

SAX J1810.8–2609: A NEW HARD X-RAY BURSTING TRANSIENT

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ABSTRACT

The transient X-ray source SAX J1810.8–2609 was discovered on 1998 March 10 with the Wide Field Cameras on board the *BeppoSAX* satellite, while observing the Galactic bulge in the 2–28 keV energy range. On March 11 a strong type I X-ray burst was detected with evidence of photospheric radius expansion. A follow-up target of opportunity observation with the narrow field instruments (NFIs) was performed on March 11 and 12, for a total elapsed time of 8.51×10^4 s. The wide-band spectral data (0.1–200 keV) obtained with the NFIs show a remarkable hard X-ray spectrum detected up to ~ 200 keV, which can be described by a power law with photon spectral index $\Gamma = 1.96 \pm 0.04$, plus a soft component which is compatible with blackbody radiation of temperature $kT \sim 0.5$ keV.

The detection of the type I X-ray burst is a strong indication that the compact object is a neutron star in a low-mass X-ray binary system. Assuming standard burst parameters and attributing the photospheric radius expansion to near-Eddington luminosity, we estimate a distance of ~ 5 kpc. The inferred 2–10 keV X-ray luminosity is $\sim 9 \times 10^{35}$ ergs s⁻¹ at the time of the discovery.

Subject headings: binaries: close — stars: individual (SAX J1810.8–2609) — X-rays: bursts

1. INTRODUCTION

During a long term 2–28 keV monitoring campaign of the Galactic bulge region with the Wide Field Cameras (WFCs) on board the *BeppoSAX* satellite, the new X-ray transient SAX J1810.8–2609 was discovered on 1998 March 10 (Ubertini et al. 1998a). The source showed a weak emission (≈ 15 mcrab) corresponding to an X-ray flux of 3.1×10^{-10} ergs cm⁻² s⁻¹ in the 2–10 keV range and was positioned in quasi-real time with the quick-look analysis (QLA) tools at $\alpha = 18^{\text{h}}10^{\text{m}}46^{\text{s}}$ and $\delta = -26^{\circ}09'1$ (equinox 2000.0) with an error radius of 3'. During the ongoing monitoring, on March 11 a strong type I X-ray burst was observed with a peak intensity of ~ 1.9 crab, from a sky position consistent with that of the persistent emission (Cocchi et al. 1999; Ubertini et al. 1998a). Two days after the source was discovered a follow-up observation was performed with the *BeppoSAX* Narrow Field Instruments (NFIs), showing that the 2–10 keV intensity had declined to ≈ 7.5 mcrab (Ubertini et al. 1998b). On 1998 March 24 the *ROSAT* High Resolution Imager (HRI) observed the error box of SAX J1810.8–2609 for 1153 s (Greiner, Castro-Tirado, & Boller 1998). A low-energy source, named RX J1810.7–2609, was detected at a position consistent with the WFC error box but not with the one obtained by the QLA of the NFI observation (Ubertini et al. 1998b; see, however, further details in § 2.1). The 0.1–2.4 keV flux of RX J1810.7–2609 was ~ 1.5 mcrab, and *ROSAT* did not detect the source in previous observations of the same sky region on 1993 September 10 (0.1–2.4 keV), with a 3σ upper limit of ~ 0.08 mcrab, and in 1990 during the All-Sky Survey, thus confirming the transient nature of the source. Very

recently, Greiner et al. (1999) have reported details of the *ROSAT* HRI target of opportunity (TOO), and of optical to infrared follow-up observations of the 20'' error box of the *ROSAT* HRI source. They tentatively suggested as a counterpart of RX J1810.7–2609 a variable object showing $R = 19.5 \pm 0.5$ on March 13 and $R > 21.5$ on August 27. The *ROSAT* HRI observation showed an unabsorbed flux of $\sim 1.1 \times 10^{-10}$ ergs cm⁻² s⁻¹. If one assumes a Crab-like spectrum, this extrapolates to $\sim 3.5 \times 10^{-11}$ ergs cm⁻² s⁻¹ in the 2–10 keV range, which is a factor of 4 lower than the *BeppoSAX* NFI detection (Ubertini et al. 1998b; Greiner et al. 1999). The variability during the *ROSAT* HRI observation was less than a factor of 3 in the 0.1–2.4 keV region, and no evidence of coherent or quasi-periodic oscillations (QPOs) in the range from 2 to 200 s was found, with a 3σ upper limit on the pulsed fraction of less than 40% (Greiner et al. 1999).

We here report on a detailed analysis of the WFC and NFI observations of SAX J1810.8–2609, and discuss the nature of the compact source in this X-ray transient.

2. OBSERVATIONS AND DATA ANALYSIS

The WFCs (Jager et al. 1997) on board *BeppoSAX* are designed for performing spatially resolved simultaneous measurements of X-ray sources in crowded fields enabling studies of spectral variability at high time resolution. The mcrab sensitivity in 2–28 keV over a 40×40 deg² field of view (FOV) and the near-continuous operation over a period of years offer the unique opportunity to measure continuum emission as well as bursting behavior from many new X-ray transients and already known (weak) transient and persistent sources. For this reason the Galactic bulge is being monitored over 1–2 months during each of the visibility periods since the beginning of the *BeppoSAX* operational life in 1996 July. During those observations, which combine to a total of ~ 3 Ms net exposure time up to 1999 November, more than 900 X-ray bursts and at least 45

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sources have been detected (Bazzano et al. 1997; Cocchi et al. 1998; Heise et al. 1999; Ubertini et al. 1999). The data of the two cameras are systematically searched for bursts or flares by analyzing the time profiles in the 2–10 keV energy range with a 1 s time resolution.

Follow-up observations with the more sensitive, broadband narrow field instruments are often performed each time a new transient source is detected in the WFC field of view. The *BeppoSAX* NFIs comprise an assembly of four imaging instruments: one low-energy and three medium-energy concentrator spectrometers, named LECS and MECS, with 37' and 56' circular FOVs and energy ranges 0.1–10 keV and 1.8–10 keV, respectively (Parmar et al. 1997; Boella et al. 1997). The other two nonimaging coaligned detectors are the High Pressure Gas Scintillation Proportional Counter (HPGSPC), operative in the range 4–120 keV (Manzo et al. 1997) and the Phoswich Detector System (PDS), operative in the range 15–200 keV (Frontera et al. 1997). On 1998 March 12.19 UT a *BeppoSAX* follow-up observation was performed with the NFIs on the WFC error box of the newly discovered source (Ubertini et al. 1998b). The total observation lasted 85.1 ks, corresponding to a net exposure time of 14.4 ks for LECS, 26.8 ks for MECS, 20.0 ks for HPGSPC, and 30.4 ks for PDS. SAX J1810.8–2609 was strongly detected in all instruments, including a high-energy tail extending up to ~ 200 keV and was the only source present in the LECS and MECS images, at an updated position consistent with the WFC error box (see § 2.1). Extraction radii of 8' and 4' have been used for source photons for the LECS and MECS images, respectively, encircling $\sim 95\%$ of the power of the concentrators' point-spread function. These data have been used for spectral analysis and light curve production. All spectra have been rebinned, oversampling the detector spectral resolution, to have at least 20 counts per channel. The bandpasses for spectral analysis were limited to 0.3–3.0 keV for the LECS, 1.6–10.5 keV for the MECS, 4–25 keV for HPGSPC, and 15–200 keV for the PDS, to take advantage of accurate detector calibration. The standard procedure of leaving free the relative normalization parameters of the different instruments within a narrow band was applied, to accommodate cross-calibration uncertainties.

2.1. The Source Position

On March 11.06633 UT a strong burst was observed from SAX J1810.8–2609; this is the only X-ray burst ever observed from the source in all the WFC data since 1996, which amounts to a total net exposure time of ~ 3 Ms. We have improved the source position in the WFC with respect to the one previously reported (Ubertini et al. 1998a) to

$\alpha = 18^{\text{h}}10^{\text{m}}45^{\text{s}}.6$ and $\delta = -26^{\circ}08'48''.5$ (1.1 error radius), by using the burst data, which have a much higher statistical quality than those of the nonburst data (see Table 1). This confirms the association with the *ROSAT* HRI source RX J1810.7–2609. We note that the original inconsistency between the *BeppoSAX* NFIs and *ROSAT* HRI (Greiner et al. 1998; Ubertini et al. 1998b) was due to an error in the aspect solution of *BeppoSAX* that resulted from an unusual attitude configuration. We have therefore refined the position of the source taking into account a new calibration (L. Piro & L. A. Antonelli, private communication). This results in $\alpha = 18^{\text{h}}10^{\text{m}}45^{\text{s}}.5$ and $\delta = -26^{\circ}08'14''$ (equinox 2000.0) with a conservative error radius of 1.5, and is now consistent with that determined by the *ROSAT* HRI. The various error circles are shown in Figure 1.

2.2. The Single X-Ray Burst

A single, strong burst was detected from SAX J1810.8–2609 on 1998 March 11.06634. The event lasted 47 s with an e -folding time of 12.5 ± 0.7 s and showed a peak intensity of 1.9 ± 0.2 crab in the 2–28 keV band (see also Cocchi et al. 1999). The time profiles in two energy bands are shown in Figure 2: a clear double-peaked structure is present at high energy (10–28 keV) suggesting photo-

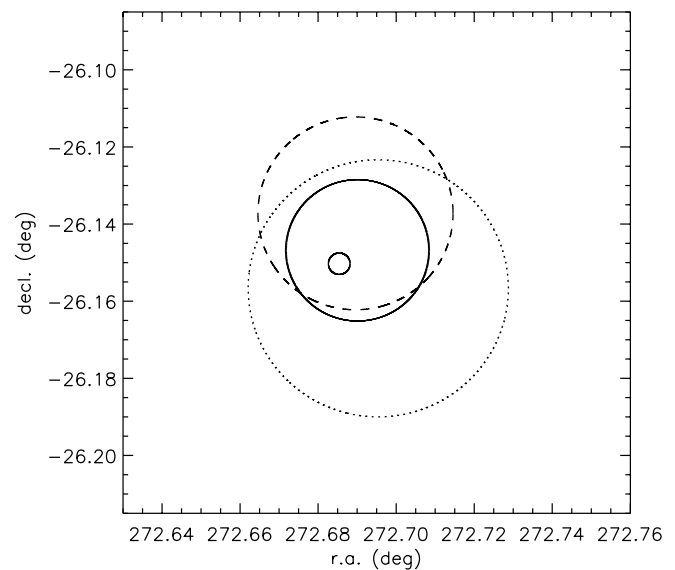


FIG. 1.—Shown are the different source error circles (99% confidence) as derived from the detection of the burst with the *BeppoSAX* WFC (large thick-lined circle), of the persistent emission by the *BeppoSAX* WFCs (dotted line), by the NFIs (broken line) and by the *ROSAT* HRI (small thick-lined circle).

TABLE 1

ALL AVAILABLE SAX J1810.8–2609 OBSERVATIONS, POSITIONS AND ASSOCIATED ERROR BOXES

Detector	Energy (keV)	Observation 1998	R.A.(2000.0)	Decl.(2000.0)	Error Circle (99% Confidence)	References
<i>BeppoSAX</i> WFCs.....	2–28	March 11 ^a	18 10 45.6	–26 08 48.5	1.1	This work; Cocchi et al. 1999
<i>BeppoSAX</i> WFCs.....	2–28	March 10–12 ^{b,c}	18 10 46.9	–26 09 24.0	2.0	This work
<i>BeppoSAX</i> NFIs.....	0.1–200	March 12–13 ^b	18 10 45.5	–26 08 14.0	1.5	This work
<i>ROSAT</i> HRI.....	0.1–2.4	March 24 ^b	18 10 44.5	–26 09 0.1	20''	Greiner et al. 1999

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Burst emission.

^b Persistent emission.

^c Source discovery.

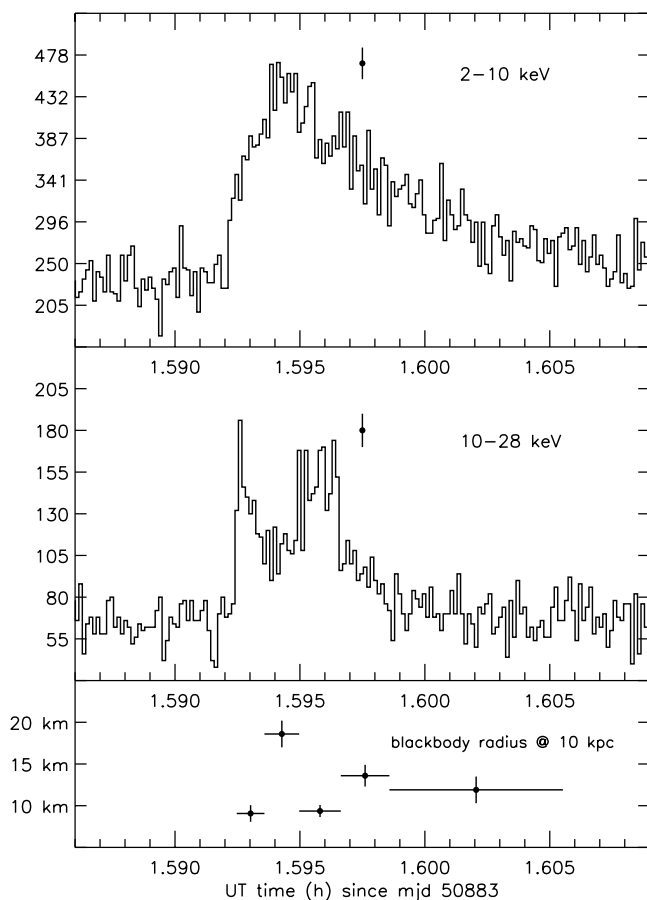


FIG. 2.—Time profile in the low (2–10 keV, *top panel*) and high (10–28 keV, *middle panel*) energy range of the SAX J1810.8–2609 1998 March 11.06634 burst. The time evolution of the blackbody radius, computed for a distance of 10 kpc, is also shown. The actual blackbody radius is a linear function of source distance.

spheric radius expansion (Lewin, van Paradijs, & Taam 1995). The spectrum of the burst obtained by integrating data over the whole burst duration is well represented by a blackbody emission with temperature $kT \simeq 2$ keV. In order to study the time-resolved spectra, we have integrated the burst data in time intervals as shown in the lower panel of Figure 2, more or less corresponding to the peak structures observed in the high-energy profile. Under given assumptions (Lewin, van Paradijs, & Taam 1993) the effective temperature T_{eff} and the bolometric flux of a burst can determine the ratio between the blackbody radius R_{bb} (that is, the radius of the emitting sphere) and the distance d of the neutron star. Assuming $d = 10$ kpc and the observed color temperatures as T_{eff} , and not correcting for gravitational redshift, the data are consistent with a radius expansion of a factor of ~ 2 during the first ~ 10 s of the event. The average blackbody radius, excluding the radius expansion part, is ~ 12 km (see Table 2) at 10 kpc. Also evident is the typical spectral softening due to the cooling of the photosphere after the contraction of the emitting region. These results clearly indicate that the burst is of type I, i.e., it is identified as a thermonuclear flash on a neutron star (NS). The total bolometric fluence of the burst, estimated by spectral analysis is $(1.45 \pm 0.06) \times 10^{-6}$ ergs cm^{-2} .

The observation of the near-Eddington profile is a clue to estimate the source distance. In fact, for a $1.4 M_{\odot}$ NS and a corresponding Eddington bolometric luminosity of

TABLE 2
BURST FIT PARAMETERS

Data Period ^a	Integration Time (s)	kT_{bb} (keV)	R_{bb} (km) ^b	χ_r^2 (26 dof)
Whole burst ...	48	1.98 ± 0.04	12.3 ± 0.6	1.89
First peak	4	2.55 ± 0.11	9.5 ± 1.1	1.46
First tail	6	1.83 ± 0.06	20.1 ± 1.7	1.29
Second peak ...	6	2.71 ± 0.09	9.7 ± 0.8	0.98
Second tail ...	7	1.94 ± 0.08	14.6 ± 1.6	1.09
Third tail	25	1.53 ± 0.07	13.2 ± 1.7	1.57

^a Refer also to lower panel of Fig. 2.

^b Estimated for a distance of 10 kpc (Cocchi et al. 1999).

2×10^{38} ergs s^{-1} we obtain $d = 4.9 \pm 0.3$ kpc, assuming standard burst parameters (here the error is purely statistical). For this distance the total burst-emitted energy is $\sim 4 \times 10^{39}$ ergs, and the observed blackbody radius scales to a value of ~ 6 km. This value of the radius could be underestimated, owing to the uncertainties in the relationship between color and effective temperature. If, as suggested by Ebisuzaki (1987), the color temperature exceeds T_{eff} by a factor ≈ 1.5 , then the neutron star radius should be at least twice the measured blackbody radius. These values therefore support a neutron star nature of the compact object.

2.3. The Wide-Band Persistent Emission

The light curve of SAX J1810.8–2609 measured with the *BeppoSAX* NFI is shown in Figure 3, in different energy ranges. There is a slight decrease of the flux in the lower energy range ($E < 10$ keV) in the first ~ 60 ks of the observations, while there is no clear evidence for a decline in the final part of the observation. This picture is consistent with the overall flux trend of this source, and with the derived e -folding time of ~ 7.5 days that is estimated from the WFC, *ROSAT* HRI, and NFI observations.

The count rate spectrum shows substantial emission at high energy. In fact, the unfolded spectrum in the energy range 15–200 keV can be fitted by a single power law of spectral index $\Gamma = 2.02 \pm 0.07$ ($\chi_r^2 = 0.76$ over 15 dof), and a flux in this range of 2.2×10^{-10} ergs cm^{-2} s^{-1} . The broadband spectral data, fitted by a single absorbed power law, results in a photon spectral index of 2.22 ± 0.02 , with a reduced chi-square $\chi_r^2 = 1.35$ over 165 dof and an average flux of 4.2×10^{-10} ergs cm^{-2} s^{-1} in the 0.1–200 keV band. It is clear that the absorbed power-law model is not satisfactory when applied to the broadband emission.

The fit is significantly improved by using a thermal Comptonization spectrum (*comptt* in XSPEC v. 10) instead of the simple power law, resulting in $\chi_r^2 = 1.12$ for 163 dof (see Table 3), which corresponds to a null hypothesis probability of 0.147. In this model, the hard X-ray tail is produced by the upscattering of soft seed photons by a hot, optically thin electron plasma (Titarchuk 1994). The seed photon temperature for this fit is 0.36 ± 0.02 keV. The hard X-ray data, however, cannot constrain the parameters of the Compton emission region (temperature and optical depth) because of the very high energy cutoff, which is above ~ 150 keV.

The addition of a soft thermal component improves both the power-law and Comptonization fits. The soft component can be modeled satisfactorily with blackbody or multicolor disk (MCD) blackbody emission (Mitsuda et al.

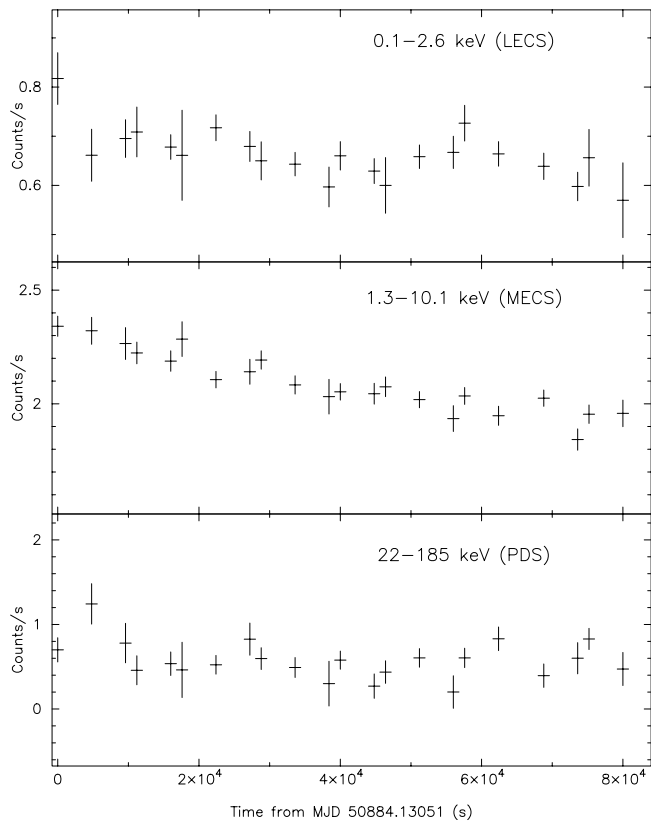


FIG. 3.—Time evolution of the X-ray emission of SAX J1810.8–2609 in three different energy bands from the LECS (*top*), MECS (*center*), and PDS (*bottom*). A weak decline at low energies ($E \leq 10$ keV) is visible, while no variation is apparent in the hard band (22–185 keV).

1984). Using single-temperature blackbody, the fits for power law and Comptonization are both compatible with a temperature value $kT \approx 0.5$ keV (see Table 3 for details), giving χ_r^2 values of 0.97 and 0.99, respectively. The power-law photon spectral index is $\Gamma = 1.96 \pm 0.04$, and the temperature of the soft Comptonized emission is 0.6 ± 0.4 keV. The estimated blackbody flux is between ~ 2.5 and $\sim 4 \times 10^{-11}$ ergs cm^{-2} s^{-1} . At the quoted source distance of 4.9 kpc this indicates an emission radius between ~ 10 and ~ 40 km. Using a MCD model to describe the additional soft component, the thermal emission is characterized by $kT_{\text{in}} = 0.6 \pm 0.1$ keV (temperature at the inner disk

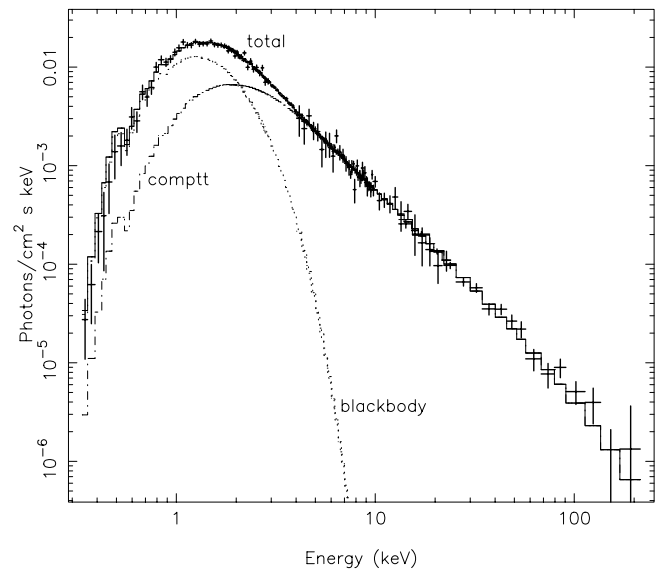


FIG. 4.—Unfolded broadband spectrum of SAX J1810.8–2609 as measured by the *BeppoSAX* NFIs on 1998 March 12–13, during a 95 sec exposure. The best model fit to a single blackbody (*dotted curve*). The thermal Comptonization (*dot-dashed curve*) emission spectrum is also shown.

radius R_{in}). For this model, the best fit gives $\chi_r^2 = 0.99$ for 161 dof. The values for $R_{\text{in}} (\cos \theta)^{1/2}$ may range from ~ 1.5 to ~ 10 km (here θ is the disk viewing angle). Hence, if this soft component originates from an optically thick region of the accretion disk, this should be expected to be not too far from the NS, unless the disk is seen at very large inclination.

The broadband source spectrum unfolded by the four instruments' response is shown in Figure 4 along with the model spectrum obtained for the blackbody component plus thermal Comptonization best fit. We note that the value of $N_{\text{H}} \approx 3.5 \times 10^{21}$ cm^{-2} obtained for the fits which include Comptonization match very well the current estimate of the Galactic column density of $\approx 3.7 \times 10^{21}$ cm^{-2} for this region (Dickey & Lockman 1990).

3. DISCUSSION

The deep and timely investigations carried out by means of repeated *BeppoSAX* observations of SAX J1810.8–2609 are consistent with a transient type I X-ray bursting source, most likely a low-mass X-ray binary (LMXB) containing a

TABLE 3

PARAMETER VALUES OF SPECTRAL MODELS FITTED TO THE PERSISTENT EMISSION

Model	Range ^a	N_{H}^b	C_{PL}^c	Γ	kT_0^d	kT_e^e	τ^f	kT_{bb}^g	Flux ^h	χ_v^i
PL	0.1–200	7.5 ± 0.2	8.5 ± 1.5	2.22 ± 0.02	...	...	...	...	4.2	1.35(165)
PL	15–200	...	6.0 ± 1.2	2.02 ± 0.07	...	...	...	...	2.2	0.76(15)
BB+PL	0.1–200	6.0 ± 0.2	5.2 ± 0.4	1.96 ± 0.04	...	...	...	0.50 ± 0.02	4.6	0.97(163)
<i>comptt</i>	0.1–200	3.5 ± 0.3	...	...	0.36 ± 0.02	107 ± 80	0.6 ± 0.5	...	4.1	1.12(163)
BB+ <i>comptt</i>	0.1–200	3.3 ± 0.4	...	...	0.6 ± 0.4	77 ± 93	1.2 ± 1.5	0.43 ± 0.09	4.3	0.99(161)

NOTE.—Errors are single-parameter 1σ errors.

^a Energy range in keV.

^b Value of Wisconsin absorption parameter in units of 10^{21} cm^{-2} .

^c Power-law (PL) normalization at 1 keV, in units of 10^{-2} .

^d Temperature of the Comptonized soft seed photons, in keV.

^e Plasma temperature, in keV.

^f Plasma optical depth for disk geometry.

^g Temperature of the blackbody (bb) component, in keV.

^h In units of 10^{-10} ergs cm^{-2} s^{-1} .

ⁱ Number of degrees of freedom is given in parentheses.

weakly magnetized NS. This source is a weak transient, as supported by the fact that it was never detected in more than 3 years of *BeppoSAX* monitoring of the Galactic bulge region (apart from these discovery and follow-up observations) and also never seen by the *RXTE* All Sky Monitor (ASM), even during the 1998 March outburst. The ASM nondetection implies an upper limit on the 2–10 keV flux of $\sim 7 \times 10^{-10}$ ergs cm $^{-2}$ s $^{-1}$. It is noteworthy that a similar weak transient behavior has also been observed in a number of recently discovered bursters, detected during dim X-ray outburst episodes with maximum intensities well below 100 mcrab and lasting ~ 1 to a few weeks (see, e.g., Heise et al. 1999).

The estimated value of distance of ~ 5 kpc, which was obtained from the observation of radius expansion during the burst (Lewin et al. 1993; Lewin et al. 1995) places SAX J1810.8–2609 at our side of the Galactic bulge (see, e.g., Christian & Swank 1997). This is consistent with the tentative detection of the optical counterpart (Greiner et al. 1999). We note that the presence of the neutron star in the system is also supported by the relatively small blackbody radius of ~ 6 km, calculated for the derived distance.

The detection of a single X-ray burst during our monitoring observations is consistent with the observed combination of burst fluence and average persistent bolometric emission, which is $\sim 5 \times 10^{-10}$ ergs cm $^{-2}$ s $^{-1}$, i.e., $\sim 0.01 L_{\text{Edd}}$ at 5 kpc. In fact, taking into account the total energy release of the burst and assuming that steady nuclear burning is negligible, we can estimate a typical value of ~ 5 days for the mean burst interval, which corresponds to the expected α parameter for helium burning (i.e., $\alpha \geq 100$; see Lewin et al. 1993) and is comparable to the e -folding decay time of 7.5 days estimated for the persistent emission. Conversely, if a significant part of the nuclear fuel is burnt steadily, the quoted value should be considered as a lower limit.

The broadband spectrum of SAX J1810.8–2609 shows a high-energy power-law tail, which is remarkably hard ($\Gamma = 2.06 \pm 0.11$ in the 15–200 keV band) and with no cutoff. There is also an indication for a soft blackbody component with temperature $kT \approx 0.5$ keV and total flux $F_{\text{bb}} \sim 3 \times 10^{-11}$ ergs cm $^{-2}$ s $^{-1}$. The ratio of the soft-component luminosity to the total X-ray (0.1–10 keV) luminosity is estimated to be in the range $\sim 10\%$ – 15% . This is consistent with upper limits obtained for X-ray bursters observed by *ASCA* in the low state (see, e.g., Revnivtsev et

al. 1999) and also with the detection of similar soft components in the spectra of 4U 0614+091 (Piraino et al. 1999), 1E 1724–3045, and SLX 1735–269 (Barret et al. 2000), which were all observed in a hard state. A recent analysis of *ROSAT* spectra of LMXBs (Schulz 1999) also shows that a soft component is present in several low-luminosity (mainly atoll type) X-ray bursters.

The luminosities in the soft and hard X-ray bands match quite well the observed correlation pattern found for neutron star binaries in the low state (Barret et al. 2000), with values of $\sim 7.5 \times 10^{35}$ ergs s $^{-1}$ in the 1–20 keV band, and $\sim 5.0 \times 10^{35}$ ergs s $^{-1}$ in the 20–200 keV band. Nevertheless, the absence of a cutoff below ~ 200 keV is particularly outstanding, as in most cases X-ray bursters with hard tail spectra do have this feature, which is suggestive of Comptonization with plasma temperatures below ~ 50 keV (Guainazzi et al. 1998; in 't Zand et al. 1999). The presence of such a cutoff was suggested as a possible criterion to distinguish NS from black hole (BH) spectra, the latter being characterized by much higher electron temperatures (Tavani & Barret 1997). The case of SAX J1810.8–2609 is not compatible with this kind of interpretation. Very recently, an analysis of *BeppoSAX* observations of the atoll X-ray burster 4U 0614+091 has revealed a similar behavior, i.e., a high-energy power-law tail with no visible cutoff (Piraino et al. 1999). Whether the spectrum of SAX J1810.8–2609 could have a cutoff just above 200 keV (that is our observational upper energy limit) is difficult to say. Our broadband spectral analysis shows that only a Comptonization fit is compatible with a low-energy absorption matching the value of Galactic column density. We conclude that, even if the data are not able to constrain the Comptonization parameters of the scattering region, we still have a good indication that Comptonization is the mechanism that produces the hard X-ray tail.

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