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LETTER

Letter to the Editor

Discovery of the X-ray transient SAX J1808.4-3658, a likely low-mass X-ray binary

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Abstract. We report the discovery of a fairly bright transient during observations with the Wide Field Cameras on board the BeppoSAX satellite in September 1996. It was detected at a peak intensity of 0.1 Crab (2 to 10 keV) and lasted between 6 and 40 days above a detection threshold of 2 mCrab. Two very bright type I X-ray bursts were detected from this transient in the same observations. These almost certainly identify this X-ray transient as a low-mass X-ray binary with a neutron star as compact component. The double-peaked time history of both bursts at high energies suggests a peak luminosity close to the Eddington limit. Assuming this to be true implies a distance to this object of 4 kpc.

Key words: stars: neutron, SAX J1808.4-3658 – X-rays: bursts

1. Introduction

Currently a program is carried out to regularly monitor the galactic bulge in 2 to 25 keV X-rays with the Wide Field Cameras (WFC) on board the BeppoSAX satellite. The main purpose of this program is to monitor relatively weak and short transient activity from various types of sources, in particular low-mass X-ray binaries (LMXBs). According to a recent count (Van Paradijs 1995), near to 30% of all ~130 known LMXBs are transient in nature. This population is concentrated in the sky towards the direction of the galactic center (e.g., Van Paradijs & White 1995, White & Van Paradijs 1996).

We here present the discovery of a relatively bright transient during observations in September 1996, which exhibited X-ray bursts, and discuss its timing and spectral behavior in X-rays. In Sect. 2, we discuss the observations, in Sect. 3 the detection and position of the transient, in Sect. 4 trends in the intensity and spectrum, in Sect. 5 the two bright X-ray bursts that were detected and in Sect. 6 we evaluate the data.

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Table 1. Main characteristics per BeppoSAX-WFC camera

Field of view	$40^o \times 40^o$ full width to zero response (3.7% of entire sky)
Angular resolution	5 arcmin
Source loc. accuracy	>0.6 arcmin (68% conf. level)
Detector technology	Multi-wire prop. Xenon counter
Photon energy range	2 to 25 keV
Energy resolution	18% at 6 keV
Time resolution	0.5 ms

2. Observations

The WFC instrument (Jager et al. 1997) comprises 2 identically designed coded aperture cameras on the BeppoSAX satellite (Boella et al. 1997) which was launched in April 1996. The main characteristics per camera are presented in Table 1. The field of view (FOV) of this instrument is the largest of any flown X-ray imaging device. The moderate angular resolution of 5 arcmin (full-width at half maximum) does not pose severe problems with regards to source confusion for the sensitivity of this instrument, even in the galactic bulge field. There are only few X-ray sources persistently brighter than 10 mCrabs (2 to 10 keV) or $\sim 2\ 10^{-10}$ erg s^{-1} cm^{-2} which are closer than 5 arcmin to the nearest such neighbor.

In the context of sensitivity it is important to note that an imaging device based on the coded aperture principle has one very basic difference with direct-imaging devices such as X-ray mirror telescopes: there is cross-talk between FOV positions that are well beyond one angular resolution distance. For the WFC, this degrades the sensitivity to any sky position within 20^o from a bright X-ray source. This has a relatively large impact on observations of the crowded galactic bulge field where the

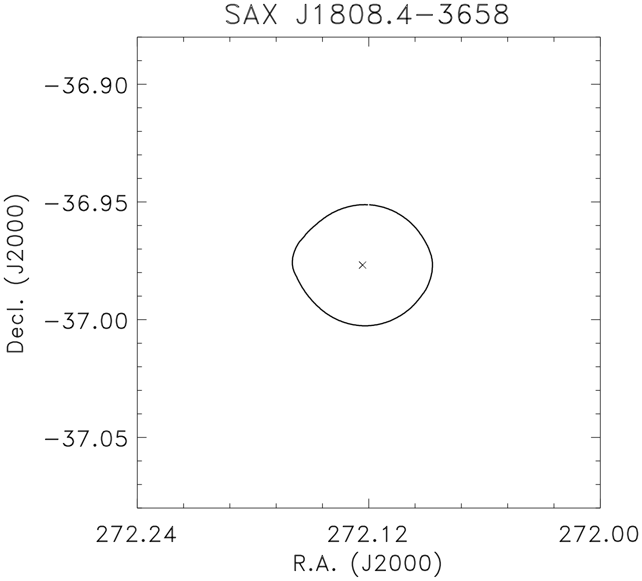

Fig. 1. Error box of steady emission (99% confidence level). The cross indicates the best fit position

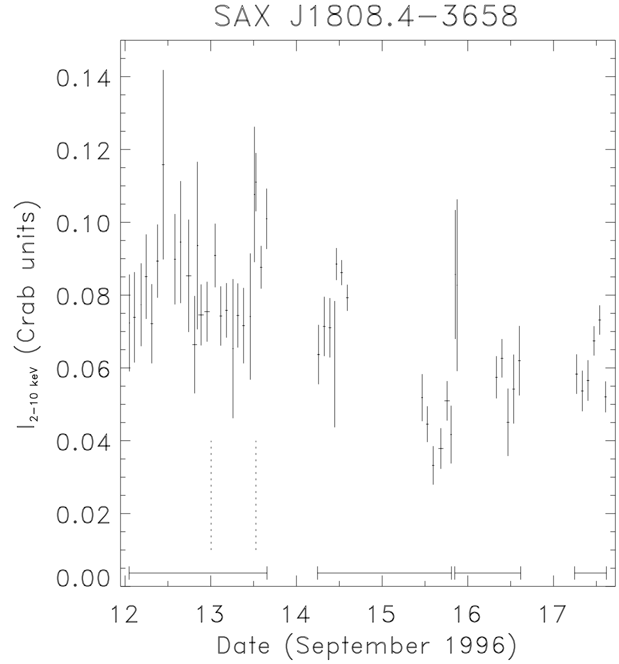

Fig. 2. Light curve of SAX J1808.4-3658between 2 and 10 keV. The horizontal bars indicate the time intervals used in the spectral modeling (see Sect. 4), the vertical dashed lines indicate the times of two X-ray bursts (see Sect. 5)

sensitivity is about two times less than at high galactic latitudes and far from bright sources.

The point source sky position accuracy of the instrument is an order of magnitude better than the angular resolution. It is limited by systematic errors. In-flight calibration (In 't Zand et al. 1997) determined that the systematics are near-Gaussian distributed with a 68% confidence error circle radius of 0.6 arcmin.

The galactic bulge was, during 1996, targeted for 22 days in August, September and October. The total exposure time of these observations is about 7×10^5 s. The source reported in this paper is 9.1 degrees from the galactic center, well within the field of view of BeppoSAX-WFC. Therefore, the coverage of the source is near to complete within this data set.

3. Detection and position

The transient was detected during the observations on September 12 through 17, 1996, for a total exposure time of 1.3 10^5 s. Fig. 1 shows the error box of the source. This was determined from 0.15 d worth of data with high statistical quality. The best fit position is

R.A. = 18h 08m 29s, Decl. = -36° 58$'$.6 (J2000.0).

A check against X-ray catalogs in the Simbad database revealed no known X-ray source in this error box or, for that matter, within 5 arcmin from the best fit position. We designate the source as SAX J1808.4-3658.

The source was not detected during the previous observation of the same sky field, 13 days before September 12. For the complete observation run between August 21 and 30, 1996, the 3σ upper limit on the intensity is 1.5 mCrab (2 to 10 keV). Also, SAX J1808.4-3658 was not detected during the following observation between October 10 and 12, 1996, for which the

Table 2. Results of spectral modeling of steady emission

Model[a]	Model parameter	$N_{\rm H}$ (10^{22} cm^{-2})	$\chi^2_{\rm r}$
PL	Γ = 2.17 ± 0.04	< 1.1	0.95
BR	kT = 7.4 ± 0.4 keV	< 0.9	1.00
PL	Γ = 1.99 ± 0.08	< 1.2	0.88
	2.06 ± 0.07		
	2.36 ± 0.16		
	2.35 ± 0.09		
BR	kT = 9.4 ± 1.1 keV	< 1.1	0.90
	8.5 ± 0.9		
	6.2 ± 1.0		
	6.0 ± 0.6		

[a]PL = power law spectrum (i.e., flux in phot s^{-1}cm^{-2}keV^{-1} is proportional to $E^{-\Gamma}$ where E is the photon energy), BR = Thermal bremsstrahlung spectrum

3σ upper limit is 2.0 mCrab. Therefore, we conclude that the transient was active between 6 and 40 days.

4. Light curve and spectrum

In Fig. 2 the light curve of the source is plotted in bins equal to one BeppoSAX orbit ($\sim$ 103 min) which is the highest time resolution the statistical quality of the data permits. The peak intensity is equivalent to about 0.1 Crab between 2 and 10 keV, on a 1 day time scale this is about 0.08 Crab. There appears to be a declining trend by about a factor of 1.5 over 5.5 days. If this trend would follow an exponential decay (like in many LMXB

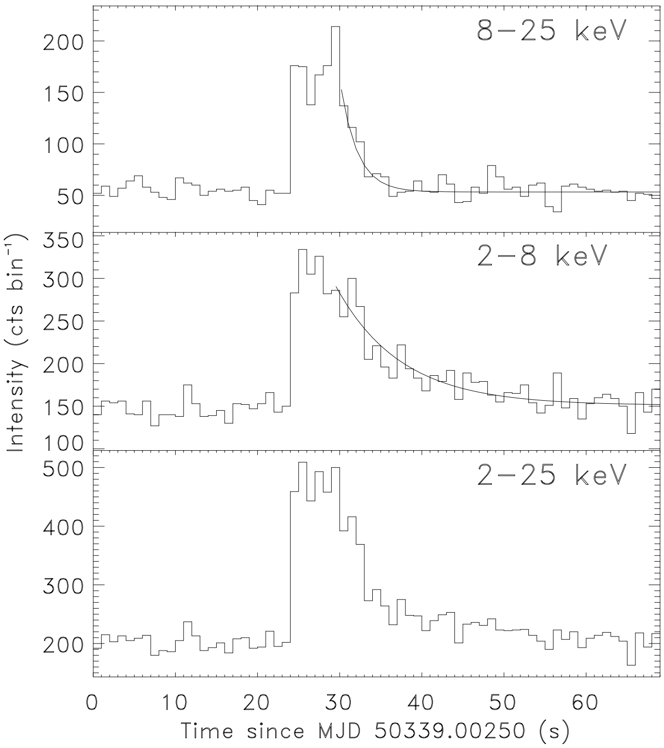

Fig. 3. Time profile of the first burst, per each of two bandpasses and for the complete WFC bandpass. The bin time is 1 s. The smooth curves are exponential models for the appropriate time profiles (see text)

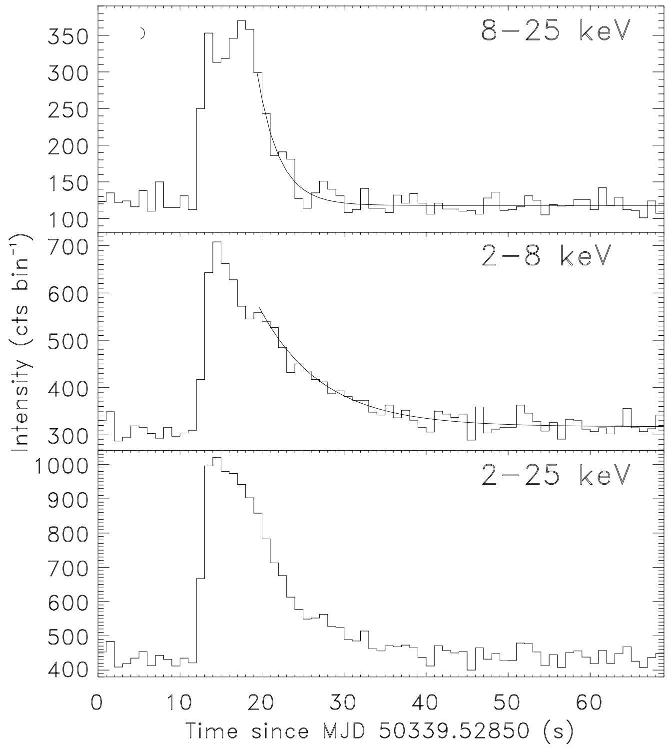

Fig. 4. Time profile of second burst from SAX J1808.4-3658

Table 3. Characteristics of two bursts

Parameter	Burst 1	Burst 2
Start time (MJD)	50339.00278	50339.52864
Instrument	WFC2	WFC2
Peak intensity (Crab, 2-8 keV)	3.8 ± 0.2	3.5 ± 0.1
Decay time τ (s, 2-8 keV)	7.8 ± 1.2	7.5 ± 0.8
Decay time τ (s, 8-25 keV)	2.1 ± 0.3	2.6 ± 0.3
BB color temperature 0-7 s (keV)	2.8 ± 0.2	2.2 ± 0.1
BB color temperature 7-14 s (keV)	–	1.7 ± 0.08

transients, see Chen, Shrader & Livio 1997, but not verifiable for this transient) the 1/e decay time would be 14 d. If the brightness of the transient would indeed have followed such an exponential decay we can estimate what the maximum intensity could have been assuming the transient peaked immediately after the previous observation on August 30 when it was not detected: 0.2 Crab units in 2 to 10 keV.

Spectra were accumulated for each of 16 observation periods in 18 channels between 3 and 10 keV (this restriction was imposed by the current status of the spectral calibration of the instrument). The spectra were fitted with two single-component models. Table 2 presents the results. The first part of the table presents the results leaving free per observation period only the normalization (267 degrees of freedom), the second part does so leaving free the index parameter (power law photon index or temperature kT) over four different time intervals (264 d.o.f.). The four intervals are indicated in Fig. 2. In all cases the hydrogen column density of cold interstellar matter $N_{\rm H}$ (applying the absorption model by Morrison & McCammon 1983) is a single free parameter and identical over all times. Three conclusions can be drawn from these results: the spectral data does not favor either model, spectral softening is occurring over the 5.5 d of observation, and $N_{\rm H}$ may be as high as about $\sim 10^{22}$ cm^{-2}.

5. X-ray bursts

Two very bright bursts were detected from this source, the time histories in 2 energy bands (2 to 8 and 8 to 25 keV) are given in Figs. 3 and 4, and some characteristics are listed in Table 3. The time histories are of all counts in the subsection of the detector illuminated by SAX J1808.4-3658. Both bursts appear quite similar. They have identical durations and similar peak intensities. Also, both bursts have the same kind of double-peak behavior particularly at high energies.

Exponential functional forms have been fitted to the time histories of both bursts in each of the two bandpasses and well after the double-peaked period, leaving free the peak intensity, decay time and background level. The results have been drawn in Figs. 3 and 4. The 1/e decay times τ thus found (see Table 3) clearly demonstrate a softening whose evolution is identical for both bursts.

The spectrum of the first 7 s of both bursts could be satisfactorily fitted with a black body model spectrum with a color temperature as indicated in Table 3. The same applies to the second interval of 7 s of the second burst (the statistical quality of the data does not permit an accurate spectral modeling of this interval for the first burst). A black body spectrum gives, when assuming isotropic emission, a direct relationship between the average radius of the emitting sphere $R_{\rm km}$ (in units of km) and the distance $d_{10\ \rm kpc}$ (in units of 10 kpc). All three spectral fits are consistent with $R_{\rm km}/d_{10\ \rm kpc}$ = 19 $\pm$ 5. This number still needs to be corrected for gravitational redshift and for the conversion of color temperature to true black body temperature. These corrections, which counteract each other and are anticipated not to exceed a factor of 2, will be dealt with elsewhere.

6. Discussion

Of the two types of X-ray bursts found in many X-ray binaries (see review by Lewin, Van Paradijs & Taam 1995), type I bursts are attributed to thermonuclear flashes on or near a neutron star surface. Detection of type I bursts is, therefore, a strong indicator for a neutron star. One diagnostic clearly distinguishes type I from the other type of bursts: only type I bursts exhibit spectral softening. A further characteristic of type I bursts is that they have black body spectra with temperatures up to a few keV. Thus, we can identify the two bursts reported here as type I bursts and conclude that there is strong evidence for the neutron star nature of this X-ray source.

Type I X-ray bursts have been seen from 42 galactic X-ray binaries according to Van Paradijs (1995). Although not all of them have confirmed optical counterparts, those 19 that do are all LMXBs. All 42 bursters have been classified as LMXBs, directly through the identification of the optical counterpart or indirectly through characteristics of the X-ray emission or association with a globular cluster. It is, therefore, almost certain that SAX J1808.4-3658 too is a LMXB with an as yet unidentified optical counterpart.

The double-peaked nature of both bursts at high energies is indicative of near-Eddington luminosities (e.g., Lewin et al. 1995). This is supported by the black body temperatures which are similar to the (likewise high) values obtained for other bursts that reach the Eddington limit (e.g., Lewin at al. 1995). If interpreted as such, an estimate can be obtained of the distance. Assuming a 1.4 $M_\odot$ neutron star with an Eddington limit of 2 10^{38} erg s^{-1} and an observed peak bolometric flux of (1.3 $\pm$ 0.3) 10^{-7} erg s^{-1}cm^{-2}, the distance is 4 kpc. The galactic latitude of -8.1° makes a distance closer than the galactic center (8.5 kpc) indeed likely. Such a close distance suggests a reasonable perspective to find an optical counterpart and we urge optical observers to follow up on the position here published. The observed peak flux of the steady emission is about 2 10^{-9} erg s^{-1}cm^{-2} in 2 to 10 keV which for the power law spectrum extrapolates to a 0.4 to 10 keV luminosity of (6 $\pm$ 2) 10^{36} erg s^{-1} and for the thermal bremsstrahlung spectrum to (5 $\pm$ 1) 10^{36} erg s^{-1}. The uncertainty in these numbers is due to that in $N_{\rm H}$, a distance of 4 kpc is assumed. The 0.4 to 10 keV peak luminosity is somewhat low though not unheard of within the group of LMXB transients (e.g., Chen et al. 1997). The distance of 4 kpc implies a burst emitting sphere radius of 8 km. This supports the neutron star identification.

It is interesting to note that SAX J1808.4-3658 was not initially reported from data obtained with the all-sky monitor on board the Rossi X-ray Timing Explorer. The source was probably too near to the sensitivity of this instrument which for sources in uncrowded fields is about 50 mCrabs per dwell (3σ, Levine et al. 1996). The closest bright source is X1822-371 at 3.5 degrees. Therefore, it appears that the source was never much brighter than the peak intensity observed with BeppoSAX-WFC.

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Note added in proof. A recent analysis of the ASM data using the position of the WFC detection reported here has revealed a detection (Remillard 1997, private communication) and confirmed our suspicion that the true peak intensity could not have been much higher than observed with WFC. In fact it was comparable. The transient rose above the ASM detection level for cataloged sources (about 20 mCrab in 2 to 12 keV for one day of observations) on about September 8, 1996, and remained detectable for about 20 days.

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