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Letter to the Editor

Discovery of the transient X-ray pulsar SAX J2103.5+4545

F. Hulleman, J.J.M. in ’t Zand, and J. Heise

Space Research Organization Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

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Abstract. We report the discovery of the X-ray transient SAX J2103.5+4545 which was active from February to September 1997. The observed peak intensity of 20 mCrab (2 to 25 keV) occurred on April 11. An analysis of data obtained around the time of the peak revealed a pulsed signal with a period of 358.61 ± 0.03 s on MJD 50569. The pulse profile has a pulsed fraction of ~ 40%. No change in the pulse period was detected, with an upper limit of 6 s yr^{-1}. The energy spectrum complies to a power law function with a photon index of 1.27 ± 0.14 and low-energy absorption equivalent to a hydrogen column density of $(3.1 \pm 1.4) \times 10^{22}$ atoms cm^{-2} of cold gas of cosmic abundances. In analogy to other X-ray pulsars with similar characteristics we propose this object to be a neutron star in close orbit around a mass-losing star of early spectral type. The B star HD 200709 is a marginal candidate optical counterpart.

Key words: binaries: close – stars: individual: HD 200709 – pulsars: individual: SAX J2103.5+4545 – X-rays: stars

1. Introduction

Currently, about 50 accretion-powered X-ray pulsars are known (e.g., Bildsten et al. 1997, Van Paradijs 1995). The majority of these are located in binary systems (a few cases are thought to accrete from molecular clouds, e.g., Corbet et al. 1995). If optically identified, the companion is usually a high-mass star. In these cases half are giant or supergiant stars and half are Oe or Be type stars. Interestingly, the subset of those that are X-ray transient all have Oe or Be type companions. This testifies in favor of the notion that such stars loose matter in an irregular fashion (e.g., van den Heuvel & Rappaport 1987).

From the typical intrinsic luminosities and distances of X-ray pulsars, it is expected that a relatively large population of faint (i.e., fainter than 10^{-9} erg cm^{-2}s^{-1}) X-ray pulsars exists in our galaxy. In fact, due to successful observations with *Ginga*, the Rossi X-ray Timing Explorer and *Asca* this has been confirmed (e.g., Kinugasa et al. 1998, Koyama et al. 1990, Marsden et al. 1998). Furthermore, Koyama et al. (1990) observed a concentration of X-ray pulsars in the Scutum arm, very likely associated with a region of recent star formation.

Send offprint requests to: J.J.M. in ’t Zand

We report the discovery of another faint transient X-ray pulsar using data accumulated by the Wide Field Cameras on board the BeppoSAX satellite. We present the observations and detection in Sect. 2, the analysis of the pulsar signal in Sect. 3, and the energy spectrum in Sect. 4. We discuss the implications of the details of the measurements for the nature of the source in Sect. 5.

2. Observations, detection and time profile

The observations were performed with the Wide Field Camera (WFC) instrument (Jager et al. 1997). This instrument consists of two coded aperture cameras that point in opposite directions at the X-ray sky. They are located on the BeppoSAX X-ray satellite (e.g., Boella et al. 1997) which is in operation since April 1996. Each camera is equipped with a multi-wire proportional xenon counter with a bandpass of 2 to 25 keV. The field of view is 40 by 40 square degrees (3.7% of the sky). The angular resolution is 5′, the accuracy to position a point source is 2 to 3 times better than that.

About 90% of the observations with WFC are carried out in secondary mode. In this mode, observations with the narrow-field instruments on BeppoSAX dictate the orientation of the satellite and, thus, the pointing direction of the WFC. The Cygnus field is frequently covered by secondary mode observations. During the first 1.5 yr of the mission the WFCs were exposed to it during 90 days, with a fairly uniform time coverage. The total effective exposure time (i.e., when the Earth is outside the field of view) is $\sim 2 \times 10^6$ s.

During April 1997, a faint (i.e., for WFC standards) transient was detected in secondary mode observations of the Cygnus field, 7.4 degrees from the bright X-ray source Cyg X-3. The error box of this transient is presented in Fig. 1. A search of this box with the Simbad database gave a negative result on an identification with any cataloged X-ray source within 20′from the best fit position. We conclude that this is a previously unknown X-ray transient. The best fit position is R.A. = $21^{\rm h}\ 03^{\rm m}\ 33^{\rm s}$, Decl. = +45°45.′0 (Eq. 2000.0). We designate the source SAX J2103.5+4545. The source is close to the Galactic plane, at $b^{\rm II} = -0.64°$. A search for catalogued optical counterparts revealed a candidate at 2.6′from the best fit position. Although it is just outside the error box, we regard

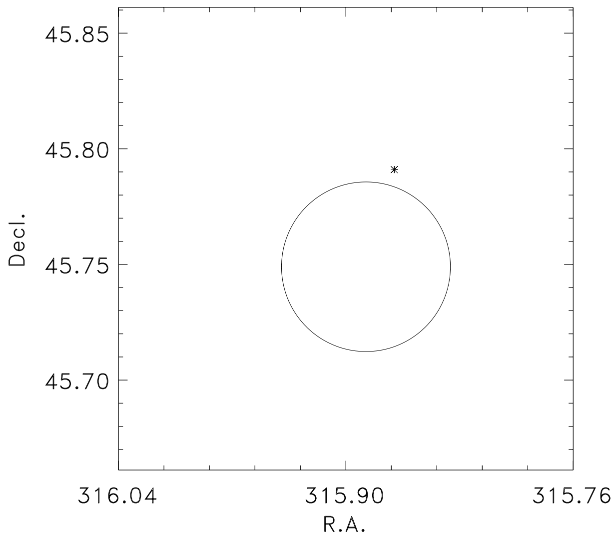

Fig. 1. Error box of SAX J2103.5+4545 at 99% confidence level, based on 2 to 10 keV data from two observation periods. Systematic and statistical sources of error are taken into account, the systematic errors dominate. The asterix points to HD 200709.

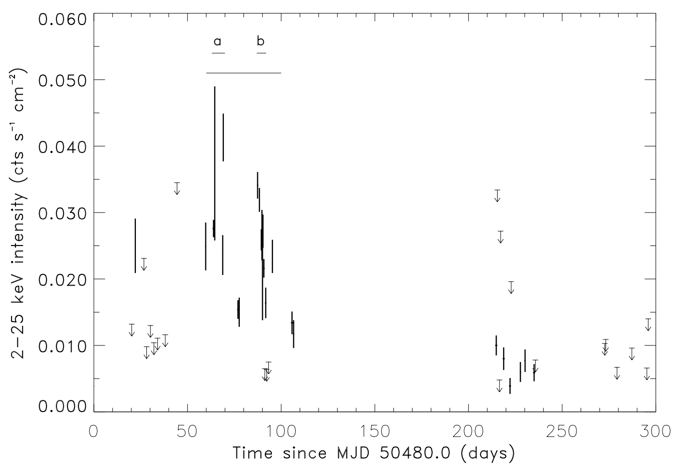

Fig. 2. Time profile of SAX J2103.5+4545. The starting point of the time axis is February 1st, 1997. The thick vertical lines indicate the error bars on intensity for detections, the thin arrows indicate 3σ upper limits. The time resolution is that of one observation period. This varies between 5 min and 1.15 days. The changing sensitivity is caused by changing off-axis angles for the source. 0.01 cts $s^{-1}cm^{-2}$ is 5 mCrab in 2 to 25 keV. The long horizontal line indicates the times for which a timing and spectral analysis was performed (see Sects. 3 and 4).

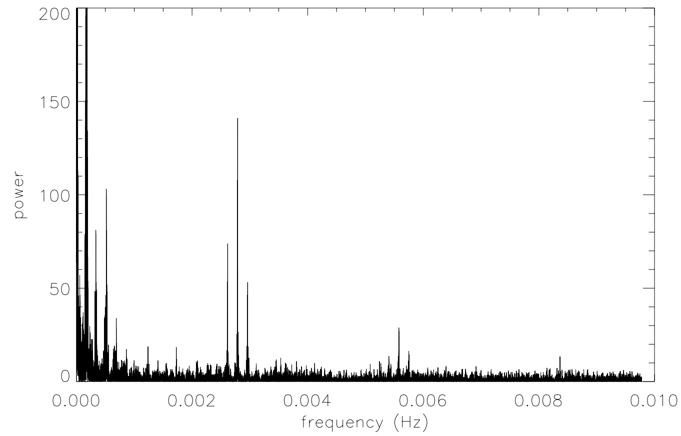

Fig. 3. Power spectrum of SAX J2103.5+4545.

it initially as a candidate to be considered. It is HD 200709, a B8V star with $m_{\rm v} = 9.21$ (Bouigue 1959).

Fig. 2 presents a time history of the intensity of SAX J2103.5+4545. The source was active for almost 8 months, from February to September 1997. No other detections occurred in the complete data set from June 1996 to March 1998. The observed peak intensity was about 0.04 cts $s^{-1}cm^{-2}$ which equals about 20 mCrab (2 to 25 keV). There is considerable variability on time scales of hours and days which is exemplified around MJD 50570 when 3σ upper limit follow detections that are a factor 3 as high. No X-ray bursts were detected.

3. Period determination and pulse shape

A time series was constructed of the intensity of SAX J2103.5+4545 in the full bandpass during MJD 50540 through 50571 with a time resolution of 1 s. The times were corrected for the Earth motion in the solar system to arrival times at the solar system barycenter. No correction was applied for the satellite motion around the earth, this results in a maximum error of these times of 0.04 s which is not important to the results. A fast Fourier transform of the time series resulted in the power spectrum as shown in Fig. 3. The spectrum shows an unambiguous peak at 2.7883×10^{-3} Hz with side lobes due to the beat with the Earth occultations each satellite orbit. A second and a third harmonic are visible. The peaks to the left are at the (higher harmonics of the) satellite orbital period.

To check whether the peak in the power spectrum could be an unforeseen instrumental effect we calculated the power spectra for the other 3 X-ray sources in the field of view (Cyg X-1, X-2 and X-3) as well as for the background. None of these spectra revealed a peak at the same frequency as observed in the power spectrum of SAX J2103.5+4545.

The statistical quality of the data does not permit detailed timing analyses, for instance to search for Doppler delays in pulse arrival times due to likely binary orbital motion. We attempted the roughest form of a timing analysis by dividing the best data in two parts and checking whether a pulse period change could be measured. The first part applies to all good-quality data between MJD 50543 and MJD 50549. This data set encompasses the time of observed peak intensity and is marked ‘a’ in Fig. 2. The second set lies between MJD 50567 and MJD 50571, and contains the times of a second peak in the time profile. It is marked ‘b’ in Fig. 2. For each time series the period was obtained using an epoch folding technique (Leahy et al. 1983). Each time series was folded into a periodogram with 10 phase bins for 128 trial periods in steps of 0.01 seconds around 358.64 s, the peak period from the power spec-

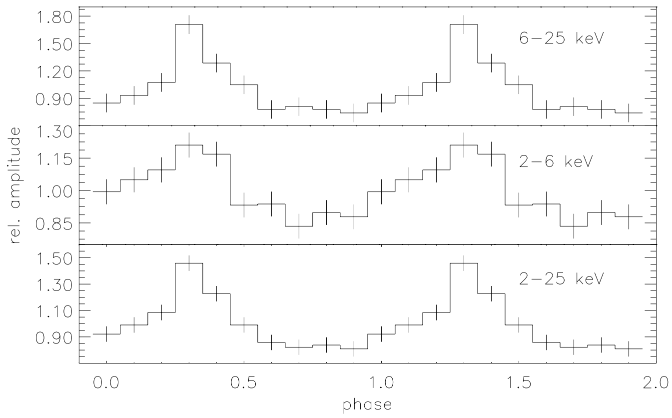

Fig. 4. Pulse profile for MJD 50567 through MJD 50571

trum (Fig. 3). For the first time series the periodogram shows two main peaks at 358.67 and 358.95 s with smaller peaks to the sides. We therefore estimate the period to be 358.81 ± 0.14 s. For the second time series the periodogram shows only one pronounced peak at 358.61 s. The accuracy of the period of this peak was determined through Monte Carlo simulations. The pulse profile was modeled by a triangular function with a base width of 30% duty cycle, in good visual agreement with the observed profiles (lower panel in Fig. 4). The time series was simulated and a periodogram generated 1000 times, each time with a different random generator seed value for the time series generation. In each case the period was determined by that of the highest peak in the periodogram. The root mean square of all 1000 periods thus determined prescribes our estimate of the 1σ error in the period. It is 0.03 s for the second data set. The observed change in period is thus 0.20 ± 0.14 s, which is not a significant value. We regard the difference between the maximum possible period in interval 'a' (358.95 s) and the period minus 1σ of interval 'b' (358.58) as the upper limit in the period change. It is 0.37 s over 23 days, or 6 s over 1 yr.

Fig. 4 shows the folded light curve for the second set 'b' in two separate bandpasses, as well as the total bandpass. The amplitude is relative to the average intensity. The pulsed fraction increases with energy, from $\sim 30\%$ at 2–6 keV to $\sim 50\%$ at 6–25 keV. In the total bandpass it is ~ 40%. The pulsed fraction is lower in the first set, and averaged over both sets it is $\sim$ 30% in the total bandpass. We conclude that there is substantial variability in the pulsed fraction, although we are not able to measure this in detail.

4. Spectrum

The source is quite weak from the perspective of WFC sensitivity and the capability to perform a spectral analysis is limited. We fitted a power law spectrum with absorption by cold interstellar material of cosmic abundances (according to the model of Morrison & McCammon 1983). This was done simultaneously to the data of the seven observations with the highest signal-to-noise ratio, leaving free per period only the normalization. Only data between 2 and 10 keV were used because the detector response at the remaining energies is not yet fully calibrated. The photon index is 1.27 ± 0.14 and $N_{\rm H} = (3.1 \pm 1.4) \times 10^{22}$ cm^{-2} (single parameter 1σ errors), the reduced χ^2 is 1.07 for 124 degrees of freedom. A thermal bremsstrahlung spectrum gives an equally good fit but the temperature is above the WFC bandpass. Both models imply an unabsorbed peak intensity of 8.8×10^{-10} erg s^{-1}cm^{-2} in 2 to 25 keV. The value of $N_{\rm H}$ is about 4 times as high as the Galactic value predicted by interpolation of maps by Dickey & Lockman (1990) which suggests circumstellar material in the line of sight. However, the statistical significance of this is very limited given the large error on $N_{\rm H}$.

5. Discussion

The transient nature of the source and the photon energies involved strongly suggest that SAX J2103.5+4545 is an accreting compact object in a binary system. The pulsations indicate a substantial magnetic field strength and, thus, suggest that the compact object is a neutron star or white dwarf. Since there is no firm distance estimate for the source (see below), it is not possible to constrain the luminosity to be able to discriminate between the neutron star and white dwarf nature. Still there are two other characteristics which hint at the nature of the compact object in SAX J2103.5+4545. First, although the pulsar signatures of white dwarfs in intermediate polars (IPs) are quite similar to those of accreting neutron stars in X-ray binaries when one looks at pulse period, pulsed fraction and pulse duty cycle (e.g., Norton & Watson 1989), the pulsed fraction of IPs, if measured, always increases to lower photon energies. This is opposite to what we see in SAX J2103.5+4545. Second, the Galactic latitude of SAX J2103.5+4545 is small which is consistent with the distribution of HMXB pulsars along the plane, in contrast with IPs which are distributed homogeneously across the sky (being relatively nearby). If SAX J2103.5+4545 belongs to the HMXB pulsar group, its transient nature places it in the subgroup of HMXBs with Oe or Be companion stars.

A young object like an early B type star is nearly always found close to its birthplace. In the line of sight of SAX J2103.5+4545 three potential places of recent star formation are within our galaxy: the OB association Cyg OB7 at approximately 700 pc (Dame & Thaddeus 1985), the Perseus arm at approximately 4 kpc (e.g., Vogt & Moffat 1975, Georgelin & Georgelin 1976) and the HI Cygnus arm at about 11 kpc (Kulkarni, Blitz & Heiles 1982). A peak flux of 8.8×10^{-10} erg cm^{-2}s^{-1} implies respective luminosities of 5×10^{34}, 1.7×10^{36} and 1.3×10^{37} erg s^{-1} for these three locations. All of these values are consistent with the Be X-ray binary interpretation of SAX J2103.5+4545.

An optical identification is suggested by the apparent proximity to HD 200709. For a main sequence B8 star, the absolute visual magnitude $M_{\rm V}$ is 0.0 (Allen 1973). Regardless of extinction, an apparent visual magnitude of $m_{\rm V} = 9.21$ implies an upper limit to the distance of 7×10^2 pc. This distance appears to be consistent with a membership of HD 200709 to Cyg OB7 although it has not been recognized as such yet. HD 200709 is not a very good candidate counterpart for two reasons: the positional coincidence is marginal and it is not recognized as an emission type star as is common for transient HMXBs, although it should be noted that the spectral classification appears to be based on multiband photometry only (Bouigue 1959).

Corbet (1986) discovered a relationship for Be X-ray binaries between pulse period and orbital period. For a pulse period of 358.61 s this implies an orbital period of ∼190 d. No evidence was found for a modulation in the X-ray emission with this period in the WFC data.

The pulse period gives a lower limit to the luminosity through the propeller effect (e.g., Illarionov & Sunyaev 1975). If the Alfvén radius is larger than the co-rotation radius (this is the location where the Keplerian period is equal to that of the neutron star), infalling matter is prevented from entering the magnetosphere because of centrifugal forces, and accretion through the magnetosphere onto the neutron star poles is impossible. In the case of spherical accretion the lower limit to the luminosity becomes: $L_{\rm min} = 4 \times 10^{37} B_{12}^2 P^{-7/3}$ erg s^{-1} (Campana et al. 1998) where P is the spin period in s and B_{12} the neutron star magnetic field in units of 10^{12} G. Standard neutron star values are assumed here for radius (10^6 cm) and mass (1.4 $M_\odot$). For a magnetic field of $B = 10^{12}$ G and a period of 358.61 s this gives $L_{\rm min} = 5 \times 10^{31}$ erg s^{-1}. This is not very constraining, due to the long pulse period.

To determine whether the measured upper limit on the pulse period derivative is meaningful, we calculated what maximum derivative is expected when the accreted matter deposits all of its angular momentum at the magnetospheric boundary and the magnetic field lines transport this momentum to the neutron star. Using the expression for the Alfvén radius by Ghosh & Lamb (1991) for spherical accretion and assuming standard values for the neutron star magnetic field, mass, moment of inertia (10^{45} g cm^2), and radius, the spin period derivative is given by $\mathrm{d}P/\mathrm{d}t = 4.1 \times 10^{-44} L^{6/7} P^2$. For the three luminosities given above, this derivative indicates a period change over 23 days of $|\Delta P| = 0.006$, 0.1 and 0.8 s. The last possibility is excluded by our observations which means that either the source is not at that distance or the change of angular momentum is not as high. We conclude that our upper limit for the period derivative is not constraining.

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