

SOFT PHASE LAGS OF PULSED EMISSION FROM THE MILLISECOND X-RAY PULSAR SAX J1808.4–3658

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ABSTRACT

We report the discovery of phase shifts between X-ray pulses at different energies in the newly discovered millisecond X-ray pulsar SAX J1808.4–3658. The results show that low-energy pulses lag high-energy pulses by as much as ~ 0.2 ms (or $\sim 8\%$ of the pulse period). The measurements were made in two different ways: (1) computing cross-power spectra between different energy bands, and (2) cross-correlating the folded pulse profiles in different energy bands; consistent results were obtained. We speculate that the observed *soft lags* might be related to the lateral expansion and subsequent cooling of a “hot spot” on the neutron star surface in which the pulsed X-ray emission originates. Also presented is the possibility of producing soft lags via Compton *downscattering* of hard X-ray photons from the hot spot in the cool surrounding atmosphere. We will discuss possible X-ray production mechanisms for SAX J1808.4–3658 and constraints on the emission environment, based on the observed soft lags, pulse profiles, and energy spectrum.

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

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) that contain a weakly magnetized neutron star are thought to be the progenitors of millisecond radio pulsars (see review by Bhattacharya & van den Heuvel 1991). Over the past two decades, extensive searches have been made for signatures of a rapidly spinning neutron star in such LMXBs (Leahy et al. 1983; Mereghetti & Grindlay 1987; Wood et al. 1991; Vaughan et al. 1994). No coherent millisecond X-ray pulsation has been detected in these attempts. Near-coherent millisecond oscillations have been observed in several sources, but *only* during thermonuclear (type I) X-ray bursts (Strohmayer et al. 1996, 1997; Zhang et al. 1996, 1998; Smith, Morgan, & Bradt 1997). They are interpreted as X-ray intensity being modulated at the spin period of the neutron star. Such an interpretation is, however, still model dependent. The lack of coherent pulsation in the persistent emission of LMXBs can perhaps be attributed to the low magnetic field believed to exist in these systems, compared with that in typical X-ray pulsars, or the smearing of the pulsar signal by such effects as gravitational lensing (Wood, Ftacilas, & Kearney 1988; Meszaros, Riffert, Berthiaume 1988) or scattering (Brainerd & Lamb 1987; Kylafis & Klimmis 1987; Wang & Schlickeiser 1987; Bussard et al. 1988).

Very recently, a coherently pulsed X-ray signal was revealed at a period of ~ 2.49 ms in the observations of XTE J1808–369 with the Proportional Counter Array (PCA) aboard the *Rossi X-Ray Timing Explorer (RXTE)* (Wijnands & van der Klis 1998) during its recent outburst (Marshall 1998). Raster scans were made to locate this newly discovered source, and the results imply that its position is consistent with that of SAX J1808.4–3658 (Marshall 1998), which was discovered by *BeppoSAX* in the midst of a previous outburst (in’t Zand et al. 1998). Moreover, the results from subsequent timing analysis of the *RXTE/PCA* observations seem to favor the *BeppoSAX* coordinates (Chakrabarty & Morgan 1998). During the pre-

vious outburst, *BeppoSAX* detected type I X-ray bursts from SAX J1808.4–3658 (in’t Zand et al. 1998). The bursting activity generally indicates the presence of a weakly magnetized neutron star in a binary system (Lewin, van Paradijs, & Taam 1995 and references therein). The binary nature of SAX J1808.4–3658 was firmly established with the detection of a 2 hr orbital period (Chakrabarty & Morgan 1998), as well as with the optical identification of the companion star (Roche et al. 1998).

The observed X-ray spectrum of SAX J1808.4–3658 is unusually hard for an X-ray pulsar (Gilfanov et al. 1998; Heindl & Smith 1998). It can be characterized by a Comptonized spectrum from a region of electron temperature $kT_e = 22$ keV and optical depth $\tau = 4$ (or 2) for a spherical (or slab) geometry (Heindl & Smith 1998; see Titarchuk 1994 for a discussion on different scattering geometries). The process of inverse Comptonization would cause high-energy photons to lag low-energy photons (see, e.g., Sunyaev & Titarchuk 1980, hereafter ST80). This consideration prompted us to search for any *hard* phase lags of X-ray emission from SAX J1808.4–3658. In this Letter, we report the discovery of significant *soft* phase lags of the pulsed emission, which are rather unexpected. In the framework of Comptonization models, the soft lags can be readily explained by Compton *downscattering* of high-energy photons, which would indicate the importance of the reprocessing of hard radiation from the neutron star surface by a cool surrounding atmosphere. We will present arguments for and against this interpretation and will also suggest an alternative scenario.

2. DATA ANALYSIS AND RESULTS

The data used for this study come from 19 PCA observations (out of a total of 21; the longer of the two observations was selected for April 18 and May 2). In particular, the event mode data with ~ 122 μ s timing resolution and 64 energy bands were selected (except for the April 13 observation in which the Good Xenon modes were used) to facilitate high-resolution timing analysis with a moderate energy resolution. A mixture of short and long pointed observations were conducted, with the effective exposure time ranging from ~ 1.4 to ~ 25 ks.

We carried out spectral analysis, using the Standard-2 data

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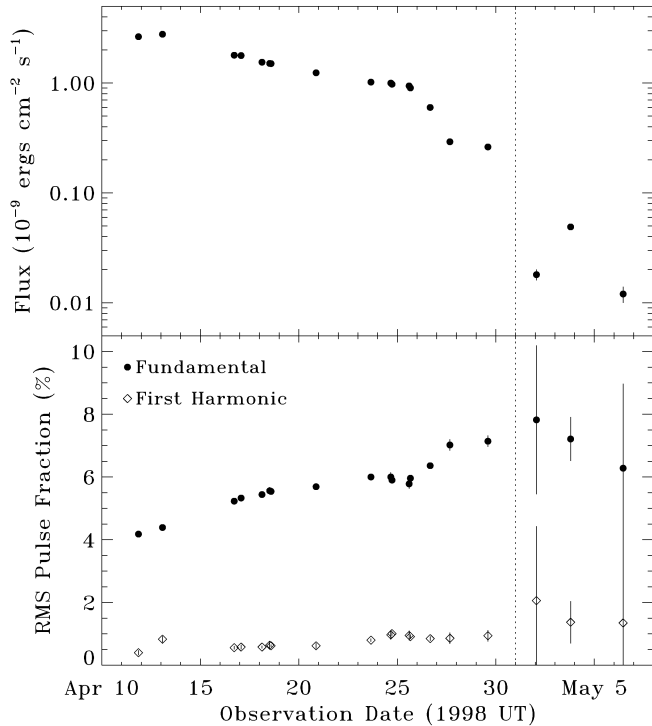


FIG. 1.—X-ray flux and fractional rms pulse amplitude. The measurements were made in the 2–30 keV band. Note that the dotted line indicates roughly the start of a period when the pulse signal was not detected with high significance.

(with 16 s timing resolution). Limited by the calibration uncertainties in the PCA response matrices, we selected only 75 out of 129 energy channels to cover an energy range 2.5–30 keV. Throughout the entire period, the observed X-ray spectrum maintains a rough power-law shape of photon index ~ 2 (see also Gilfanov et al. 1998 and Heindl & Smith 1998). The addition of a soft component (e.g., blackbody) improves the model fit significantly in terms of χ^2 statistics, confirming the reported soft excess (Heindl & Smith 1998). For each observation, we computed the observed X-ray flux by taking into account the PCA pointing offset (1/4, except for the first observation, where the offset is $\sim 12/3$). Figure 1 shows the decaying of the outburst, during which the X-ray flux varied by more than 2 orders of magnitude. Following the initial phase of an exponential decay, the flux started to drop precipitously around April 26. At the lowest fluxes, source confusion and background subtraction become serious problems for analyzing PCA observations. A raster scan was purposefully planned and carried out at the beginning of the last observation (on May 6), which showed that the detected X-ray emission was indeed from SAX J1808.4–3658 and that no apparent contaminating sources were present in the PCA field of view.

Because of large Doppler effects due to the orbital motion of SAX J1808.4–3658, it is more convenient to adopt a reference frame centering on the neutron star and rotating with the binary motion. After correcting photon arrival times for *RXTE*'s motion with respect to the barycenter of the solar system, we proceeded to take out the effects of binary motion by using the measured binary parameters (Chakrabarty & Morgan 1998).

We folded the corrected light curves (with background subtracted) at the pulse period in several energy bands. The mea-

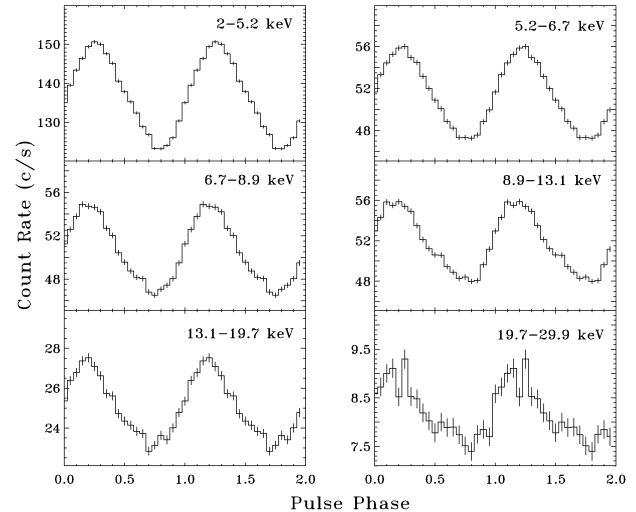


FIG. 2.—Sample pulse profiles. Folded are the light curves in six energy bands for the observation taken on 1998 April 23 (see Fig. 1). Note that each profile is repeated in two cycles for clarity.

sured fractional rms pulse fraction in the summed band (2–30 keV) is also plotted in Figure 1. An anticorrelation is apparent in the figure between the X-ray flux and fractional pulse amplitude. When the flux dropped below 2×10^{-11} ergs cm^{-2} s^{-1} on May 2, the pulse signal became barely detectable. The detection significance jumped up the next day, as the source flux increased by roughly a factor of 3, and dropped again in the last observation, as the source flux decreased again.

Typical pulse profiles are shown in Figure 2 (also see Wijnands & van der Klis 1998), taking the results from the April 23 observation (with an exposure time ~ 17 ks). The pulse profiles can be modeled adequately by a single sine function, but the fits are much improved with the inclusion of contributions from high-order harmonics. To improve statistics, we combined data from the observations between April 11 and 29 (as indicated in Fig. 1, with a total exposure time ~ 150 ks), when the pulse signal is detected with high significance, to obtain the average pulse profiles. By modeling these profiles, we measured average fractional rms pulse fractions for the fundamental component and high-order harmonics. The results are summarized in Figure 3. For the April 11 observation, our results are in agreement with those derived by Wijnands & van der Klis (1998). The fractional pulse amplitude shows an initially decreasing trend with energy for the fundamental component, but the opposite for the first harmonic (the error bars are quite large for the second harmonic). It seems to level off for both components above ~ 10 keV.

Finally, for each 128 s data segment, we constructed a power-density spectrum (PDS) and a cross-power spectrum (CPS) between the 2–3 keV band and each of several higher energy bands. Except for the observations on May 2 and 6 (in Fig. 1), the pulse signal shows up prominently as a peak in the PDS. There is also significant broadband power extending up to a few tenths Hz before dropping off toward higher frequencies. Individual CPSs are then properly weighted and co-added to obtain the average CPS for the observations between April 11 and 29. The average phase difference between X-ray pulses in two energy bands is directly derived from the average CPS. The results imply that low-energy pulses lag high-energy pulses, as shown in Figure 4. Actually, the soft lags are also

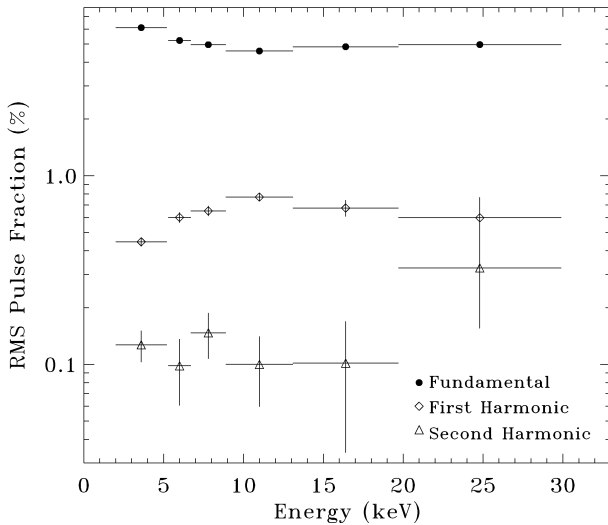


FIG. 3.—Energy dependence of measured pulse amplitudes. The results were obtained by averaging over data from the observations between April 11 and 29, as indicated in Fig. 1. Note that the error bars for the fundamental component are totally negligible compared with the size of the symbols used and therefore the initial decreasing trend of the pulse amplitude is highly significant.

apparent in Figure 2. By cross-correlating the folded pulse profiles at different energies, we also derived soft phase lags, which are consistent with those derived from the average CPS.

3. DISCUSSION

For SAX J1808.4–3658, the observed characteristics of the pulsed X-ray emission (pulse profiles and phase lags) and the overall energy spectrum can provide useful insights into X-ray production processes and the emission environment. The pulsed X-ray emission was detected in all observations. Integrating the best-fit Comptonization model (ST80) for the May 6 observation when the minimum flux was reached, we derived a bolometric luminosity $\sim 1.0 \times 10^{35}$ ergs s^{-1} (assuming a source distance 4 kpc; in’t Zand et al. 1998). The lack of centrifugal inhibition of accretion flows to the magnetic poles at such a low corresponding accretion rate implies the presence of a very weak magnetic field in the system ($\leq 0.4\text{--}1.3 \times 10^8$ G; cf. Wijnands & van der Klis 1998). Such a weak field is quite unusual for an accreting X-ray pulsar but is certainly consistent with our current knowledge about type I X-ray bursters.

If the soft phase lag is due to Compton *down*scattering of pulsed hard X-ray emission by a relatively cool medium, the observed pulse profile would be more sinusoidal at low energies, which is indeed observed (see, e.g., Fig. 3). The leveling-off of the fractional pulse amplitudes seems to indicate the fact that the intrinsic values are approached at high energies. This then implies that the intrinsic pulse profile is highly sinusoidal.

The size of the scattering medium can be constrained by the observed soft lags. For simplicity, we assume that the input photons are monochromatic with energy E_i . The photons that emerge from the cloud with *lower* energy E_l arrive at a distant observer later than those with *higher* energy E_h . The delay in the arrival time, δt , is given by $\sim \Delta u/lc$, where Δu is the difference in the average number of scatters experienced by seed photons before emerging with energies E_l and E_h , and l is the photon mean free path. The electron temperature of the cloud

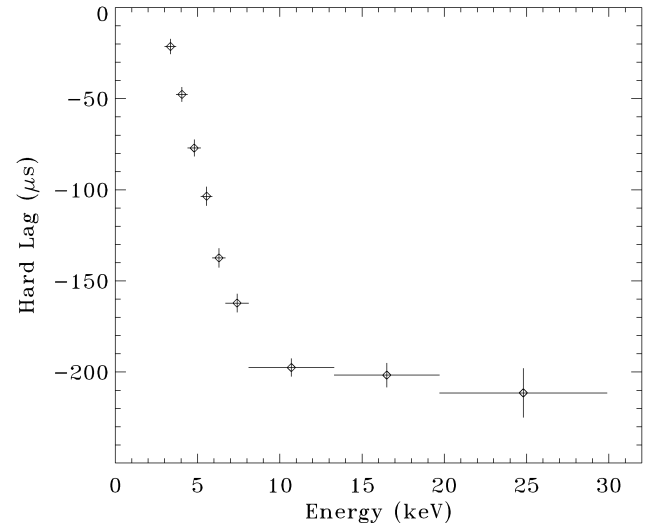


FIG. 4.—Measured hard X-ray lags with respect to the 2–3 keV band. Note that the data points are plotted arbitrarily in the middle of each energy band. The results have been averaged over the observations between April 11 and 29. The negative values emphasize the fact that hard X-rays actually *lead* soft X-rays.

is likely to be a fraction of keV, as required by the energetics in the vicinity of the neutron star. For cases where $kT_e \ll E_i$, the average fractional energy loss of input photons after each scatter is nearly independent of T_e and is given by $\Delta E/E \approx -E/m_e c^2$, where m_e is the electron mass. Integrating over multiple scatters, we have $\Delta u = m_e c^2 (1/E_l - 1/E_h)$. Substituting this result into the expression for δt gives

$$\delta t \sim \frac{r}{c\tau} \left(\frac{m_e c^2}{E_l} - \frac{m_e c^2}{E_h} \right), \quad (1)$$

where r is the radius of a spherical “cloud” into the center of which input photons are injected and $\tau = r/l$ is its optical depth. The measured soft lag scales very roughly as E^{-1} , as shown in Figure 4, and it seems to level off above 10 keV. In reality, however, the situation is much more complicated. The input photons may be distributed over a large energy range as well as over an extended region spatially. Moreover, the analysis deals only with broad energy bands rather than the energy of individual photons. Convolved with input photon distribution in both energy and space, the soft-lag plateau seems to imply that the “effective” energy of input photons is ~ 10 keV. Because it takes more than 100 scatterings for a 10 keV photon to reach the reference band and the average number of scatterings is on the order of τ^2 (ST80), the cloud must be quite large ($\tau \geq 10$). It would then be imperative that the hot spot is viewed directly, since the scattering process would significantly soften the spectrum (ST80). Hard photons from the hot spot are down-scattered in the cool surroundings to produce the observed soft lags and, perhaps, also the soft excess observed. A fit to the initial portion of the curve with equation (1) yields $r/c\tau \approx 1.75 \mu s$, hence, $r \sim 0.5\tau$ km. Therefore, the cloud is a few kilometers in size. Given the compactness of the binary system for SAX J1808.4–3658, significant X-ray heating of the companion star is expected (see discussion in Chakrabarty & Morgan 1998). As a result, the mass loss from the companion star is much enhanced, perhaps forming a relatively dense wind

that scatters hard X-rays originating in the vicinity of the neutron star. It is, however, not clear how to produce a “hole” through such an extended cloud toward the hot spot.

Alternatively, the soft lags might be caused by hydrodynamical propagation of the hot spot over the neutron star surface. Compared with typical X-ray pulsars, SAX J1808.4–3658 only contains a very weakly magnetized neutron star. The magnetic confinement of plasma in the hot spot is therefore relatively weak. Consequently, the plasma could spread out over the neutron star surface relatively easily, at hydrodynamical velocities on the order of sound speed. During the lateral expansion, the outskirts of the hot spot cools down—the temperature is approximately inversely proportional to the square root of the spot size. For a circular spot of radius 0.5 km and of temperature 25 keV, the propagation timescale is roughly 3×10^{-4} s. This process could therefore account for the observed soft lags, if the soft photons that lag originate in the cool outskirts of the expanding hot spot. Assuming $E \propto kT$, since $kT \propto r^{-1/2}$ and $r \sim c_s \delta t$, we get $\delta t \propto E^{-2}$, which is not inconsistent with the data (see the initial portion of the curve shown in Fig. 4). In the context of this model, the pulse profile is also expected to be smoother at low energies because the softer photons come from a larger area (and thus are more integrated).

The X-ray pulsation is detected at high energies (see Fig. 2), implying that the hot spot produces very hard photons. For LMXBs that contain a weakly magnetized neutron star, the physical processes for producing hard X-ray radiation have been discussed in literature since the late 1960s. Zeldovich & Shakura (1969) presented a model where the gravitational energy of matter accreted onto the neutron star is released in a thin layer above the neutron star surface. Variations of this idea have also been proposed and formulated quantitatively in detail models (see, e.g., Alme & Wilson 1973 and Basko & Sunyaev 1975a for accretion in the presence of a magnetic field; Turolla et al. 1994 for spherical accretion; and Kluźniak & Wilson 1991 for “gap accretion”). The deep layers of the neutron star

atmosphere are heated by the outer layer and produce soft thermal photons. The soft photons are subsequently Compton upscattered by hot electrons in the outer layer and form a thermal Comptonized spectrum (ST80). Titarchuk, Lapidus, & Muslimov (1998) verified Zeldovich & Shakura’s calculation and showed that for a layer of optical depth a few, *the product of the optical depth and plasma temperature is almost invariant*. Therefore, the Comptonized spectrum from the layer maintains roughly the same shape as long as the mass accretion rate is about 10% of the Eddington limit or less. Note that the *hard* lags of the emission due to Compton upscattering are negligible because of the compactness of the region. For SAX J1808.4–3658, the mass accretion rate is less than $10^{-9} M_\odot \text{ yr}^{-1}$ throughout the recent outburst, so the optical depth of the accretion column is always relatively small. The combination of low magnetic field and thin accretion column can easily result in hot spots with a temperature $kT_e \sim 20$ keV, as observed (Heindl & Smith 1998). Also observed is the expected constancy of the X-ray spectral shape during the outburst (Gilfanov et al. 1998). It is worth noting that similar models cannot be applied to typical X-ray pulsars where magnetic field is strong. In those cases, the proton energy loss due to Coulomb collisions becomes negligible compared with that due to nucleon-nucleon collisions, and thus the mean free path for energy release can become quite large (Basko & Sunyaev 1975b). As a result, the temperature of the Comptonizing layer is relatively low, so the spectrum is usually soft.

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