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LAG OF LOW-ENERGY PHOTONS IN AN X-RAY BURST OSCILLATION: DOPPLER DELAYS

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ABSTRACT

Numerous X-ray bursts show strong oscillations in their flux at several hundred hertz as revealed by *Rossi X-Ray Timing Explorer*. Analyzing one such oscillation from the X-ray binary Aquila X-1, I find that low-energy photons (3.5–5.7 keV) lag high-energy photons (>5.7 keV) by approximately 1 rad. The oscillations are thought to be produced by hot spots on the spinning neutron star. The lags can then be explained by a Doppler shifting of emission from the hot spots, higher-energy photons being emitted earlier in the spin phase as the spot approaches the observer. A quantitative test of this simple model shows a remarkable agreement with the data. Similar low-energy lags have been measured in kilohertz quasi-periodic oscillations and in the accreting millisecond pulsar SAX J1808.4−3658. A Doppler delay mechanism may be at work there as well.

Subject headings: accretion, accretion disks — black hole physics — stars: neutron — X-rays: stars

1. INTRODUCTION

The *Rossi X-Ray Timing Explorer* (*RXTE*) has uncovered strong oscillations of X-ray flux during X-ray bursts in several low-mass X-ray binaries (Strohmayer et al. 1996). Current interpretation favors a rotation mechanism for the burst oscillations: asymmetric nuclear burning leaves a "hot spot," which rotates with the neutron star and produces a strong modulation (Strohmayer et al. 1998). The frequency of the burst oscillation is then the spin frequency of the neutron star, or twice the spin frequency for two spots (Miller 1999). Oscillations have been discovered in X-ray bursts from the following systems: 4U 1728−34 (363 Hz; Strohmayer et al. 1996; Strohmayer, Zhang, & Swank 1997), KS 1731−260 (524 Hz; Smith, Morgan, & Bradt 1996), a source near the galactic center (589 Hz; Strohmayer, Jahoda, & Giles 1997), Aquila X-1 (549 Hz; Zhang et al. 1998), 4U 1636−536 (581/290 Hz; Strohmayer et al. 1998; Miller 1999), and 4U 1702−429 (330 Hz; Markwardt, Strohmayer, & Swank 1999). The observed frequencies are close to the 401 Hz spin frequency of the accreting millisecond pulsar SAX J1808.4−3658 (Wijnands & van der Klis 1998), further strengthening the identification of these frequencies with the neutron star spin.

The detailed energy dependence of these burst oscillations is one avenue that remains to be explored. Here I show that the low-energy photons in a burst oscillation from Aql X-1 lag the high-energy photons by roughly 15% of the oscillation period. Lags of the same sign and similar magnitudes have also been detected in other fast signals from low-mass X-ray binaries: the kilohertz quasi-periodic oscillations (QPOs; Vaughan et al. 1997, 1998; Kaaret et al. 1999) and the SAX J1808.4−3658 pulsed emission (Cui, Morgan, & Titarchuk 1998).

A simple mechanism of Doppler-shifted emission may explain these lags. Strong Doppler effects are expected to be important, since the fast spin rates imply high speeds ($\beta = v/c \sim 0.1$). As a hot spot on the spinning neutron star approaches the observer (at early phases), the emission is Doppler boosted and blueshifted; as it recedes (at later phases), the emission is deboosted and redshifted. At early phases the spectra are also attenuated because of the smaller projected area. The result is that low-energy photons are preferentially emitted after the high-energy photons. A quantitative test of this Doppler delay scenario matches the observed low-energy lags in Aql X-1 well. The possibility of Doppler effects and the fact that they may manifest in pulse-phase spectroscopy has been noted before by Strohmayer et al. (1998).

In the next section I present the measurement of the lag in the X-ray burst from Aql X-1. In § 3 I describe a simple model for the relativistic effects and compare the predicted delays to those observed. Section 4 discusses these results in a broader context.

2. MEASUREMENTS

For this analysis I consider the X-ray burst from Aql X-1 starting 1997 March 1 23:27:40 UTC (see Zhang et al. 1998 for a report of this burst). I use data from the *RXTE* Proportional Counter Array (PCA) in an event mode with high time resolution (122 μs) and high energy resolution (64 channels). A section of the light curve is shown in Figure 1 (*top*). There are gaps in the event mode data since the required telemetry rate is high. Within the 4 s time window shown in Figure 1 (*top*), the power density spectrum for all the channels shows a strong oscillation at 549.7 Hz (Fig. 1, *bottom*). In the following I calculate Fourier transforms within this time window.

Phase delays in a signal between two energy bands are quantified by means of cross spectral analysis (van der Klis et al. 1987; for more information, see Vaughan et al. 1994; Nowak et al. 1999). The cross spectrum is defined as $C(j) = X_1^*(j)X_2(j)$, where the X's are the measured complex Fourier coefficients for the two energy bands at a frequency ν_j. The phase lag between the signals in the two bands is given by the argument of C (its position angle in the complex plane). The error in the phase lag is calculated here from the coherence function uncorrected for counting statistics (Nowak et al. 1999). The cross-correlation code used here has been employed to calculate phase lags in black hole candidates (Ford et al. 1999), SAX J1808.4−3658, and kilohertz QPOs and matches the results reported in the literature.

Figure 2 shows the resulting phase lags from the cross spectra of the 4 s of data described above. Negative numbers indicate that the oscillations in the low-energy band (3.5–5.7 keV) lag those in the higher energy bands. The lags are calculated by averaging the signal in the range 549.6–550.1 Hz. The delays in each band up to 30 keV (where background dominates) are

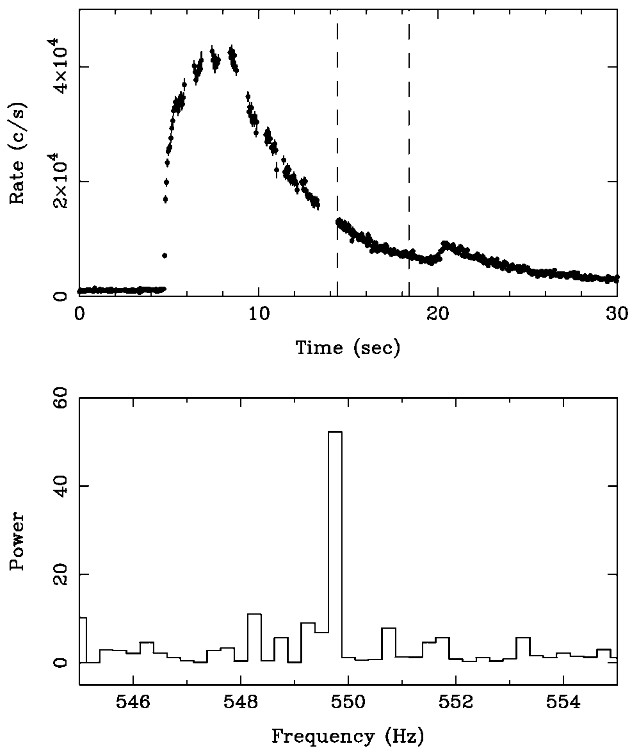

FIG. 1.—Light curve (*top*) and power spectrum (*bottom*) for the 1997 March 1 X-ray burst from Aql X-1. The power spectrum is from 4 s of data taken in the time window shown by the dashed lines. Data gaps are due to telemetry overloads in this PCA mode.

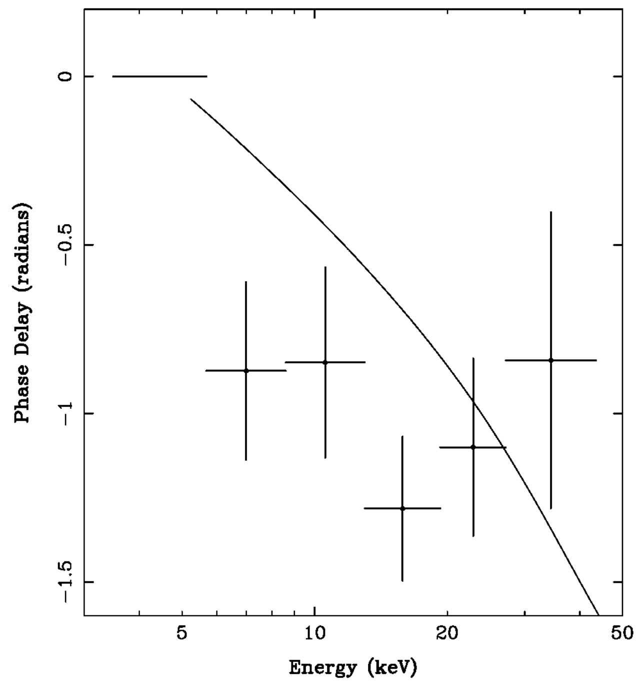

FIG. 2.—Phase delay measurements for the X-ray burst oscillation shown in Fig. 1 relative to the 3.7–5.7 keV band. A negative value indicates that low-energy photons lag high-energy photons. The solid line is the Doppler delay model for two hot spots (see text).

3 σ significant. The delay between 3.5–5.7 keV and the entire 5.7–43.6 keV band is 0.93 ± 0.18 rad, 5 σ significant.

Dead-time effects can in principle affect the measured phase lag. The data considered here are in the tail of the burst (rate of 9280 counts s^{-1}, full energy band) where dead time is less important. One method of correcting for dead time is to subtract a cross vector averaged over high frequencies at which no correlation is expected (van der Klis et al. 1987). Employing this correction does not change the values measured here.

Because of the data gaps, it is not possible to perform cross-correlations on long stretches of data earlier in the burst. Cross-correlations on 0.5 s intervals of data earlier in the burst return large errors on phase delays with inconclusive results.

3. MODEL

As a simple model for the lags I consider discrete hot spots on the surface of the rotating neutron star. The rest-frame emission of the clump is a blackbody. The observed spectrum at frequency ν at spin phase θ is

$$F_\nu(\nu) = A_0 \cos\delta[\gamma^{-1}(1 - \beta\mu\cos\theta)^{-1}]^3 \times \nu^3[\exp(\nu/kT) - 1]^{-1},$$

where $\beta = v/c$, γ is the Lorentz factor, $kT = kT_0\gamma^{-1}(1 - \beta\mu\cos\theta)^{-1}$ (with kT_0 the rest-frame temperature), μ is the sine of the angle between the spin axis and the line of sight, and A_0 is a normalization. The above formula is a relativistic transformation of the blackbody that shifts kT and modifies the normalization such that F/ν^3 is conserved (see Rybicki & Lightman 1979). The $\cos\delta$ term is an area projection factor, with δ the angle between the normal and line of sight in the rest frame ($\delta \sim \pi - \theta$). The phase angle θ is defined such that phase zero is with the spot approaching the observer directly. The spots are considered small and isotropically emitting in the rest frame.

I take $kT_0 = 1$ keV, $\beta = 0.1$. These are values appropriate for the neutron star; a more exact value of kT_0 is in principle possible from the spectral fits, but this depends on the fraction of the surface contributing to the modulated hot spot emission. A more exact value of β depends on the neutron star radius. I also take $\mu = 1$, i.e., a line of sight through the equator. The spin frequency is 275 Hz, and two antipodal hot spots produce an oscillation at 550 Hz. Such a geometry, where the ~550 Hz signal is a harmonic of the spin, is suggested by recent results on other burst oscillations (Miller 1999). The resulting spectra are blackbodies whose temperature shifts by 10% over the period. Averaged over phase, the spectrum is approximately blackbody in shape with kT within 1% of the input kT_0.

The spectra as a function of θ, folded through the *RXTE* response matrix, yield light curves of count rates in various energy bands. From these light curves I calculate the phase lag in the 550 Hz signal with the fast Fourier transform and cross-correlation program used in the measurements above. The results of this calculation are shown with the data in Figure 2. There are no free parameters, only the assumptions taken above. The calculated lags will decrease if kT_0 is increased or β is decreased. The smaller delay for higher kT_0 happens since the peak of the light curves comes later in phase for higher energy photons, corresponding to a smaller delay between high- and low-energy photons. Observing at higher inclinations (decreased μ) will also decrease the lag. The light curves that yield these predicted lags generally have maxima at earlier phases for higher energies and are more sharply peaked in shape at higher energies.

This simple model neglects general relativistic effects (e.g., Strohmayer 1992; Miller & Lamb 1998). Two main factors from general relativity will affect the observed light curves. Gravitational bending makes the spots observable at $\theta < 0$ or $\theta > \pi$, stretching the pulse. Light-travel time delays, longer for more extreme bending, will also shift the pulse. These effects depend on the compactness of the star. Given the quality of the present data, a more detailed treatment including these effects is not justified. An overall gravitational redshift also means that kT in the local frame is higher, as in X-ray burst spectral models.

4. DISCUSSION

The previous sections show that low-energy photons lag high-energy photons in the oscillation signal of an X-ray burst from Aql X-1. The sign and magnitude of the lags are in agreement with the simple model considered in § 3 of two hot spots on the neutron star producing Doppler-boosted and Doppler-shifted spectra as the star rotates.

This Doppler delay mechanism for producing low-energy lags may describe not only the lags in the X-ray burst oscillations but also the lags in the accreting millisecond pulsar SAX J1808.4−3658 (Cui, Morgan, & Titarchuk 1998) and the (lower frequency) kilohertz QPOs (Vaughan et al. 1997, 1998; Kaaret et al. 1999). Both show a lag of low-energy photons relative to high-energy photons with magnitudes of roughly ~100 μs (~0.3 rad) for SAX J1808.4−3658 and ~30 μs (~0.2 rad) for the kilohertz QPOs in similar energy bands to those considered here. Some models link the frequency of the kilohertz QPOs to a Keplerian motion in the disk (Miller, Lamb, & Psaltis 1998; Stella & Vietri 1999; but see Titarchuk, Lapidus, & Muslimov 1998). If any of the kilohertz QPOs is a result of Keplerian motion, one might expect a soft lag due to Doppler delays. Such lags have been observed in what is likely the lower frequency of the two QPOs.

Doppler delays are an alternative to previous mechanisms invoked to produce lags. Comptonization has been one process used to explain low-energy lags in SAX J1808.4−3658 (Cui et al. 1998). Low-energy lags are produced if high-energy photons are injected into a relatively cool Comptonizing cloud. This is the opposite of the situation normally considered: Comptonization by a hot cloud in the same region. A hot cloud produces a lag of high-energy photons, as shown quantitatively for fast signals by Lee & Miller (1999). Another mechanism suggested for low-energy delays is an extended, cooling hot spot with lower energy photons from the outer regions (Cui et al. 1998).

More measurements of phase lags in X-ray burst oscillations are clearly needed, in particular in the ~350 Hz oscillations that are likely from single spots. Improved statistics will also yield a better test of the predicted energy dependence of the lags.

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