X-ray and optical-to-infrared follow-up observations of the transient X-ray burster SAX J1810.8–2609

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ABSTRACT

We have performed a *ROSAT* follow-up observation of the X-ray transient SAX J1810.8–2609 on 1998 March 24 and detected a bright X-ray source (named RX J1810.7–2609) which was not detected during the *ROSAT* all-sky survey in September 1990. Optical-to-infrared follow-up observations of the $10''$ radius *ROSAT* HRI X-ray error box revealed one variable object ($R = 19.5 \pm 0.5$ on March 13, $R > 21.5$ on 1998 August 27) which we tentatively propose as the optical/IR counterpart of RX J1810.7–2609 $\equiv$ SAX J1810.8–2609.

Key words: accretion, accretion discs – stars: binaries: general – stars: individual: SAX J1810.8–2609 ($\equiv$ RX J1810.7–2609) – infrared: stars – X-rays: stars.

1 INTRODUCTION

The ~ 50 known X-ray bursters are thought to belong to the class of low-mass X-ray binaries (LMXB), i.e. their companions are thought to be low-mass ($\lesssim 0.5\,M_\odot$) late-type stars with $M_V \gtrsim 0$ (see e.g. Lewin, van Paradijs & Taam 1995). The optical emission is usually dominated by reprocessed X-ray radiation off the accretion disc and the contribution from the secondary is generally negligible. Thus, if the X-ray emission in a LMXB is transient, reprocessing results in a variable optical and IR source.

SAX J1810.8–2609 is a new transient in the Galactic bulge which was discovered with the Wide Field Camera 2 onboard *BeppoSAX* (Ubertini et al. 1998a). The source has been detected on 1998 March 10 UT at a level of 15 mCrab (2–9 keV), at R.A. = $18^h10^m46^s$, Dec. = $-26°09'.1$ (equinox 2000.0; preliminary error radius of $3'$). An X-ray burst of 45 seconds duration was detected from this source on March 11.06634 with a peak intensity of about 1.6 Crab (Ubertini et al. 1998a). A *BeppoSAX* follow-up observation with the narrow-field instruments (NFI) on 1998 March 12 detected the source at a flux level of $1.5 \times 10^{-10}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (corresponding to 7 mCrab) with a power-law spectrum with photon index -2.2 (Ubertini et al. 1998b). The error radius of $1'$ of the originally published NFI position was later corrected to $3'$ (Ubertini et al. , in preparation) because the aspect

solution for that NFI target-of-opportunity observation (TOO) was particularly unfavourable due to the lack of bright stars in the pointing direction (a rather rare aspect control configuration).

Here we report follow-up observations of SAX J1810.8–2609 with the aim of identifying its optical/infrared counterpart: with *ROSAT* in X-rays to improve the position (Greiner et al. 1998); immediate optical/infrared observations to search for fading emission and later some deep imaging to possibly identify the donor.

2 ROSAT OBSERVATIONS

A target-of-opportunity observation with the *ROSAT* HRI was performed on 1998 March 24 of the error box of SAX J1810.8–2609. The total exposure time was 1153 s and obtained within one observation interval (22:14:46–22:33:59 UT). One strong X-ray source was detected at a mean count rate of $0.54 \pm 0.02\,\mathrm{count\,s^{-1}}$. The best-fitting X-ray position is R.A. = $18^h10^m44^s.5$, Dec. = $-26°09'01''$ (equinox 2000.0), with an error radius of $\pm10''$ (comprising a 5σ statistical error of $2''.5$ and a systematic bore sight uncertainty of $8–9''$). This *ROSAT* position is not consistent with the only catalogued source IRAS 18077-2609 as mentioned in Ubertini et al. (1998a; see also Fig. 1).

In view of the original discrepancy between this *ROSAT* HRI

ROSAT HRI
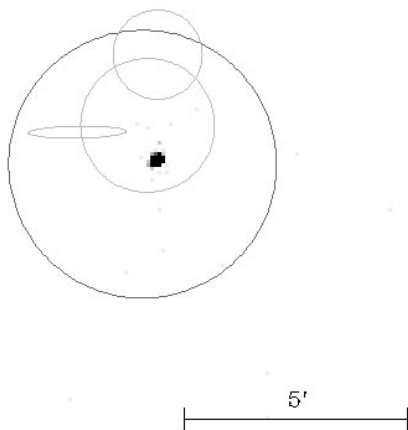**24 Mar 1998**
1.1 ksec

SAX J1810.8−2609

5′

Figure 1. The inner part of the HRI field of view with the strong X-ray source SAX J1810.8−2609 ≡ RX J1810.7−2609. The large, 3′ radius circle which is nearly centred around RX J1810.7−2609 is the *BeppoSAX* W2 error circle (Ubertini et al. 1998a), while the two smaller circles are the original (Ubertini et al. 1998b; top) and updated *BeppoSAX* NFI error circles (Ubertini et al., in preparation; bottom). The ellipse marks the error box of IRAS 18077-2609. North is up and east to the left. No other X-ray sources are detected within 10′ of RX J1810.7−2609.

position and the *BeppoSAX* NFI position the following checks have been performed on the *ROSAT* attitude data (courtesy W. Grimm/GSOC):

(i) the log-file of the attitude computation does not reveal any irregularities;

(ii) the locations of the minimum number of three optical stars was always available;

(iii) the distribution of the residua between expected and measured attitude for each time bin is identical to the mean value of the last 7 years;

(iv) during the observation the attitude wobbles by $\pm 2'$ (as expected) around the mean value of R.A. = 2°.2947 and Dec. = −26°.1503 (equinox 2000.0);

(v) the catalogue positions of the three optical stars used in the attitude determination have been checked against the PPM catalogue and were found to be accurate to $\pm 1''$.

The main conclusion is that the attitude during this *ROSAT* observation of SAX J1810.8−2609 is in no way abnormal as compared to those derived over the last 7 years. The subsequent solution of the *ROSAT*–*BeppoSAX* discrepancy by recognizing a rare aspect control configuration of the *BeppoSAX* satellite during their TOO leads to the conclusion that the bursting and persistent source seen by the *BeppoSAX* satellite and the source RX J1810.7−2609 seen by *ROSAT* are the same source.

The X-ray intensity of RX J1810.7−2609 during the *ROSAT* HRI observation does not vary by more than a factor of 3, and no X-ray burst is detected during the observation. No coherent or quasi-periodic oscillations are found in the 2−200 s range,

Table 1. *ROSAT* observations of the SAX J1810.8−2609 location before and after the recent outburst.

Date	Obs-ID[1]	T_{exp} (s)	offaxis angle	CR[2] (count/s)
1990 Sep. 12–16	− P	230	0-55′	< 0.029
1993 Sep. 10	400396P	2014	52′	< 0.027
1998 Mar. 24	180267H	1153	0.′25	0.54 ± 0.02

[1] The letter gives the *ROSAT* detector identification: P ≡ PSPC, H ≡ HRI.
[2] Count rates are calculated for the 0.1–2.4 keV range (= PSPC channels 11-240). Upper limits are 3σ confidence level.

yielding a 3σ upper limit of the pulsed fraction of 40 per cent. Overall, the X-ray light curve is consistent with a constant source.

The location of SAX J1810.8−2609 was covered by the *ROSAT* all-sky survey in September 1990 for a total of 230 s. No source was detected at that time, yielding a 3σ upper limit of 0.029 PSPC count s^{-1}. In addition, the SAX J1810.8−2609 location is also in the field of view (though very far off-axis) of the pointing 400396 (PI: C. Motch) on 1993 September 10. The roughly 2 ks exposure results in a 3σ upper limit of 0.027 PSPC count s^{-1}. A summary of the relevant numbers is given in Table 1. These non-detections at a sensitivity level of a factor of 20 below the count rate detected during the HRI TOO (note that the HRI is a factor of about 3 less sensitive for hard-spectrum X-ray sources than the PSPC) proves the transient nature of the detected *ROSAT* HRI source RX J1810.7−2609.

Despite its location near the Galactic plane ($b = -3°.5$), the source SAX J1810.8−2609 is located in a direction of relatively low absorbing column: the total Galactic column is $N_H^{gal} = 3.7 \times 10^{21}$ cm^{-2} (Dickey & Lockman 1990) corresponding to $A_V^{gal} = 2.7$ mag (using the relation $A_V = 17/23 \times N_H$ [10^{21} cm^{-2}] from Predehl & Schmitt 1995). Using this absorbing column (together with the Morrison & McCammon 1983 cross-section model) and a power-law model with photon index −2.2 as derived from the *BeppoSAX* NFI pointing (Ubertini et al. 1998b) we find an unabsorbed flux of 1.1×10^{-10} erg cm^{-2} s^{-1} in the *ROSAT* band (0.1–2.4 keV) or correspondingly 3.5×10^{-11} erg cm^{-2} s^{-1} in the 2–10 keV band – i.e., a factor of 4 lower than during the *BeppoSAX* observations on Mar. 10–12, 1998 (Ubertini et al. 1998b). The luminosity during the HRI observation is 1.2×10^{36} $(D/10 \text{ kpc})^2$ erg s^{-1} (0.1–2.4 keV).

3   OPTICAL-TO-INFRARED OBSERVATIONS

Immediately after notification of the SAX J1810.8−2609 transient images in the Bessel B and R and the Gunn-z bands were taken on 1998 Mar. 13 with the Danish 1.5-m telescope (+DFOSC) at ESO's La Silla (Chile) Observatory. Further imaging was obtained with the same instrument on 1998 July 25 and Aug 27–28. The full observing log is displayed in Table 2. The raw frames were processed with standard techniques within the IRAF*environment,

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* IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
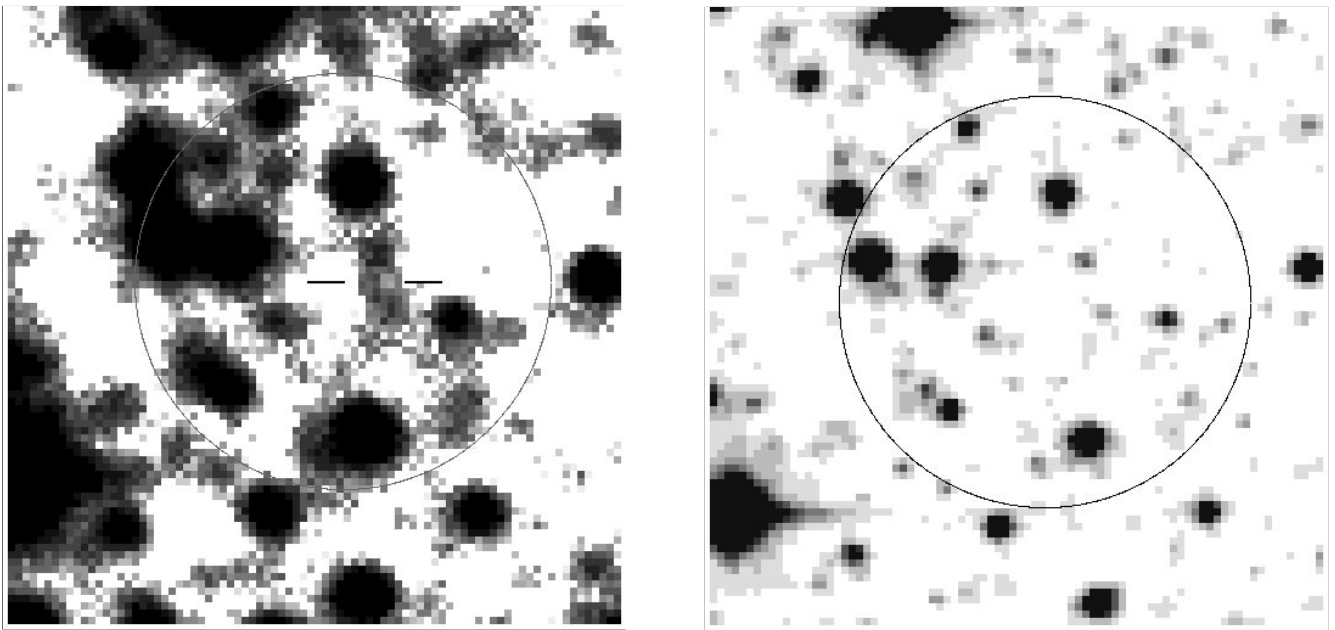
Figure 2. A $40'' \times 40''$ field containing the $10''$ radius X-ray error box overlayed on the Gunn-z band images obtained on 13 March (left) and 28 August 1998 (right). North is up and East to the left. The variable object and tentative counterpart to SAX J1810.8–2609 is marked with two dashes in the left image.

which included bias subtraction and flat-fielding (using flat-field images obtained during twilight). The resultant B, R and Gunn-i band frames were calibrated using T Phe and other stars in the standard field SA 110 (Landolt 1992). SEXTRACTOR (Bertin & Arnouts 1996) was used to obtain the magnitude estimates.

Several objects are seen within the HRI error circle. But a comparison of the March 13 images with those obtained in July/August reveals only one object which is not seen in the deeper images obtained on 1998 Aug 27–28 (Fig. 2; limiting magnitudes are $B > 22.5$ mag, $R > 21.5$ mag, i > 20 mag). Though a direct numerical comparison of the frames taken in March and August, respectively, is hardly possible due to different seeing conditions ($1''.6$ on March 13 and $0''.9$ on August 27) and the non-circular shape of the stellar images, this object is (1) the only new object and (2) seen in three colours. For this new object we measure $B = 21.5 \pm 0.5$ mag and $R = 19.5 \pm 0.5$ mag, and a signal-to-noise ratio of 5 in the R and Gunn-z band images (we have unfortunately no flux calibration for the Gunn-z band image). Its position is R.A. $= 18^h10^m44.^s4$, Dec. $= -26°09'00''$ (equinox 2000.0), with an error radius of $\pm 1''$.

We also obtained service observations at the United Kingdom 3.8-m Infrared Telescope (UKIRT) in Hawaii on 1198 August 14 after the more accurate *ROSAT* position had been determined. J- and K-band frames were acquired using the IRCAM3 infrared camera. IRCAM3 is a near-IR detector ($1-5\,\mu m$) with a 256×256 pixel InSb array. The image scale is $\sim 0''.3$ pixel^{-1} giving a field of view of 73×73 arcsec^2. A 17-arcsec dithering around the *ROSAT* coordinates was performed, thus obtaining five frames ($40\,s$ each in the J-band and $20\,s$ each in the K-band) in order to determine and subtract the background from each of the individual images. The resultant frames were calibrated using the standard star FS27 (Cassali & Hawarden 1992). Fig. 3 shows a blow-up of one of these K-band images together with the identification of various objects (see Table 3). The object described above is not

Table 2. Optical-to-infrared observations of SAX J1810.8–2609.

Date (1998)	UT	Telescope	Filter	T_{exp} (s)
Mar. 13	07:26	1.5-m Danish	Gunn-z	240
Mar. 13	07:30	1.5-m Danish	R	240
Mar. 13	07:39	1.5-m Danish	B	240
Jul. 25	03:01	1.5-m Danish	Gunn-z	300
Aug. 27	00:05	1.5-m Danish	B	240
Aug. 27	00:31	1.5-m Danish	Gunn-i	240
Aug. 27	00:50	1.5-m Danish	R	240
Aug. 28	23:22	1.5-m Danish	Gunn-z	240
Sep. 15	23:05	0.9-m Dutch	B/R/Gunn i	120/60/60
Aug. 14	09:15	3.8-m UKIRT	J	200
Aug. 14	09:30	3.8-m UKIRT	K	100

seen in these images, and limiting magnitudes are $K > 16.5$ mag and $J > 17.5$ mag (August 14).

4 DISCUSSION

Based on (1) the expectation of correlated X-ray/optical variability in LMXBs as described in the introduction, and (2) our finding of only one variable object in the optical/IR bands which moreover has a brightness change in the direction as expected for an LMXB counterpart, we tentatively propose this variable object as the counterpart of the transient X-ray burster SAX J1810.8–2609 $\equiv$ RX J1810.7–2609.

The number density of variable stars at 20th mag is poorly known. Simple scaling from extensive searches for variable stars in the 14–17 mag range suggests about 80 $\square^{-2}$ brighter than 20th mag at low galactic latitudes (e.g. Hudec 1998, Hudec & Wenzel

1996). This implies a chance probability of 2×10^{-3} to find an unrelated variable star inside the $10''$ *ROSAT* HRI error box, thus strengthening our conclusion to have found the counterpart of RX J1810.7–2609.

If we correct our brightness measurements for the total Galactic extinction of $A_V^{gal} = 2.7$ mag, we obtain a colour of $B - R = 0.4$ mag during the 1998 March observation. This is consistent with the expected colour of a disc which is heated by strong reprocessing and thus would have colours similar to a hot star: $B - R \approx -0.1$ mag.

The non-detection of persistent *K*-band emission during 1998 August is also consistent with the expectation for the donor (assuming a quiescent system in which the accretion disc does not dominate the light). With a ratio $A_K/A_V = 0.112$ (Rieke & Lebofsky 1985) the total Galactic *K*-band extinction is $A_K = 0.31$ mag. With a location only 6 degrees away from the Galactic Centre, the distance of SAX J1810.8–2609 is likely of the order of 8 kpc. Indeed, Cocchi et al. (1999)recently estimated a distance of 5 kpc from one particularly bright X-ray burst which showed signatures of photospheric radius expansion. With this distance and using a mean $(V - K)_0 = 1$ mag (Johnson 1966), our *K*-band limi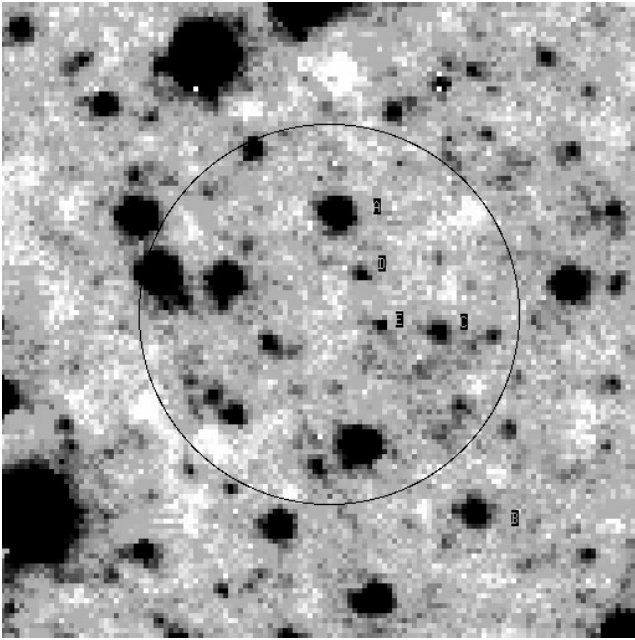ting magnitude of $K > 16.5$ mag implies $M_V > 4.1$ mag, consistent with a late-type main-sequence donor, and similar to other X-ray bursters. With a range of $6 < M_V < 10$ mag for late-type main-sequence donors and intrinsic colours of $2 < (V - K)_0 < 4.5$ mag the expected *K*-band magnitude of the quiescent donor is $K \sim 17.5$–19 mag, thus making even spectroscopy feasible.

The amplitude of $\Delta R \gtrsim 2$ mag between 1998 March and August requires a difference in the X-ray illumination (flux) of about a factor of 100 (according to the relation between X-ray flux and reprocessed visual flux found by van Paradijs & McClintock 1994). Such a factor in flux difference is reasonable to be valid for this transient (though we are not aware of an X-ray observation during 1998 August).

We therefore conclude that the brightness and colours of the proposed counterpart to SAX J1810.8–2609 obtained during two epochs in 1998 are consistent with the expectations for a transient X-ray burst source. Deeper follow-up infrared photometry and further spectroscopy are necessary to validate our tentative identification.

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Figure 3. A 38×38 arcsec^2 field in the *K*-band, as obtained at UKIRT on 1998 August 14. It includes the 10-arcsec radius *ROSAT* X-ray error box for SAX J1810.8–2609. North is up and east to the left. Local standards are marked (Table 3).

Table 3. *BRiJK* magnitudes for local standards in the SAX J1810.8–2609 field.

Star ID	B	R	i	J	K
A	19.06 ± 0.10	16.04 ± 0.06	14.66 ± 0.06	12.93 ± 0.04	11.81 ± 0.04
B	19.64 ± 0.10	16.73 ± 0.10	15.37 ± 0.09	13.50 ± 0.05	12.56 ± 0.05
C	19.46 ± 0.10	16.99 ± 0.08	15.76 ± 0.10	14.17 ± 0.06	13.42 ± 0.07
D	21.10 ± 0.20	18.10 ± 0.15	16.85 ± 0.15	15.30 ± 0.15	–
E	–	18.50 ± 0.20	17.50 ± 0.20	15.30 ± 0.15	14.30 ± 0.10

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