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DISCOVERY OF MICROSECOND SOFT LAGS IN THE X-RAY EMISSION OF THE ATOLL SOURCE 4U 1636−536

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ABSTRACT

Exploiting the presence of kilohertz quasi-periodic oscillations (QPOs) in the timing power spectrum, we find that the soft X-ray emission of the neutron star X-ray binary and atoll source 4U 1636−536, modulated at the QPO frequency, lags behind that of the hard X-ray emission. Emission in the 3.8–6.4 keV band is delayed by 25.0 ± 3.3 μs relative to the 9.3–69 keV band. The delay increases in magnitude with increasing energy. The soft lag could be produced by Comptonization of hard photons injected into a cooler electron cloud or by intrinsic spectral softening of the emission during each oscillation cycle.

Subject headings: accretion, accretion disks — stars: individual (4U 1608−52, 4U 1636−536) — stars: neutron — X-rays: stars

1. INTRODUCTION

Millisecond quasi-periodic oscillations (QPOs) in the X-ray emission of X-ray binaries are likely related to physical processes occurring near the compact object and thus may provide information about accretion flow in the strong gravitational fields near the compact object (for a brief review, see Kaaret & Ford 1997). The existence of the QPOs can be exploited to measure additional properties of the X-ray emission mechanisms and geometry. Here we use kilohertz QPOs with relatively high coherence, $\nu/\Delta\nu > 100$, to measure microsecond lags between emission in different X-ray energy bands.

In § 2, we describe the observations and technique used to calculate the time lags. In § 3, we present the results of the lag measurements. We conclude, in § 4, with brief comments on the physical implications.

2. OBSERVATIONS AND ANALYSIS

The following results use data from the Proportional Counter Array (PCA) (Zhang et al. 1993) on the *Rossi X-ray Timing Explorer* (Bradt, Rothschild, & Swank 1993) with 122 μs time resolution for X-rays in the 2–70 keV band. The data presented here for 4U 1636−536 are from a 23 ks interval beginning 1998 February 24, 23:26:20 UTC, during which QPOs were detected.

Before attempting to measure time delays, we investigated the QPOs. We performed Fourier transforms on 1 s segments of data with no energy selection, yielding a Nyquist cutoff frequency of 4096 Hz and a transform window function with a width of approximately 1 Hz. The power spectra within 128 s intervals were summed. The total power spectrum for each 128 s interval was searched for QPO peaks above 100 Hz. A function, consisting of a Lorentzian plus a constant, was fitted for each trial frequency, defined as those points with power more than 2 σ above the average. All 128 s intervals for which QPO peaks were detected with greater than 2 σ significance were retained. In the case of multiple QPO detections in one interval, the QPO with the highest significance was chosen. Typically, the QPOs were detected at better than 4 σ significance.

The single QPO peak had a centroid varying in the range of 775–895 Hz (see Fig. 1). The centroid frequency could be determined to an accuracy better than 0.4 Hz. The QPO peak widths had an average of 4.7 Hz. The intrinsic variation in the centroid is far larger than the centroid measurement error or the QPO peak width.

In using an oscillation (whether coherent or quasi-periodic) to measure a time delay between different energy bands, the cross spectrum is integrated over a selected frequency range. A narrow frequency range reduces the noise in the measurement, but the range must be sufficiently broad to contain the oscillation power. In the standard approach, a fixed frequency range is used for the full duration of an observation (see, e.g., Vaughan et al. 1997). Due to the large variations in the QPO centroid in our observation, we chose instead to integrate the cross spectrum over a range varying with the QPO centroid. We selected an integration range of approximately twice the average QPO peak width. Compared with the fixed frequency range of 120 Hz required to contain the wandering QPO peak, the signal-to-noise ratio for the measurement of a time delay in our observation of 4U 1636−536 is improved by roughly a factor of 3.

We calculated the cross spectrum between a pair of energy bands for each 1 s of data and found the average and variance for each 128 s interval. A complex cross correlation vector was calculated for each 128 s interval by integrating over a 10 Hz frequency range centered on the QPO peak centroid found for that interval. We summed the complex cross correlation vectors found for each interval in order to derive a complex cross correlation vector for the whole observation. The phase lag given by the argument of this total complex cross correlation vector was then converted to a time delay using the average of the QPO centroid frequencies found in the 128 s intervals. The error was calculated from the variance in the real and imaginary components of the total cross correlation vector. Intrinsic as well as statistical fluctuations contribute to the error estimate. We also estimated the time delay for the

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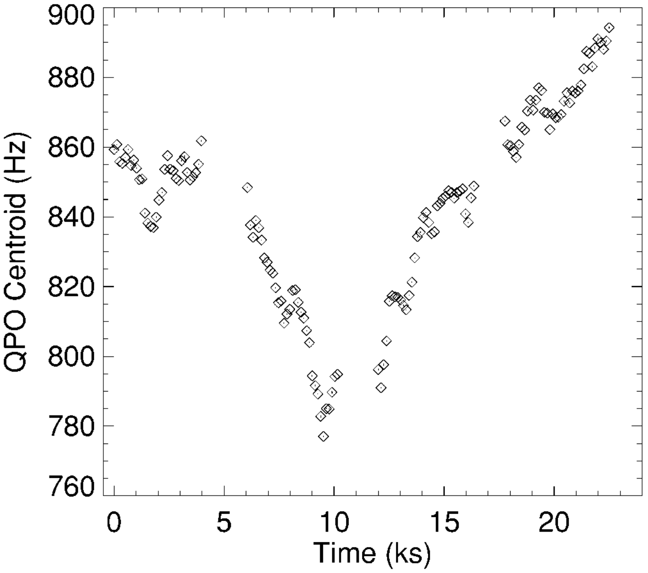

FIG. 1.—Centroid of the QPO peak vs. time for 4U 1636−536. The time zero is 1998 February 24, 23:26:20 UTC.

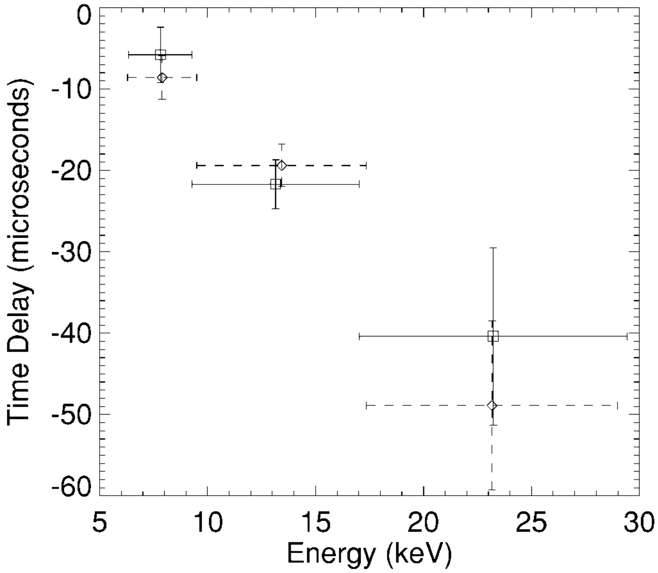

FIG. 2.—Time delay vs. energy for 4U 1636−536 (*squares*) and 4U 1608−52 (*diamonds*). The error bar on energy indicates the band used to calculated the delay. The delays are relative to the 3.8–6.4 keV band for 4U 1636−536 and to the 3.9–6.3 keV band for 4U 1608−52. Following Cui et al. (1998), the negative values emphasize the fact that the hard X-rays actually lead the soft X-rays.

whole observation by averaging time delays calculated for each 128 s interval. The two methods gave consistent results, which is expected since the fractional range of the QPO centroid variation is relatively small, about 14%. We cannot distinguish whether the lags remain constant in phase or in time as the centroid frequency varies. We quote the time delay found from the total cross correlation vector. To determine the correct sign for the lags, we tested our analysis code using simulated data and observations of SAX J1808.4−3658 for which the correct sign can be determined by direct examination of the pulse-folded light curve in the various energy bands (Cui, Morgan, & Titarchuk 1998).

3. RESULTS

Time delays, for 4U 1636−536, were calculated from 138 segments of 128 s each in which QPOs were detected. The soft emission in the 3.8–6.4 keV band lags the hard emission above 9.3 keV by 25.0 ± 3.3 μs. The coherence, calculated following the prescription of Vaughan & Nowak (1997), is consistent with unity and is above 0.75. The detection of the lags is significant at the 7 σ level. The lag for the 6.4–9.3–17.0–29.4 keV energy bands versus the 3.8–6.4 keV band are shown in Figure 2. We indicate the lags as negative in order to emphasize that the hard emission precedes the soft emission. The magnitude of the delay increases with energy.

We also divided the data into the four contiguous segments of QPO detections apparent in Figure 1. We find no strong evidence for variability of the time delay between any two segments. The most significant difference is only 1.6 σ.

To check our analysis and also to have a second source for comparison, we analyzed data for 4U 1608−52 for a 13 ks interval beginning 1996 March 3, 19:18:20 UTC, extracted from the public archive. The 4U 1608−52 data show a single QPO varying over the range 820–890 Hz. We find the same sign and similar magnitudes of delay in 4U 1608−52 as in 4U 1636−536. We detected QPOs in 66 segments of 128 s each and used an integration width of 12 Hz to better match the QPO width in 4U 1608−52. The soft emission in the 3.9–6.3 keV band lags the hard emission above 9.5 keV by 21.4 ± 2.7 μs. The energy dependence of the lag is shown in Figure 2. Delays are shown for the 6.3–9.5–17.4–29.0 keV energy bands relative to the 3.9–6.3 keV band. The energy bands were selected to best match those used in the 4U 1636−536 analysis, allowing for gain changes in the PCA. Vaughan et al. (1997) found delays of similar magnitude but opposite sign for part of this same observation. The sign was later corrected (Vaughan et al. 1998) and is now consistent with our results.

4. DISCUSSION

The facts that the hard emission precedes the soft emission and that the modulation of the QPO is higher in the hard band (Zhang et al. 1996) suggest that the process generating the QPO acts earlier and more strongly at higher energies. The soft lag could be produced either by reprocessing of the hard emission into a softer band or by spectral softening of the intrinsic emission during each oscillation cycle.

The lag is opposite in sign to that generally expected in Comptonization models, in which the spectrum is usually generated by upscattering soft photons (Sunyaev & Titarchuk 1980), but could be due to Compton scattering of hard photons injected into a scattering medium that is cooler than the injected photon spectrum. This mechanism has been suggested for the X-ray millisecond pulsar, SAX J1808.4−3658 (Cui et al. 1998). Using the delay between the 3.8–6.4 and 9.3–17.0 keV bands leads to an estimate (Cui et al. 1998) of ~0.1τ km for the size of the Comptonization region with optical depth τ. For $\tau \sim 12$, as typically found for 4U 1636−536 (Christian & Swank 1997), the Comptonization region would be very compact, at most a few kilometers.

Additional observations are required to measure more accurately the variation of the lags with energy in order to determine if the soft lags are generated by Comptonization or by intrinsic softening of the emission on each QPO cycle. Also, more realistic theoretical modeling, including the generation of the input hard photons, is required to interpret the observations adequately.

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