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THE ERRATIC LUMINOSITY BEHAVIOR OF SAX J1808.4−3658 DURING ITS 2000 OUTBURST

Rudy Wijnands,[1,2] Mariano Méndez,[3] Craig Markwardt,[4] Michiel van der Klis,[5]
Deepto Chakrabarty,[1] and Ed Morgan[1]

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ABSTRACT

We report on the highly variable and erratic long-term X-ray luminosity behavior of the only known accretion-driven millisecond X-ray pulsar SAX J1808.4−3658 during its 2000 outburst, as observed with the *Rossi X-ray Timing Explorer* (*RXTE*) satellite. The maximum observed luminosity is $\sim 2.5 \times 10^{35}$ ergs s^{-1} (3–25 keV; for a distance of 2.5 kpc), which is approximately a factor of 10 lower than that observed during the 1996 and 1998 outbursts. Due to solar constraints, the source could not be observed for several months with *RXTE* before 2000 January 21. Therefore, the exact moment of the outburst onset is unknown, and the peak luminosity could have been significantly higher. On some occasions SAX J1808.4−3658 was observed with luminosities of $\sim 10^{35}$ ergs s^{-1}, but on other occasions it could not be detected with *RXTE*, resulting in typical upper limits of a few times 10^{33} ergs s^{-1} (3–25 keV). The nondetections of the source during its 2000 outburst obtained with the *BeppoSAX* satellite demonstrate that its luminosity was at times less than 10^{32} ergs s^{-1} (0.5–10 keV). However, only a few days after these *BeppoSAX* observations, we detected the source again with *RXTE* at high luminosities, giving a factor of greater than 1000 of luminosity swings in this systems on timescales of days. The last detection of SAX J1808.4−3658 with *RXTE* was on 2000 May 13, almost 4 months after the first detection during this outburst. Due to the lack of sensitivity and observations during the 1996 and 1998 outbursts, it cannot be excluded that after those outbursts the source remained active for months and that the source behavior during the 2000 outburst is not unique. Long duration activity at low luminosities has been observed in other transients (both neutron stars and black holes), although not with such extreme variability, which might point to a different origin for this behavior for the millisecond X-ray pulsar.

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

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) are binary systems containing a compact object (either a neutron star or black hole) which is accreting matter from a low-mass companion star ($<1\ M_{\odot}$). A particular subclass of LMXBs, the X-ray transients, have received special interest. Due to the high variations in accretion rate, these systems can be studied under a very wide range of physical conditions. They exhibit (sometimes recurrent) outbursts during which they resemble in detail the persistent LMXBs. Most of the time, however, these X-ray transients are in quiescence, during which no, or hardly any, accretion onto the compact object takes place.

The outburst profiles of the X-ray transients are very diverse and, although the most recent versions of the disk instability model can explain the outburst light curve properties in general, some important issues remain unexplained (see Lasota 2001 for a review of disk instability models). In most sources, the X-ray flux during the outburst decreases steadily to quiescence levels, although some transients exhibited a much more complex behavior (see, e.g., Chen, Shrader, & Livio 1997 and Bradt et al. 2000). Some sources exhibit periods of low-level activity for several months to several years, long after the outburst is over. Both black hole systems (e.g., 4U 1630−47 or XTE J0421+560; Kuulkers et al. 1997; Bradt et al. 2000; Parmar et al. 2000) and neutron star systems (e.g., Aql X−1 and 4U 1608−52; Bradt et al. 2000) can exhibit this behavior. Besides the low-level of activity observed after a full outburst, Aql X−1 also exhibited so-called "failed" outbursts, during which the source does not reach typical outburst luminosity but low-level activity is present for weeks (Bradt et al. 2000). The physical processes behind these long episodes of low-activity are unclear. One possibility is that these states indicate that the conditions for exhibiting outbursts are marginal, and when systems accrete close to the critical value they might show low-level activity for several weeks to months (see also Bradt et al. 2000). In the remainder of this paper, we refer to these long episodes of low-level activity in X-ray transients as "the low-activity state."

1.1. *SAX J1808.4−3658*

In 1996 September, using the *BeppoSAX* Wide Field Cameras (WFC), a new X-ray transient (designated SAX J1808.4−3658) was discovered (in 't Zand et al. 1998). The neutron-star nature of the compact object in this system was deduced from the observations of type-I X-ray bursts, from which also a distance of ~ 2.5 kpc was derived (in 't Zand et al. 1998; 2001). The source had a maximum luminosity of $\sim 2.5 \times 10^{36}$ ergs s^{-1} (3–25 keV) and could be detected for several weeks. The source remained dormant until 1998 April 9, when it was detected again, but this time with the proportional counter array (PCA) on board the *Rossi X-ray Timing Explorer* (*RXTE*; Marshall 1998). Using the *RXTE*/PCA data, coherent 401 Hz pulsations

[1] Center for Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307; rudy@space.mit.edu.
[2] Chandra Fellow.
[3] Space Research Organization Netherlands Laboratory for Space Research, Sorbonnelaan 2, NL-3584 CA, Utrecht, The Netherlands.
[4] NASA/Goddard Space Flight Center, Code 662, Greenbelt, MD 20771.
[5] Astronomical Institute "Anton Pannekoek," University of Amsterdam, Kruislaan 403, NL-1098 SJ Amsterdam, The Netherlands.

were discovered in the X-ray flux of SAX J1808.4−3658, making this source the first known accretion-driven millisecond X-ray pulsar (Wijnands & van der Klis 1998a). It was also found that the neutron star is in a 2 hr binary with a very low mass companion star (Chakrabarty & Morgan 1998; see Bildsten & Chakrabarty 2001 for a discussion of the possible brown dwarf nature of the companion star of SAX J1808.4−3658). During its 1998 outburst, its aperiodic rapid X-ray variability (Wijnands & van der Klis 1998b) and its X-ray spectrum (Gilfanov et al. 1998; Heindl & Smith 1998) were remarkably similar to those of other LMXBs with similar luminosities. Therefore, it is very puzzling why persistent millisecond pulsations have so far only been detected from this source and not from any other neutron star LMXBs.

During its 1998 outburst, the source was detected for a few weeks (see, e.g., Gilfanov et al. 1998 or Cui, Morgan, & Titarchuk 1998 for its 1998 light curve) before it returned to quiescence. SAX J1808.4−3658 was detected for a third time on 2000 January 21 (again with the *RXTE*/PCA), but this time at a flux level of about a tenth of the fluxes observed during the 1996 September and 1998 April outbursts (van der Klis et al. 2000). When the source was detected, the pulsations at 401 Hz were observed, and during several *RXTE* observations very strong violent flaring behavior with a repetition frequency of about 1 Hz was present (van der Klis et al. 2000; Wijnands et al. 2000). During this outburst, several *BeppoSAX* observations were also performed to study the broadband spectrum of the source. Here we report on the 2000 outburst light curve of SAX J1808.4−3658 as obtained with the *RXTE*/PCA. The coherent pulsations are reported by Morgan et al. (2001, in preparation) and the *BeppoSAX* observations by Wijnands et al. (2001).

2. OBSERVATIONS AND ANALYSIS

After SAX J1808.4−3658 was first detected on 2000 January 21, the source was frequently monitored with *RXTE* as part of our AO4 Target of Opportunity (TOO) program on this source. A total of 41 observations were obtained for a total of ~ 150 ks on-source time. During the observations, the data were taken simultaneously in the Standard 1 (1 energy channel and 1/8 s time resolution) and Standard 2 (129 channels; 16 s resolution) modes and the event mode E_125US_64M_0_1S (64 channels; 122 μs resolution). The only observation during which different modes were used was 40035-01-04-00G. After a brief interval of nondetections of SAX J1808.4−3658, the source was found to be active again and *RXTE* was slewed in real time to the position of SAX J1808.4−3658. As a consequence, the high-timing modes used during this observation were the same as those used on the previous target and were the GoodXenon1_16s and GoodXenon2_16s modes (combined they have 256 channels for 2–60 keV and a time resolution of ~ 1 μs). In this paper, we only use the data obtained with the standard modes. The results obtained with the high-time resolution modes are presented in Morgan et al. (2001, in preparation).

The Standard 2 mode data were used to extract the count rates of the source and the X-ray spectra. The count rates were only extracted for proportional counter units (PCUs) 0 and 2, which were always on during our observations. Spectra were extracted for all the detectors which were on during the particular observations. We used the tools provided with "Ftools" version 5.0.4 to extract the background data (using the "faint source" model) which were used to correct the count rates and the spectra. We fitted the X-ray spectra between 3 and 25 keV (with a 1% systematic error added). The spectra were fitted with a power law with a free-floating absorption column density (the column densities obtained from the fit were consistent with zero *and* with the Galactic value of 1.3×10^{21} cm^{-2} toward SAX J1808.4−3658; Dickey & Lockman 1990). During several observations, the power law alone did not produce an acceptable fit to the data and an extra low-energy (<5 keV) component needed to be added. However, when fitting this component with a blackbody, very low kT (<0.5 keV) values were obtained. Presently, it is unclear whether this component is real or if it is due to residual calibration uncertainties of the detectors at low energies. We will not discuss this further in our paper. When no source flux could be detected we obtained 95% confidence upper limits to the flux by fixing the power-law photon index to 2. The actual limits for the individual observations (0.02–0.2 $\times 10^{-10}$ ergs s^{-1} cm^{-2}) depended upon the on-source time and the number of PCUs on during those observations.

In our analysis we also included the data obtained as part of *RXTE*/PCA monitoring of the Galactic bulge region. Observations began in 1999 February and typically take place twice per week, except for approximately 2.5 months between November and February when the Sun is near the Galactic center (Markwardt et al. 2000; Markwardt 2000). The data (in GoodXenon mode) are obtained by orienting the spacecraft to scan a large region. Intensities of known sources are derived by fitting a collimator model to the observed light curve, including the contribution of a diffuse emission component (see Markwardt et al. 2001, in preparation for details). SAX J1808.4−3658 lies at the endpoint of one of the scans, and because the spacecraft must dwell at that point momentarily the exposure is 2–3 minutes. The scans are, thus, sensitive to variations at the greater than 10^{-12} ergs s^{-1} cm^{-2} level. Our TOO observations were performed until 2000 March 1, but the bulge scan observations continue.

3. RESULTS

The 2–60 keV count rate curve of SAX J1808.4−3658 during its 2000 outburst is shown in Figure 1. For display purposes, we only use the data obtained with the *RXTE*/PCA bulge scan up to 2000 October 26. During the bulge scan observations performed after that date, the source was not detected and only count rate upper limits could be obtained. The gap in the data (between 1999 November 2 and 2000 January 21) in Figure 1*a* is due to solar constraints, which did not allow *RXTE* observations of SAX J1808.4−3658 in this period. Clearly, three episodes of distinct behavior can be observed for this source. Before 1999 November 2, the source was undetected with typical upper limits on the luminosity of a few times 10^{33} ergs s^{-1} (3–25 keV; hereafter, the quoted luminosities are for this energy range and for a distance of 2.5 kpc or as otherwise noted). However, the source was found to be active on 2000 January 21 with a maximum reached luminosity of $\sim 2.5 \times 10^{35}$ ergs s^{-1} (on 2000 February 2).

In Figures 1*b* and 1*c*, close-ups of the count rate curve are displayed to show the strong variability more clearly. As can be seen, the source was highly variable on timescales of days, with episodes of clear activity (luminosities up to

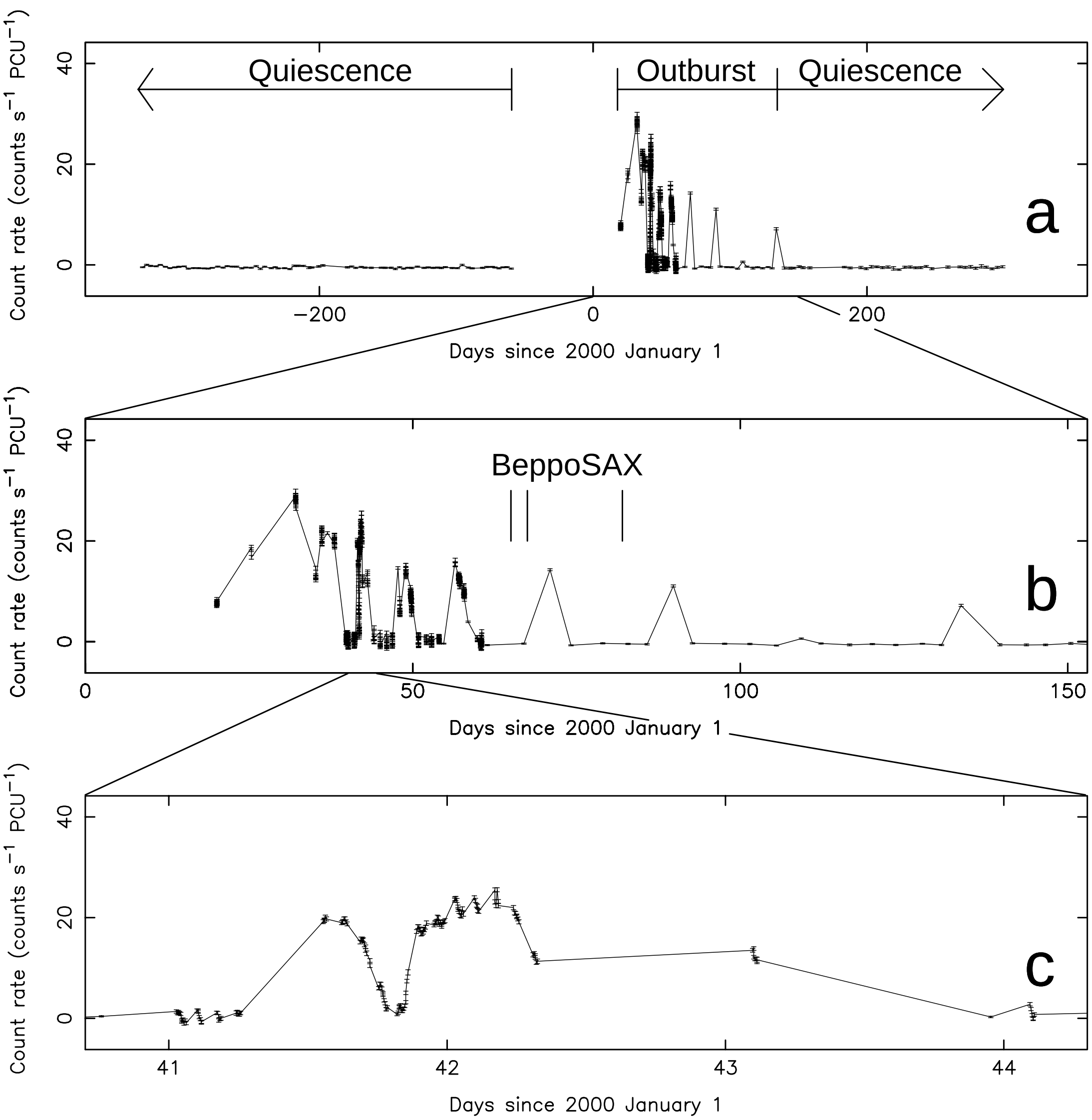

FIG. 1.—*RXTE*/PCA 2–60 keV count rate curve of SAX J1808.4−3658 during its 2000 outburst. In (*a*) the most extensive curve (up to 2000 October 26) is shown, and in (*b*) and (*c*) close-ups of the data are shown to illustrate the strong variability more clearly. In (*b*) the vertical lines indicate when the three *BeppoSAX* observations were taken (see Wijnands et al. 2001). The count rates are background subtracted. The data points obtained as part of the TOO proposal represent 256 s of data, whereas those from the *RXTE*/PCA bulge scan data have a variable length (typically 2–3 minutes). The gap in the data in (*a*) is due to solar constraints, which did not allow *RXTE* observations of SAX J1808.4−3658 in this period.

$\sim 10^{35}$ ergs s^{-1}) followed by episodes of nonactivity (with *RXTE*/PCA upper limits on the luminosity of typically a few times 10^{33} ergs s^{-1}). In Figure 1*b*, the times of the *BeppoSAX* observations (2000 March 5–6, 8, and 22–23; Wijnands et al. 2001) are indicated, clearly showing that they were all taken during intervals when the source was in a nonactive episode. Consequently, during these observations the source was not detected, with an upper limit on the luminosity of less than 10^{32} ergs s^{-1} (0.5–5.0 keV). However, only a few days later, on March 11, SAX J1808.4−3658 could again be detected with *RXTE*/PCA at $\sim 10^{35}$ ergs s^{-1}, demonstrating a factor of greater than 1000 swing in luminosity on timescales of days. The active episodes last typically only a few days, but the nonactive episodes could last for weeks, to up to $\sim$44 days (although active episodes with a duration of less than 3 days might have remained undetected due to the 3–4 day sampling of the data). From Figure 1*c*, it is apparent that the source was also highly variable on timescales of only a few hours. In particular, the decrease in count rate with a factor of $\sim$20 (from 100 to 5 counts s^{-1}) occurred in $\sim$5 hr and the subsequent increase took only $\sim$1 hr. The last time SAX J1808.4−3658 could be detected was on 2000 May 13 in a bulge scan observation. Since then the source has remained undetectable with the *RXTE*/PCA (with upper limits of typically 10^{33} ergs s^{-1}), and it is presumed to be in quiescence.

During the 2000 outburst, SAX J1808.4−3658 was spectrally very constant with a power-law photon index varying between 1.9 and 2.4 (a mean of 2.16). No correlations were found between the spectral parameters and time, count rate, or with the episodes of the violent flaring. As expected, the count rates were nicely correlated with the X-ray fluxes, and the count rates shown in Figure 1 can be converted to fluxes using a linear relationship of flux (10^{-10} ergs s^{-1} cm; 3–25 keV) $= 0.12 \pm 0.01 \times$ count rate (counts s^{-1} PCU^{-1}; 2–60 keV). Because the errors on the count rates are significantly smaller than those on the obtained fluxes, we only show the count rate curve. Furthermore, the *RXTE*/PCA bulge scans resulted only in count rate determinations of SAX J1808.4−3658. Due to the very brief exposures on the source and its very low count rates (<30 counts s^{-1} PCU^{-1} after background subtraction), the data did not allow us to fit the spectral data to obtain the spectral parameters. However, because the source spectra did not change significantly during all our TOO observations, it is likely that also during the bulge scan observations, the source had a similar power-law-shaped X-ray spectrum.

4. DISCUSSION

We presented the *RXTE*/PCA light curve of the only known millisecond X-ray pulsar during its 2000 outburst. The maximum observed luminosity was only $\sim 2.5 \times 10^{35}$ ergs s^{-1} (assuming a distance of 2.5 kpc), which is about a factor of 10 lower than the luminosities observed during the 1996 and 1998 outbursts. However, due to solar constraints the source could not be observed with *RXTE* before 2000 January 21, so the exact moment of the start of the outburst is unknown, and the peak luminosity could have been significantly higher. The source exhibited strong variability by a factor of ~ 20 on timescales of 1–5 hr, but by even larger factors on timescales of days. Therefore, the source became frequently too dim to be detected with *RXTE*. The last detection with *RXTE* was on 2000 May 13, almost 4 months after the source was first detected. SAX J1808.4−3658 was also observed (on March 5–6, 8, and 22–23) during its 2000 outburst with *BeppoSAX*, but during these observations it could not be detected, with an upper limit on its luminosity of $\sim 10^{32}$ ergs s^{-1} (0.5–5 keV) (Wijnands et al. 2001). However, on March 11 and 30, we detected the source again in the bulge scan observations, giving a luminosity of about $\sim 10^{35}$ ergs s^{-1} (3–25 keV). This demonstrates that the source was variable with a factor of about 1000 on timescales of only a few days.

The erratic 2000 outburst behavior of SAX J1808.4−3658 raises the question whether this was a unique event, or if this behavior is more common for this source. By closely examining the data obtained for the previous outbursts, we might be able to provide some answers. The 1996 outburst was only observed with the *BeppoSAX*/WFC. The recent detection of a third type I X-ray burst with the WFC, ~ 30 days after the peak of the 1996 outburst, clearly demonstrates that accretion was still occurring in this system several weeks after the WFC could no longer detect the persistent flux (with upper limits on the persistent emission of $\sim 2 \times 10^{35}$ ergs s^{-1}; 2–28 keV; in 't Zand et al. 2001). Although this is only a small fraction of the duration of the 2000 low-activity state, it indicates that the source could have been accreting considerably longer during this outburst than previously assumed.

The complete *RXTE*/PCA light curve obtained during the 1998 outburst is shown in Cui et al. (1998), from which it is clear that during the last three observations, the source flux behaved erratically. After the luminosity had decreased steadily to $\sim 10^{34}$ ergs s^{-1} (2–30 keV), it briefly increased again a few days later to $\sim 4 \times 10^{34}$ ergs s^{-1} (during the next to last observation). During the last observation, the luminosity had decreased to around 10^{34} ergs s^{-1}, but the source was still detected (thus, during all 1998 observations the source was detected) and the behavior of the source after this last observation is unknown, but it cannot be excluded that the source entered a similar low-level activity state as we observed during the 2000 outburst. To conclude, we cannot rule out that these low-activity states of SAX J1808.4−3658 are a common feature of the behavior of the source. However, to conclusively answer this question several new outbursts of this source have to be observed with X-ray instruments with enough sensitivity and monitoring capabilities (i.e., the *RXTE*/PCA bulge scans; note that the *RXTE* all-sky monitor or the *BeppoSAX*/WFC were not sensitive enough to detect this source during its 2000 low-activity state; J. in 't Zand 2001, private communication).

The low-activity state of SAX J1808.4−3658 resembles similar states observed for several other transients (see § 1). Because it is unknown when SAX J1808.4−3658 was first active in the 2000 outburst, it is difficult to distinguish for this source between a failed outburst (similar to what was observed for Aql X-1; Bradt et al. 2000) and a low-activity state that occurred after a major outburst. Even the duration of the low-activity state of SAX J1808.4−3658 (~ 114 days) is in between the duration of the failed outburst ($\sim$70–80 days) and the low-activity state after a major outburst ($\sim$150–160 days) of Aql X−1 (note that the low-activity states observed for 4U 1608−52 and 4U 1630−47 can last for several years). The question remains if disk instability models can explain these low-activity states. The most recent versions of the disk instability models take also into account irradiation of the disk by the central X-ray emitting region (Dubus, Hameury, & Lasota 2001; see Lasota 2001 for a review). Such models can produce the exponential decay of the X-ray light curves of certain X-ray transients but cannot explain other types of light curves. Other processes like an irradiation-induced increase of the mass transfer rate from the companion star might be responsible for the different type of light curves or for the low-level activity states (see, e.g., Kuulkers et al. 1997 for a discussion about this as a possible explanation for the low-level activity in 4U 1630−47).

It is difficult to understand the dramatic, factor-of-greater-than 1000 luminosity variations we observe in SAX J1808.4−3658 as owing to similarly dramatic variations in the mass accretion rate over such short (~ 1 day) timescales. Perhaps more modest variations can trigger transitions between two significantly different luminosity states. One possible mechanism is the centrifugal inhibition of magnetic accretion expected below a critical accretion rate—the so-called "propeller" regime (Illarionov & Sunyaev 1975). The onset of such centrifugal inhibition has been invoked to explain the sharp steepening of the light curve decay at the end of the 1998 outburst of SAX J1808.4−3658 (Gilfanov et al. 1998), as well as the 1997 outburst of the neutron star transient Aql X−1 (Campana et al. 1998). In the 1998 outburst of SAX J1808.4−3658, the transition occurred when the X-ray luminosity dropped below 4×10^{35} ergs s^{-1} (assuming a 2.5 kpc distance), corresponding to a critical mass accretion rate of $\dot{M}_{\rm crit} = 3.4 \times 10^{-10}\ M_{\odot}\ {\rm yr}^{-1}$. If the propeller effect is indeed responsible for the sharp break in the 1998 light curve, then small but erratic variations around $\dot{M}_{\rm crit}$ could in principle give rise to the enormous luminosity swings we observed in 2000. It is interesting to note that the peak 2000 luminosity of 2.5×10^{35} ergs s^{-1} is very close to the critical transition value inferred from the 1998 outburst, consistent with a propeller interpretation. Although it is not clear what might cause the required small variations in the mass accretion rate around $\dot{M}_{\rm crit}$, such variations may be characteristic of the outburst tails in soft X-ray transients. In that case, the dramatically variable behavior observed in SAX J1808.4−3658 (but not in other transients) may be an accident of the system's $\dot{M}_{\rm crit}$, which depends upon the neutron star's spin period and magnetic field strength.

The propeller mechanism might also explain why SAX J1808.4−3658 became as faint as it did in between the active episodes (to quiescent luminosities; Dotani, Asai, & Wijnands 2000). It is unclear whether or not the nonactive episodes during the 2000 outburst in between the active ones can be regarded as true quiescent states, because of the presence of an inner accretion disk in the system (down to the magnetosphere of the system), which is presumably absent in quiescence. But it is also unclear how (or even if) such an accretion disk would affect the X-ray properties of the source compared to the true quiescent state.

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