The Astrophysical Journal, 653: L133–L136, 2006 December 20

ORDER IN THE CHAOS: SPIN-UP AND SPIN-DOWN DURING THE 2002 OUTBURST OF SAX J1808.4−3658

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Received 2006 August 17; accepted 2006 November 7; published 2006 December 8

ABSTRACT

We present a timing analysis of the 2002 outburst of the accreting millisecond pulsar SAX J1808.4−3658. A study of the phase delays of the entire pulse profile shows a behavior that is surprising and difficult to interpret: superposed to a general trend, a big jump by about 0.2 in phase is visible, starting at day 14 after the beginning of the outburst. An analysis of the pulse profile indicates the presence of a significant first harmonic. Studying the fundamental and the first harmonic separately, we find that the phase delays of the first harmonic are more regular, with no sign of the jump observed in the fundamental. The fitting of the phase delays of the first harmonic with a model that takes into account the observed exponential decay of the X-ray flux (and therefore of the mass accretion rate onto the neutron star) gives important information on the torque acting on the neutron star during the outburst. We find that the source shows spin-up in the first part of the outburst, while a spin-down dominates at the end. From these results we derive an estimate of the neutron star magnetic field strength.

Subject headings: pulsars: general — pulsars: individual (SAX J1808.4−3658) — stars: magnetic fields — stars: neutron — X-rays: binaries

Online material: color figure

1. INTRODUCTION

In 1998, the idea that neutron stars in low-mass X-ray binaries (LMXBs) are spinning at millisecond periods was spectacularly demonstrated by the discovery of coherent X-ray pulsations at ∼2.5 ms in SAX J1808.4−3658, a transient X-ray source with an orbital period of 2 hr (Wijnands & van der Klis 1998). For almost four years SAX J1808.4−3658 has been considered to be a unique object in which some peculiarity of the system allowed the detection of the neutron star spin. However, in the last few years six other accreting millisecond pulsars have been discovered (see Wijnands 2004 for a review); all of them are transient, with spin periods in the range between 1.7 and 5.4 ms.

SAX J1808.4−3658 was soon recognized as a weakly magnetized ($<10^{10}$ G), rapidly rotating (401 Hz) accreting neutron star (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998). It is usually found in quiescence, where it shows a luminosity below 10^{32} ergs s^{-1}, and exhibits quasi-periodic outbursts, roughly every 2 years, with peak luminosity around 10^{36} ergs s^{-1}. It shows all the phenomenology of a typical LMXB (i.e., type-I X-ray bursts and burst oscillations, kilohertz quasi-periodic oscillations, etc.), together with coherent pulsations, which makes this system unique. Although other X-ray millisecond pulsars have been discovered recently, SAX J1808.4−3658, the only accreting millisecond pulsar for which more than one X-ray outburst has been observed, still remains the richest laboratory for the study of old accreting neutron stars in binary systems.

Still, no detailed timing studies have been published for this source so far. During the 2002 outburst of SAX J1808.4−3658, the persistent accretion-powered X-ray pulsations were detected with a fractional rms amplitude of 3%–10%. The pulsar spin frequency derived from these data was approximately 400.97521 Hz at the start of the outburst, and a mean spin-down rate of about 2×10^{-13} Hz s^{-1} has been claimed (Chakrabarty et al. 2003; see also Morgan et al. 2003).

In this Letter we report the results of the detailed timing analysis of the 2002 outburst of SAX J1808.4−3658; we find that the source shows a puzzling behavior of the phase delays, which can be interpreted analyzing separately the fundamental and first harmonic of the pulse profile.

2. TIMING ANALYSIS AND RESULTS

SAX J1808.4−3658 was in outburst in 2002 between October 15 and November 26 and was extensively observed by the *Rossi X-Ray Timing Explorer* (*RXTE*). We analyze here all the available observations of the *RXTE* data archive taken during this outburst. We mainly use data from the *RXTE* Proportional Counter Array (PCA; Jahoda et al. 1996), which consists of five identical gas-filled proportional counter units (PCUs), with a total effective area of ∼6000 cm^2, sensitive in the energy range between 2 and 60 keV. We used data collected in generic Events mode, with a time resolution of 125 μs and 64 energy channels. These files were processed and analyzed using FTOOLS version 5.3.1. In order to eliminate the Doppler effects caused by the Earth and satellite motion, the arrival times of all the events were converted to barycentric dynamical times at the solar system barycenter. The position adopted for the source was that of the proposed radio counterpart (0″.4 uncertainty, which is compatible with that of the optical counterpart; Rupen et al. 2002; Giles et al. 1999). The PCA light curve of the 2002 outburst of SAX J1808.4−3658 is shown in Figure 1 (*top*). For the spectral analysis we also used data from the High-Energy X-Ray Timing Experiment (HEXTE, ∼20–200 keV energy range; Rothschild et al. 1998).

To analyze these data we used the procedure that is extensively described in Burderi et al. (2007). We corrected the arrival times of all the events for the delays caused by the motion of the neutron star in the binary system, using the most updated orbital parameters (Papitto et al. 2005). To compute phases of good statistical significance we divided the whole

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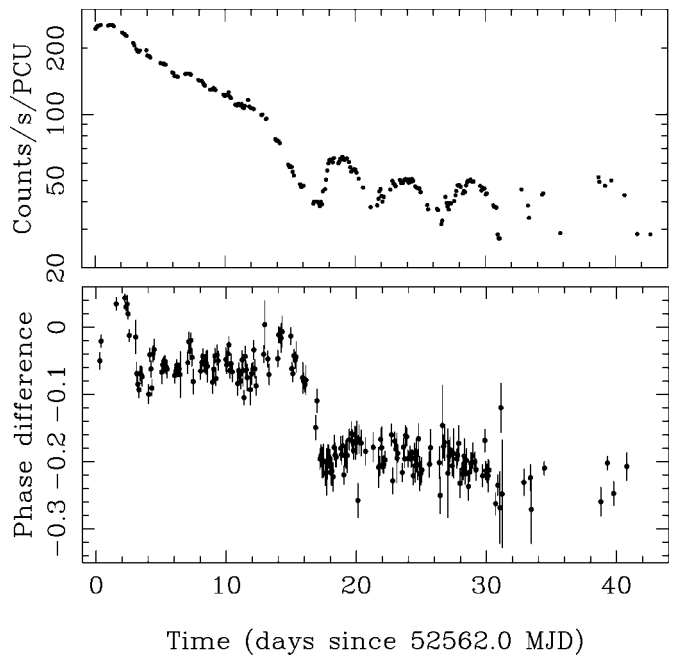

FIG. 1.—*Top*: PCA count rate of SAX J1808.4−3658 during the 2002 outburst. The start time, T_0, is MJD 52,562, corresponding to 2002 October 15. *Bottom*: Phase differences, fundamental minus harmonic, vs. time. The jump of the phase of the fundamental at day 14 is clearly visible in the differences.

observation in intervals of 2 hr, approximately the orbital period of the system; in this way we average over periodic phase residuals, if any, caused by errors in our assumed orbital parameters (see, e.g., Galloway et al. 2002; Burderi et al. 2007). We epoch-folded each interval of data in which the pulsation was significantly detected at the spin period of 2.493919760956 ms with respect to the same reference epoch, T_0 = MJD 52,562, corresponding to the beginning of the outburst. The fractional part of the phase was obtained by fitting each pulse profile with two sinusoids of fixed periods (corresponding to the fundamental, with period equal to the spin period, and the first harmonic, with period equal to half the spin period, respectively). In this way we obtain the phase delays shown in Figure 2 for the fundamental (*right*) and first harmonic (*left*), respectively.

The phase delays of the fundamental show a puzzling behavior, with a clear jump by about 0.2 in phase that occurs at day 14 after the beginning of the outburst. Interestingly, in the outburst light curve, the 14th day corresponds to a change of the steepness of the exponential flux decay (see Fig. 1, *top*); while before this day the X-ray flux decreases exponentially with a characteristic time of about 10 days, after this day the characteristic time of the exponential decay becomes about 3 days (a similar behavior of the light curve was observed for the 1998 outburst of SAX J1808.4−3658; Gilfanov et al. 1998). After day 17 from the beginning of the outburst the X-ray flux shows rapid oscillations of the count rate on timescales of hours to days. On the other hand, the phase delays of the first harmonic do not show any evidence of such a jump. Note that

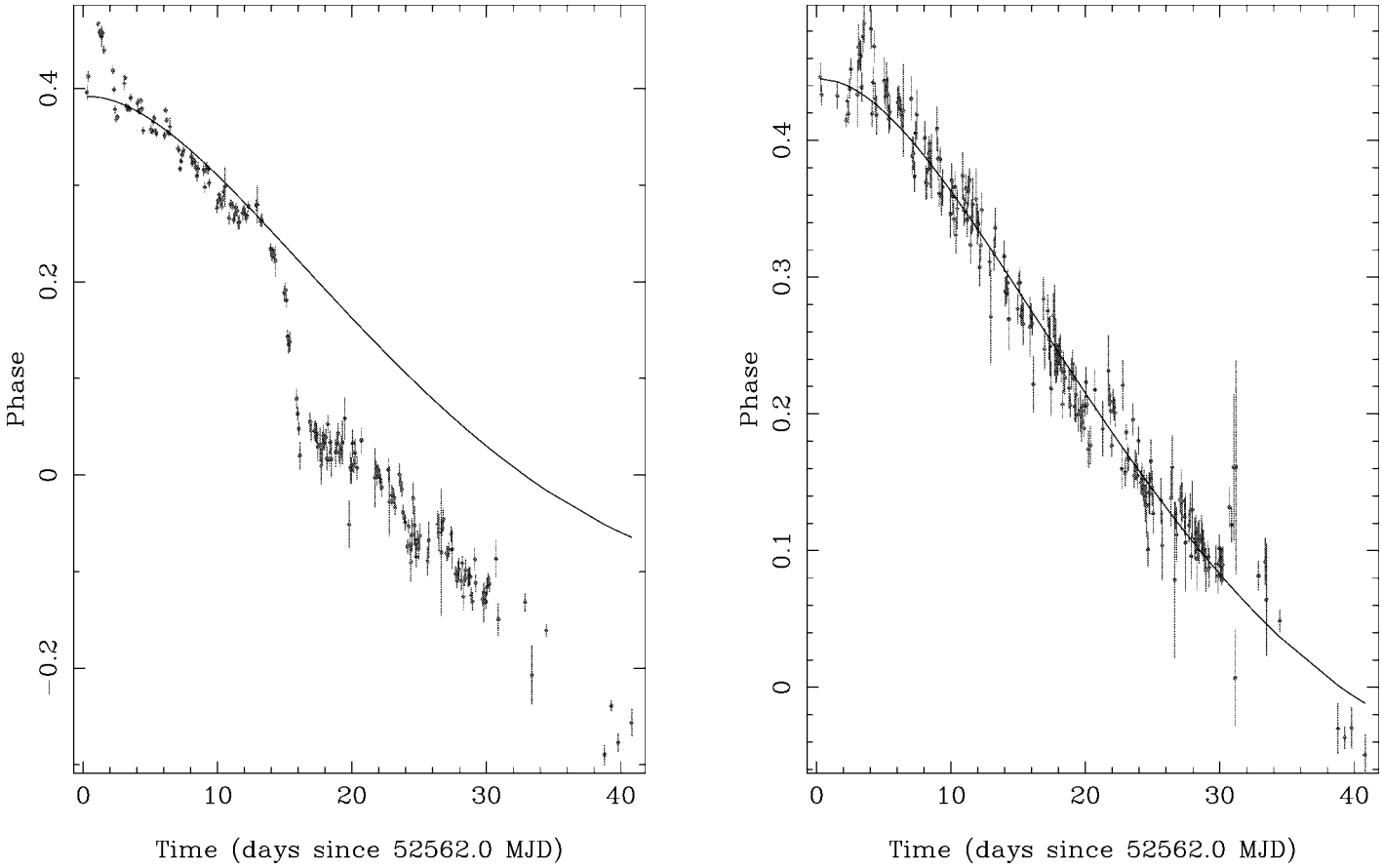

FIG. 2.—*Left*: Phase vs. time for the fundamental of the pulse frequency of SAX J1808.4−3658. *Right*: Phase vs. time for the first harmonic of the pulse frequency of SAX J1808.4−3658. On top of the data, the best-fit function (the sum of eq. [1] and a quadratic term) is plotted as a solid line. [*See the electronic edition of the Journal for a color version of this figure.*]

TABLE 1
Best-Fit Parameters of the Phase Delays of the First Harmonic

Parameter	Value	Parameter	Value
B	$(-0.8 \pm 2.6) \times 10^{-3}$	$\Delta\nu_0$	$-(3.61 \pm 0.72) \times 10^{-7}$ Hz
C	0.282 ± 0.054	$\dot{\nu}_0$	$(4.40 \pm 0.81) \times 10^{-13}$ Hz s^{-1}
D	$(2.85 \pm 0.59) \times 10^{-4}$	$\dot{\nu}_{sd}$	$-(7.6 \pm 1.5) \times 10^{-14}$ Hz s^{-1}
$\dot{M}_0$	$(1.81 \pm 0.32) \times 10^{-9}\ M_\odot$ yr^{-1}	ν_0	$400.975209690 \pm 7.2 \times 10^{-8}$ Hz

Notes.—The best-fit function is given by eq. (1) + $D(t - T_0)^2$, where $D = (1/2)\dot{\nu}_{sd}$. The reference time T_0 is the beginning of the observation, that is, 52,562 MJD. Quoted errors are at 90% c.l. and do not include the systematic uncertainties discussed in the text.

this is not an effect of the larger error bars of the phases of the harmonic, as it can be seen from Figure 1 (*bottom*), where we plot the differences between the phases of the fundamental and the phases of the harmonic as a function of time. For a global shift of the pulse profile the phases of the fundamental and harmonic should shift in the same way and the phase differences should remain constant. On the other hand, a variation of the differences indicates a shift of the phase of the fundamental with respect to the harmonic caused by a change of the shape of the pulse profile. In the plot of the phase differences it is possible to see that the big jump at day 14 is still visible in the differences and is much larger than the associated error bars, meaning that it is present in the fundamental and not in the harmonic. We conclude that in this case the behavior of the harmonic is genuinely simpler than the behavior of the fundamental, and therefore we tried to fit it to an appropriate model.

In order to derive the differential correction to the spin frequency, $\Delta\nu_0$, and the spin frequency derivative, $\dot{\nu}$, we have to derive a functional form for the time dependence of the phase delays. For a constant variation of the spin frequency ($\dot{\nu} =$ const), the phase delays (which are defined as the double integration over time of $\dot{\nu}$) will be a parabolic function of time. However, since for SAX J1808.4−3658 the X-ray flux is observed to vary with time, we expect a more complex dependence of time. To derive this expression, we use the following simple assumptions:

1. The bolometric X-ray luminosity L is a good tracer of the mass accretion rate, $\dot{M}$, *via* the relation $L = (GM/R)\dot{M}$, where G, M, and R are the gravitational constant and the neutron star mass and radius, respectively. Therefore, we assume for the mass accretion rate the following dependence on time: $\dot{M}(t) = \dot{M}_0 \exp[(t - T_0)/\tau]$, where τ, the characteristic time of the flux exponential decay, is 9.27 days from a fit of the X-ray light curve.

2. The accreted matter transfers to the neutron star its specific angular momentum at the corotation radius (see, e.g., Rappaport et al. 2004). In general, the matter should transfer to the neutron star its specific angular momentum at the accretion radius (that is, the magnetospheric radius, the radius at which the Keplerian accretion disk is truncated by the neutron star magnetic field). Since for accreting millisecond pulsars, the magnetospheric radius must be very close to the corotation radius (about 3 neutron star radii in the case of SAX J1808.4−3658), our assumption can be considered a good approximation and, in any case, gives a lower limit to the mass accretion rate needed to obtain the observed torque. Therefore, the rate of angular momentum transferred to the neutron star is $\dot{L} = 2\pi I\dot{\nu} = \dot{M}(GMR_{CO})^{1/2}$, where I is the neutron star moment of inertia, ν its spin frequency, and R_{CO} the corotation radius. We do not consider here any form of threading of the accretion disk by the magnetic field of the neutron star (see, e.g., Rappaport et al. 2004).

From these assumptions, with some algebra, we derive the following expression for the phase delays caused by accretion torque due to an $\dot{M}$ decreasing exponentially with time:

$$\phi(t) = \phi_0 - B(t - T_0) - C \exp[-(t - T_0)/\tau], \qquad (1)$$

where ϕ_0 is a constant, all the times are expressed in days, $C = 1.067 \times 10^{-4} I_{45}^{-1} P_{-3}^{1/3} m^{2/3} \tau^2 \dot{m}_0$, where I_{45} is the moment of inertia in units of 10^{45} g cm^2, P_{-3} is the spin period in milliseconds, m is the neutron star mass in solar masses, $\dot{m}_0$ is the accretion rate at $t = T_0$ in units of $10^{-10}\ M_\odot$ yr^{-1}, and, finally, $B = \Delta\nu_0 + C/\tau$, where $\Delta\nu_0$ is the differential correction to the spin frequency adopted for the folding of the light curves. Note that we are neglecting here the change to a steeper fall-off of the light curve that occurs at day 14.

However, as it becomes clear in the following, after day 14 the mass accretion rate is already so low that any spin-up torque becomes negligible (with respect to the behavior of the phase delays which instead tend to flattens; see below). Therefore, including a reduction of τ in the model after day 14 (which further reduces the already negligible spin-up) does not change the results.

We tried to fit the phase delays of the first harmonic with equation (1), but we obtained a poor description of the data, corresponding to a χ^2/dof = 613.1/199.[4] Indeed, using this model, we can obtain a good fit of the first 14 days of the outburst, but with respect to this fit, we observe a flattening of the phase delays after day 14. To describe this flattening we added to the model described by equation (1) quadratic term corresponding to a constant spin-down. In this way we obtained a significant improvement of the fit (χ^2/dof = 485.0/198; this χ^2 is still large, but now we do not see any systematic trend in the residuals with respect to the best-fit model). Although in this way we have obtained a great improvement of the quality of the fit, the obtained χ^2 is still unacceptable because of localized residuals around day 4 and day 30–31 from the beginning of the outburst. These residuals cannot be taken into account modifying the fitting function, but the uncertainties derived from a fit that is not acceptable in the statistical sense may be underestimated. To obtain more conservative uncertainties for our best-fit parameters, we therefore increased by a factor 1.5 the errors of all our phase points, obtaining in this way a χ^2/dof = 215/198 (that is now very close to 1), and we have recalculated all the uncertainties on our best-fit parameters. The best-fit parameters and the corresponding uncertainties (at 90% c.l.) are shown in Table 1; the best-fit function is plotted

[4] Note that fitting these data to simple linear or parabolic functions gives similar (slightly worse) results, corresponding to χ^2/dof = 623.4/200 or χ^2/dof = 622.4/199, respectively.

on top of the data in Figure 2. For a comparison, we have plotted the best-fit function of the first harmonic on top of the fundamental.

The last issue we have to discuss looks at the systematic uncertainties induced by the uncertainty on the source position. As discussed in Burderi et al. (2007), these systematics give both a systematic uncertainty on the linear term (that is the spin frequency correction) and on the quadratic term (that is the spin frequency derivative). For an error circle of 0″.4 around the position of SAX J1808.4−3658, we find that the systematic uncertainty on this two terms are $\Delta\nu_{\rm sys} = 7.9 \times 10^{-8}$ Hz and $\Delta\dot{\nu}_{\rm sys} = 1.8 \times 10^{-14}$ Hz s^{-1}, respectively. This increases the total uncertainty on the spin frequency to 1.1×10^{-7} Hz, and the total uncertainty on the spin-up and spin-down terms, which become $\dot{\nu}_0 = (4.40 \pm 0.83) \times 10^{-13}$ Hz s^{-1} and $\dot{\nu}_{\rm sd} = -(7.6 \pm 2.3) \times 10^{-14}$ Hz s^{-1}, respectively. Even considering these systematic uncertainties, both the spin-up and spin-down terms are still significant at more than 4 σ (note that all the reported uncertainty are at 90% c.l.).

Finally, in order to compare the derived spin-frequency derivative with the mass accretion rate $\dot{M}_0$ as inferred from the bolometric X-ray flux of the source, we performed a spectral analysis of the PCA and HEXTE spectra at the beginning of the outburst (i.e., at 2002 October 15 and 16). Keeping the absorption to the source fixed at $N_{\rm H} = 3.0 \times 10^{21}$ cm^{-2} (the Galactic X-ray absorption in the direction of SAX J1808.4−3658 at a distance of 3.5 kpc; Galloway & Cumming 2006), a very good fit to the 2.5–200 keV spectrum of SAX J1808.4−3658 is given by a disk blackbody plus a cutoff power law, and a Gaussian emission line with centroid fixed at 6.4 keV (the fluorescence K-shell iron line). We extrapolated the observed X-ray flux in a broadband energy range in order to evaluate the bolometric accretion luminosity, which resulted to be $\sim 1 \times 10^{37}$ ergs s^{-1} on 2002 October 15 assuming a distance of 3.5 kpc and correcting for the interstellar absorption.

3. DISCUSSION AND CONCLUSIONS

The results described in the previous section demonstrate that the timing analysis for an accreting pulsar is more complex than expected. The phase delays of the fundamental clearly show a jump by 0.2 in phase that may be due to instabilities induced by the accretion of matter onto a weakly magnetized star. Indeed, if the magnetic field is not strong enough to completely dominate the motion of matter to the polar caps, we can expect that variations in the accretion flow may cause small movements of the footpoint on the neutron star that can give rise to the shift in phase that we observe. On the other hand, the phase delays of the first harmonic show a more regular behavior and can be fitted to a model derived from the theory of the accretion torque, as it becomes clear below. Therefore, the first harmonic might have some fundamental physical meaning, probably related to the fact that this may represent the accretion onto both the polar caps.

As mentioned above, the results of the fitting of the phase delays of the harmonic are in agreement with torque onto the neutron star predicted by the accretion theory. A simple second-order polynomial or a model taking into account the exponential decrease with time of $\dot{M}$ do not give a good fit of the phase delays in the whole time range; these models give a good fit if we consider only the first 15 days of the outburst. We obtain a good fit of the phase delays during the whole outburst using the model described by equation (1) and adding to this model a quadratic term, which describes the flattening of the phases at the end of the outburst. This means that the neutron star is spinning up at the beginning of the outburst, as expected when the mass accretion rate is relatively high, but spins-down at the end of the outburst.

This gives very important information on the torque acting onto the neutron star in this system, implying that, when the mass accretion rate has significantly decreased, the torque onto the neutron star changes sign. This can be caused, for instance, by a threading of the accretion disk, which becomes important at low accretion rate (see Rappaport et al. 2004, eq. [23]). In this case, we can evaluate the magnetic field of SAX J1808.4−3658 from our measured value of the spin-down using the relation $\mu^2/(9r_{\rm CO}^3) = 2\pi I\dot{\nu}_{\rm sd}$. The magnetic field found in this way is $B \sim (3.5 \pm 0.5) \times 10^8$ G, in perfect agreement with previous constraints (see, e.g., Psaltis & Chakarabarty 1999; Di Salvo & Burderi 2003).

On the other hand, the spin-up observed in the first part of the outburst will give information on the mass accretion rate at the reference time $t = T_0$, that is, $\dot{M}_0 \simeq 1.8 \times 10^{-9}\ M_\odot$ yr^{-1}. This gives a bolometric X-ray luminosity at the beginning of the outburst of $\sim 2 \times 10^{37}$ ergs s^{-1}. This is about a factor of 2 higher than the bolometric X-ray luminosity inferred by the SAX J1808.4−3658 *RXTE* spectra (about 1×10^{37} ergs s^{-1} assuming a distance of 3.5 kpc). On the other hand, assuming that the mass accretion rate, $\dot{M}_0$, inferred from our timing analysis is correct, from a comparison with the observed X-ray flux, we can conclude that the source should be at a distance of ∼5 kpc.

This work was partially supported by the Ministero della Istruzione, della Università e della Ricerca (MIUR).

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