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SWIFT OBSERVATIONS OF SAX J1808.4−3658: MONITORING THE RETURN TO QUIESCENCE

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ABSTRACT

The transient accreting millisecond pulsar SAX J1808.4−3658 has shown several outbursts to date but the transition from outburst to quiescence has never been investigated in detail. Thanks to the *Swift* observing flexibility, we monitored for the first time the decay to quiescence during the 2005 outburst. At variance with other transients, wide luminosity variations are observed. In addition, close to quiescence, SAX J1808.4−3658 seems to switch between two different states. We interpret them in terms of the accretion states accessible to a magnetized, fast-rotating neutron star.

Subject headings: accretion, accretion disks — stars: individual (SAX J1808.4−3658) — stars: neutron

Online material: color figures

1. INTRODUCTION

SAX J1808.4−3658 (SAX J1808 in the following) was the first neutron star transient during whose outbursts coherent pulsations were detected (Wijnands & van der Klis 1998). This source, together with six other low-mass transients (see Wijnands 2005 for a review), forms a separate (sub)class within neutron star transients (see Campana et al. 1998a for a review). Distinctive properties, besides coherent pulsations, are weaker outburst peak luminosities [$\sim$(1–5) $\times$ 10^{36} erg s^{-1}], very low mass companions (mass functions $<2 \times 10^{-3}\, M_\odot$), short orbital periods ($P_{\rm orb} \lesssim 4.3$ hr), very faint quiescent luminosities ($\lesssim 5 \times 10^{31}$ erg s^{-1}), and absence of a soft X-ray spectral component in quiescence.

A further difference with respect to "classical" neutron star transients concerns the return to quiescence following an outburst. The best light curve to date of "classical" neutron star transients is represented by *BeppoSAX* observations of Aql X-1 (Campana et al. 1998b). Below a luminosity level of $\sim 10^{36}$ erg s^{-1} Aql X-1 turned off with an exponential decay with an *e*-folding time of $\sim$1 day. The source then remained quiescent for at least 1 month following the 1998 outburst (Campana et al. 1998b) and for 5 months following the 2000 outburst (Rutledge et al. 2001; Campana & Stella 2004). The return to quiescence for transient pulsating neutron stars has been monitored for SAX J1808 (Wijnands et al. 2003; Wijnands 2005) and for XTE J1751−305 (Markwardt et al. 2002) and *Swift* J1756.9−2508 (Krimm et al. 2007). The behavior of the latter two sources was somewhat similar to Aql X-1 with a fast decay, even though in the case of XTE J1751−305 there was still activity 15 days after the transition to quiescence had occurred (according to *RXTE* PCA, corresponding to a 0.5–10 keV unabsorbed luminosity of $\sim 10^{35}$ erg s^{-1} for a source distance of 7 kpc). In case of SAX J1808 the decay was completely different from that observed in Aql X-1. The most striking feature is the strong erratic variability by a factor of $\gtrsim$30. This erratic behavior was not concentrated in the first few weeks after turnoff but lasted for months (e.g., Wjinands et al. 2003). The most likely explanation for this behavior comes from the similarities with dwarf novae where a similar behavior has been observed (Kato et al. 2004; Patterson et al. 2002) and to a lesser extent in black hole transients (Kuulkers et al. 1996). In the case of dwarf novae this has been interpreted as due to a combination of short orbital period and low mass ratio (Osaki & Meyer 2002; Truss et al. 2002).

Here we report on a monitoring campaign carried out with *Swift*, following the 2005 outburst. At variance with previous monitoring with *RXTE* PCA we are able to follow the source down to very low levels, a factor of $\sim$50 fainter than before, close to quiescence. In § 2 we discuss the data and their analysis. Section 3 contains our discussion and conclusions.

2. DATA ANALYSIS

Swift carried out 23 observations of SAX J1808 between 2005 June 17 and October 28. XRT collected a total of 4899 s of data in Window Timing (WT) mode and 72,922 s of data in Photon Counting mode (see Table 1). In WT mode a 1D image is obtained reading data compressing along the central 200 pixels in a single row. PC mode produces standard 2D images (for more details see Hill et al. 2004). WT data were mainly collected during the early stages of the outburst when the source was brighter. PC data collected during this period are piled up.

The XRT data were processed with standard procedures (`xrtpipeline` ver. 0.11.6 within FTOOLS in the Heasoft package ver. 6.4), filtering, screening, and grade selection criteria (Burrows et al. 2005). For the WT data, we extracted source events in a square region with a side of 20 pixels. Ancillary response files were generated with `xrtmkarf` and accounted for different extraction regions, vignetting, and point-spread function (PSF) corrections. In PC mode we extracted data with variable extraction regions depending on source strength, ranging from an annular region with inner (outer) radius of 10 (40) pixels when the source was very bright, down to a 10 pixel circular region when the source was very faint in order to increase the source signal versus the background.

2.1. *Outburst Light Curve*

The first observations caught SAX J1808 during the latest stages of the outburst phase at a count rate level (corrected for pileup) of more than 10 counts s^{-1}. Starting from MJD 53,564 the source decreased its count rate by a factor of $\sim$600 in 20

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TABLE 1
Observation Log

ObsID	Date (2006)	WT Exp. Time (s)	PC Exp. Time (s)	Count Rate (counts s^{-1})	Counts
00030034001	Jun 17	119	787	4.46	3510 (P)
00030034002	Jun 20	0	1061	1.49	1581 (P)
00030034003	Jun 23	761	206	3.01	620 (P)
00030075001	Jun 29	1043	0	4.09	4396
00030034005	Jul 7	866	0	8.14	7157
00030034006	Jul 13	733	394	3.10	1221 (P)
00030034010	Aug 2	0	416	8.88E−03	4 [A]
00030034011	Aug 5	0	1041	6.31E−03	7 [A]
00030034012	Aug 13	1028	2486	1.84	4574 (P)
00030034013	Aug 21	0	1675	9.05E−03	15 [A]
00030034014	Aug 28	68	1928	1.36	2622 (P)
00030034015	Aug 30	0	2550	6.26E−02	160
00030034016	Aug 31	0	2838	9.87E−03	28 [A]
00030034017	Sep 2	0	2084	5.48E−03	11 [A]
00030034018	Sep 14	0	9011	1.50E−03	14 [B]
00030034019	Sep 25	123	7329	6.47E−03	47 [A]
00030075020	Sep 30	42	4922	4.89E−03	21 [A]
00030034021	Oct 4	0	7757	1.74E−03	12 [B]
00030034020	Oct 11	0	2986	4.89E−03	15 [A]
00030034022	Oct 12	0	4689	1.64E−03	7 [B]
00030034023	Oct 16	0	6742	1.83E−03	12 [B]
00030034024	Oct 20	0	4736	<3.49E−03	16
00030034025	Oct 28	116	7284	<3.00E−03	22

Notes.—Labels in the last column as follows: (P) piled-up photon counting data; [A] state A observation; [B] state B observation.

days (unfortunately no observations were taken during this period due to the occurrence of number of gamma-ray bursts; see Fig. 1). Two observations within 3 days showed the source at a level of 0.01 counts s^{-1} well above the quiescent level. After this sharp decay, SAX J1808 entered a "flaring" behavior (Wijnands et al. 2003; Wijnands 2005). Our data show that this activity lasted for about 1 month; after that the source returned to its quiescent state with some comparatively small-scale variability (factor of ∼5) superimposed (see also below).

2.2. *Spectral Analysis: Bright End*

We fit the entire data set with an absorbed blackbody plus power law model, keeping the same value of the column density for all the spectra. The best column density is $(1.3 \pm 0.1) \times 10^{21}$ cm^{-2} (90% confidence level, modeled with TBABS). In Table 2 we report the results of our spectral modeling. From this table and Figures 2 and 3 it is clear that during the outburst decay and flaring period the power-law photon index ($\Gamma \sim 2.3$) and the blackbody temperature ($kT \sim 0.65$ keV) remained almost constant. This behavior occurs in the (unabsorbed) 0.3–10 keV luminosity range of 7×10^{34}–10^{36} erg s^{-1} (i.e., a factor of ∼15), assuming a source distance of 3.5 kpc (Galloway & Cumming 2006).

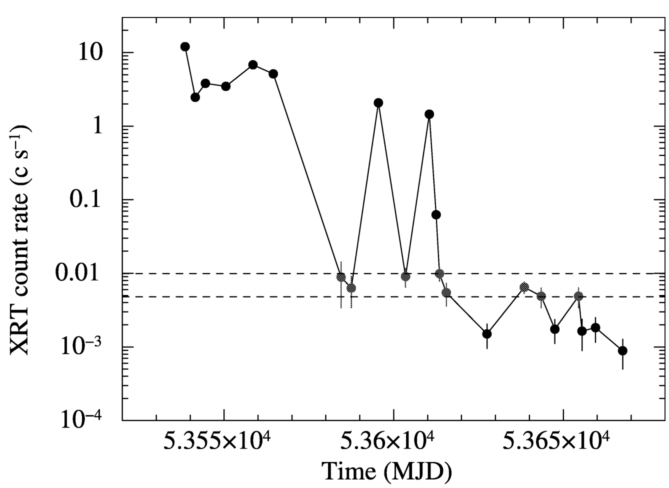

Fig. 1.—SAX J1808 light curve observed with *Swift* XRT during the 2005 outburst. [*See the electronic edition of the Journal for a color version of this figure.*]

2.3. *Spectral Analysis: Faint End*

At lower luminosities the number of collected photons is very small and we have to stack together different observations. One important consideration comes from the observation that 8 out of 13 observations found the source with a count rate in the narrow interval 5–10 counts ks^{-1}, whereas the other 5 all lie within 0.8–2 counts ks^{-1}. The mean of the first group is 6.3 ± 1.1 counts ks^{-1} and of the second is 1.3 ± 0.4 counts ks^{-1}. This is rather peculiar and hints at the existence of two different states in the deep faint-end tail of the outburst. Due to the small number of photons these spectra can be easily fit

TABLE 2
Spectral Fits

Date	BB Temperature (keV)	BB Radius (km)	PL Index	Luminosity[a] (erg s^{-1})
2005 Jun 17[b]	$0.72^{+0.13}_{-0.13}$	$2.3^{+1.0}_{-0.9}$	$2.24^{+0.15}_{-0.11}$	1.0×10^{36}
2005 Jun 20[b]	$0.80^{+0.17}_{-0.14}$	$1.2^{+0.6}_{-0.6}$	$2.51^{+0.41}_{-0.38}$	2.4×10^{35}
2005 Jun 23[b]	$0.59^{+0.15}_{-0.13}$	$2.4^{+1.6}_{-1.6}$	$2.26^{+0.11}_{-0.08}$	7.2×10^{35}
2005 Jun 29[b]	$0.78^{+0.19}_{-0.19}$	$1.0^{+0.4}_{-0.4}$	$2.37^{+0.15}_{-0.12}$	3.3×10^{35}
2005 Jul 7[b]	$0.44^{+0.23}_{-0.33}$	$2.2^{+2.2}_{-1.9}$	$2.41^{+0.07}_{-0.03}$	5.7×10^{35}
2005 Jul 13[b]	$0.57^{+0.10}_{-0.09}$	$2.2^{+0.9}_{-0.8}$	$2.18^{+0.11}_{-0.08}$	4.2×10^{35}
2005 Aug 13[b]	$0.68^{+0.24}_{-0.19}$	$0.9^{+0.6}_{-0.5}$	$2.22^{+0.12}_{-0.09}$	2.0×10^{35}
2005 Aug 28[b]	$0.78^{+0.18}_{-0.17}$	$0.8^{+0.4}_{-0.4}$	$1.94^{+0.16}_{-0.05}$	1.4×10^{35}
State A[c]	$0.20^{+0.05}_{-0.05}$	$1.3^{+0.3}_{-0.5}$	1.93 fixed	5.0×10^{32}
State B[d]	0.20 fixed	<0.3	1.93 fixed	1.5×10^{32}

[a] Unabsorbed 0.3–10 keV luminosity at a source distance of 3.5 kpc.
[b] Overall reduced $\chi^2 = 1.06$ with 1213 degrees of freedom.
[c] Reduced $\chi^2 = 0.75$ with 16 degrees of freedom.
[d] Reduced $\chi^2 = 1.38$ with 7 degrees of freedom.

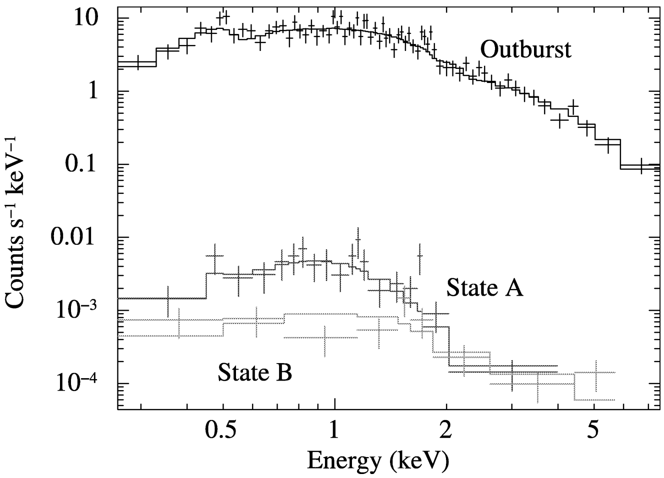

FIG. 2.—XRT spectra of SAX J1808.4−3658. The topmost spectrum is a representative of the outburst state. The middle spectrum refers to state A and the lowest one to state B (see text for more details). All spectra were fitted with an absorbed blackbody plus power law model. [*See the electronic edition of the Journal for a color version of this figure.*]

with single power law models. For state A we derive a photon index of $\Gamma = 2.7 \pm 0.3$ and a mean unabsorbed 0.3–10 keV luminosity of 5.0×10^{32} erg s^{-1}; for state B we have $\Gamma = 1.7 \pm 0.6$ and a luminosity of 1.5×10^{32} erg s^{-1}. These values have been derived binning the data to 5 photons per energy bin and applying the Churazov weighting in the fitting procedure (see Fig. 2). This indicates that state B is not yet the true quiescent state, characterized by a single power law spectrum with index $\Gamma = 1.93^{+0.37}_{-0.29}$ and a source luminosity of $(5.2 \pm 0.1) \times 10^{31}$ erg s^{-1} (Heinke et al. 2007), i.e., a factor of ∼3 smaller than state B luminosity. Assuming this power-law component as a stable component (at least in photon index) present in state A and B spectra, one can investigate whether a blackbody component is present. Fitting the state A spectrum with a fixed power law photon index (with $\Gamma = 1.93$) and a free blackbody component, we derive $kT = 0.20 \pm 0.05$ keV and a radius of $R = 1.3^{+0.3}_{-0.5}$ km. The improvement over the simple power law fit is at a level of 2.2 σ by means of an F-test. For state B we are not able to constrain the blackbody component. However, if we assume the same blackbody temperature as in state A (i.e., 0.2 keV) we can derive an upper limit on its radius of $R < 0.3$ km, indicating that if present and at the same temperature it must be smaller in size.

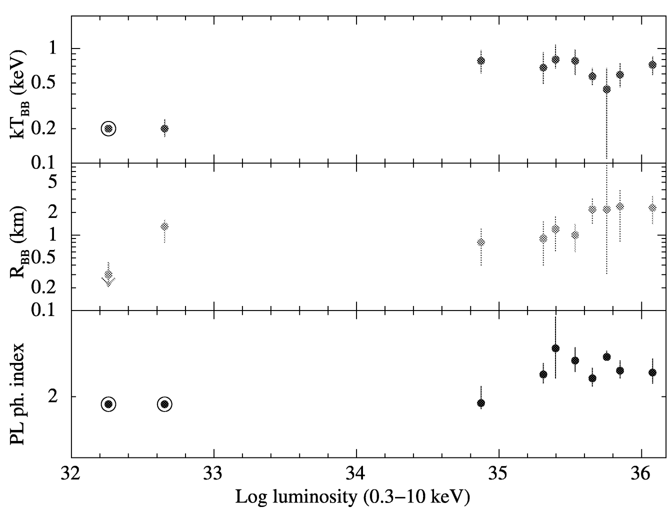

FIG. 3.—Evolution of spectral parameters across the outburst. Circled values indicate a fixed parameter in the fitting procedure. [*See the electronic edition of the Journal for a color version of this figure.*]

3. DISCUSSION AND CONCLUSIONS

SAX J1808 is the prototype of the accreting millisecond X-ray pulsar (AMP) class. The source underwent several outbursts to date which have been monitored in great detail thanks to *RXTE* observations (Wijnands 2005; Wijnands et al. 2003). These observations however were limited to the brightest part of the outburst, the PCA on *RXTE* being a collimated instrument (and therefore heavily background limited). Here we report on the first campaign aimed at studying the faintest tail of the outburst and return to quiescence. Thanks to the fast repointing and flexible scheduling capabilities of the *Swift* satellite, we monitored the return to quiescence of SAX J1808 during the 2005 outburst. The bright phase of the outburst is similar to what has been observed in the past: following the peak and the smooth decay a flaring behavior sets in with at least three rebrightening episodes. After this the source turns to quiescence even if some low-level activity (factor of ∼5) is still present.

The puzzling result of this observational campaign on SAX J1808 is that out of 13 observations with luminosity below $\sim 10^{34}$ erg s^{-1}, the source was found with a luminosity around $\sim 5 \times 10^{32}$ erg s^{-1} eight times (see Fig. 1), i.e., at a luminosity level ∼10 times higher than the true quiescent level (Campana et al. 2002; Heinke et al. 2007). Given the wild luminosity variations this is somewhat strange and calls for the presence of a “metastable” state. This luminosity level is difficult to interpret in case of standard disk accretion but finds a natural explanation if the accretion process is mediated by the magnetic field of the fast-spinning neutron star. When the magnetospheric radius (i.e., the radius at which the neutron star magnetic field starts controlling the accretion flow) is larger than the corotation radius, the system is in the (so called) propeller regime. In this case matter is halted from the rotating magnetosphere and does not accrete onto the neutron star surface (see, e.g., Campana & Stella 2000 and references therein). When the magnetospheric radius becomes larger than the light cylinder radius ($r_{\rm lc} = cP/2\pi$, where c is the velocity of light and P the spin period), the magnetic field cannot corotate any more with the neutron star and a dipole loss will take place. The luminosity range spanned in the propeller regime is $\sim 440 P_{2.5}^{3/2} M_{1.4}^{-3/2}$ (where $P_{2.5}$ is the spin period in units of 2.5 ms and $M_{1.4}$ the neutron star mass in units of 1.4 $M_\odot$; see Campana & Stella 2000). In order to have the “metastable” state coincide with the lowest luminosity in the propeller regime (i.e., just before the reactivation of the pulsar), we have to require a magnetic field of $\sim 7 \times 10^7$ G, in line with previous estimates: $\sim(1–10) \times 10^8$ G using disk-magnetosphere interaction models (Psaltis & Chakrabarty 1999), $\sim(1–6) \times 10^8$ G using simple considerations on the position of the magnetospheric radius during quiescent periods (Di Salvo & Burderi 2003); $(0.4–1.5) \times 10^8$ G modeling period changes during outbursts with a magnetic torque model (Hartman et al. 2008).

The lowest luminosity level in the proposed interpretation is ascribed to the interaction of a turned-on pulsar with the interbinary and circumstellar environment. Variability is expected at this stage due to the rapidly changing environment as observed, e.g., in the millisecond radio pulsar PSR J1740−5340 (D’Amico et al. 2001; Ferraro et al. 2001), which gets eclipsed over a range of orbital phases for different orbital cycles.

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