%$, significantly lower than the $\sim 100\%$ value of X-ray emitting pulsars. Assuming a distance to the system of 4 kpc, our observations would imply a 5σ luminosity limit $L_{1.4\ \mathrm{GHz}} \sim 10$ mJy kpc^2 and $L_{430\ \mathrm{MHz}} \sim 5$ mJy kpc^2, then quite good. For a distance of 4 kpc, we would expect a dispersion measure to this source of ~ 90 pc cm^{-3}, given the Taylor & Cordes (1993) model for Galactic electron density. As the dispersion smearing across one of the Arecibo receiver 10-kHz channels is only ~ 0.1 ms, our pulsed search was sensitive to the shortest period pulsars. Brazier & Johnston (1999) argue that many young pulsars are visible as X-ray pulsars but not as radio pulsars because they are beaming away from Earth and not because they have intrinsically lower radio fluxes. Looking at their Fig. 1 we see there are only a few radio pulsars or candidate neutron stars known with similar $\dot{E}$ and luminosity, so it is likely that our non-detection could also be attributed to an unfavorable beaming.

3.3. Radio emission from accreting X-ray pulsars

If SAX J0635+0533 is indeed an accretion-driven Be/X-ray binary pulsar, as already noted by Cusumano et al. (2000), this would imply an unusually low magnetic field strength $\lesssim 10^9$ G similar to SAX J1808.4−3658 (Gaensler et al. 1999). Given also the highly variable X-ray flux for the two systems, it would be tempting to expect some transient non-magnetospheric radio emission. Our ~ 4 hours observation time is much too short to say anything in this respect. A joint X-ray/radio monitoring program would be necessary to see if any simultaneous, delayed or anti-correlated emission is present. Fender et al. (1997b) showed that there is a statistically significant anticorrelation between X-ray pulsations and radio emission, though none of the 22 X-ray pulsars observed in the centimeter band with a fairly good sensitivity has ever been convincingly detected as a synchrotron radio source (Fender et al. 1997a).

Also, the lack of radio emission from the Be-star itself is not surprising given its distance. A survey of a sample of 13 optically and IR bright classical Be-stars made from the Australia Telescope Compact Array failed to detect any star at 4.8 GHz (Clark et al. 1998) with a 3σ flux level of ~ 0.1 mJy.

4. Conclusions

We have performed sensitive radio observation of SAX J0635+0533 at 1.4 and 4.8 GHz with the VLA and pulsar search at 430 MHz with the Arecibo telescope. We do not detect any flux at the Be-star position, but a relatively strong, flat spectrum source lies within the $30''$ X-ray error circle. Its properties do not support the association with the X-ray source and no sign of pulsed emission is found at a relatively high sensitivity limit. Then, assuming the system is a Be/X-ray pulsar, the lack of radio emission at our flux limits does not allow us to distinguish between an accretion or rotation-powered system. However it shows that:

– the system probably has a short binary period and therefore it is quite different from PSR B1259−69;
– if periodic/flaring radio emission is present, our observation was far too short to be conclusive in this respect;
– the radio emission could be quenched by the high density Be-star wind or the pulsar is beaming away from the Earth;
– the system could be an accreting X-ray pulsar, though transient non-magnetospheric weak radio emission could still be present.

Given the variable nature of the X-ray source it is also unlikely that any accurate timing can be performed in order to check for gamma-ray emission at 33.8 ms from 2EG J0635+0521. However its gamma-ray spectral index and flux stability favor an isolated neutron star. Until the arrival of more sensitive gamma-ray instruments such as GLAST, the association between the two sources will likely remain uncertain. As Kaaret et al. (1999) and Cusumano et al. (2000), we conclude that SAX J0635+0533 is most likely a compact Be-star/neutron-star X-ray binary pulsar, though with an unusually short pulse period. Further X-ray observations are required both to confirm the 33.8 ms period (and measure a spin-up/down) and to determine the (likely short) binary period.

After this paper was submitted we became aware of new X-ray results by Kaaret et al. (2000) which suggest an orbital period of $\simeq 11$ days and a large $\dot{\nu}$ which is more typical of young, rotation-powered pulsars rather than of accretion-powered X-ray binaries.

Acknowledgements. The National Radio Astronomy Observatory is a facility of the National Science Foundation. L.N. acknowledges the support of CNR through a short-term mobility program. B.M.G. acknowledges the support of NASA through Hubble Fellowship grant HST-HF-01107.01-A awarded by the Space Telescope Science Institute which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555.

References

Becker W., Truemper J., 1997, A&A 326, 682
Brazier K.T.S., Johnston S., 1999, MNRAS 395, 671
Clark J.S., Steele I.A., Fender R.P., 1998, MNRAS 299, 1119
Cusumano G., Maccarone M.C., Nicastro L., et al., 2000, ApJ 528, L25
Fender R.P., Bell Burnell S.J., Waltman E.B., 1997a, Vistas Astron. 41, 3
Fender R.P., Roche P., Pooley G.G., et al., 1997b. In: Winkler C., Courvoiser T.J.-L., Durouchoux P. (eds.) Proc. 2nd INTEGRAL workshop, The transparent Universe, ESA SP-382, p. 303
Frail D.A., Moffett D.A., 1993, ApJ 408, 637
Gaensler B.M., Stappers B.W., Getts T.J., 1999, ApJ 522, L117

Johnston S., Manchester R.N., Lyne A.G., et al., 1996, MNRAS 279, 1026
Johnston S., Manchester R.N., McConnell D., Campbell-Wilson D., 1999, MNRAS 302, 277
Kaaret P., Cottam J., 1996, ApJ 462, L35
Kaaret P., Piraino S., Halpern J., Eracleous M., 1999, ApJ 523, 197
Kaaret P., Cusumano G., Sacco B., 2000, ApJ, accepted
Kaspi V.M., Tavani M., Nagase F., et al., 1995, ApJ 453, 424
Leahy D.A., Harrrison F.A., Yoshida A., 1997, ApJ 475, 823
Merck M., Bertsch D.L., Dingus B.L., et al., 1996, A&AS 120, 465
McLaughlin M., Cordes J., 2000, ApJ 538, (in press)
Nicastro L., Dal Fiume D., Orlandini M., et al., 1998, Nucl. Phys. B 69/1-3, 257
Tavani M., Arons J., 1997, ApJ 477, 439
Taylor J.H., Cordes J.M., 1993, ApJ 411, 67
Windhorst R.A., van Heerde G.M., Katgert P., 1984, A&AS 58, 1