MEASUREMENT OF HARD LAGS AND COHERENCES IN THE X-RAY FLUX OF ACCRETING NEUTRON STARS AND COMPARISON WITH ACCRETING BLACK HOLES

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ABSTRACT

Using the Rossi X-ray Timing Explorer, we have measured lags of the 9–33 keV photons relative to the 2–9 keV photons in the timing noise between 0.01 and 100 Hz in the accreting neutron stars 4U 0614+09 and 4U 1705–44. We performed similar measurements on the accreting black hole candidates Cyg X-1 and GX 339−4 as a comparison. During the observations, these sources were all in low (hard) states. We find phase lags of between 0.03 and 0.2 rad in all of these sources, with a variation in frequency much less than expected for a lag constant in time. We also measure a coherence consistent with unity in all sources. As already noted for the black hole candidates, these data are inconsistent with simple Comptonization models invoking a constant time delay. Comptonization in a nonuniform medium can perhaps explain the lags. However, the magnitudes of the lags imply that the hot electron gas extends to more than 10^3 Schwarzschild radii. This may constitute an energy problem. We argue that while a large hot cloud is possible for black holes, which may hide some of their accretion energy in advection, such a distribution may not be possible for neutron stars, in which all the accretion energy is eventually released at the neutron star surface. This casts doubt on the Comptonization model, although the energy problem may be resolved, for example, by a wind from the inner disk.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (Cygnus X-1, GX 339−4, 4U 1705−44, 4U 0614+09) — stars: neutron — X-rays: stars

1 INTRODUCTION

The X-ray properties of black hole X-ray binaries in the “low state” are strikingly similar to those of atoll sources (accreting low magnetic field neutron stars) in the “island state” (van der Klis 1994a, 1994b). Both emit X-ray spectra that are dominated by a hard power-law component, \( N(E) \propto E^{-\alpha} \), whose photon index \( \alpha \) increases (i.e., whose spectra soften) as the mass accretion rate \( M \) increases (Tanaka & Lewin 1995; Barret & Vedrenne 1994; van Paradis & van der Klis 1994). The power density spectra of the X-ray flux variations of both types of sources are dominated by a broadband component, which is flat below a break frequency \( \nu_b \) and turns to a power law \( P(\nu) \propto \nu^{\beta} \) above \( \nu_b \), with \( \beta \approx 1 \) just above the break (see van der Klis 1995).

As \( M \) increases, so does \( \nu_b \); the observed values of \( \nu_b \) are similar for the black hole and neutron star systems and cover the range 0.01–30 Hz. As \( \nu_b \) varies, the high-frequency part of the power density spectrum tends to remain the same (Belloni & Hasinger 1990; Miyamoto et al. 1992), although this relation is not always exact in detail. Generally it is observed that the power level of the flat part of the power density spectrum is anticorrelated with \( \nu_b \) (and \( M \)) in black hole candidates (Méndez & van der Klis 1997, and references therein) and in neutron stars (Yoshida et al. 1983; Prins & van der Klis 1997; Ford & van der Klis 1998; Méndez et al. 1998).

Another characteristic of the low states of black hole X-ray binaries (BHXBs) is the phase lag of high-energy photons with respect to low-energy photons (“hard lags”) in flux variations covering timescales between \( 10^{-2} \) and \( 10^2 \) s (see Miyamoto et al. 1992). This phase lag is roughly constant over this range, at a level of order 0.1 rad, and does not vary much with \( \nu_b \) (i.e., \( M \)) for a given source or between sources. These phase lags have been interpreted (e.g., Payne 1980) as travel time differences of photons in a hot Compton scattering electron gas (e.g., Sunyaev & Trümper 1979), which is also the medium in which the power-law photon spectrum is thought to be formed (e.g., Hua & Titarchuk 1995; Dove et al. 1997). In accreting neutron stars, lags have been measured in the kilohertz oscillation signals (Vaughan et al. 1997). These very small lags put stringent constraints on the physical size of any cloud which might Comptonize the photons in the fast signals.

It is clearly of interest to know whether the similarities between island-state atoll sources and low-state BHXBs extend to their time lag properties. We present here the results of a time lag analysis of two atoll sources at frequencies below 100 Hz and compare the results to an identical analysis of two BHXBs.

In § 2 we describe the observations and data analysis. The results of our analysis are presented in § 3. They are discussed in the framework of the Comptonization model in § 4. We conclude that this model has fundamental problems.

2 OBSERVATIONS AND ANALYSIS

We have used data from the Rossi X-ray Timing Explorer (RXTE) proportional counter array (PCA) obtained during the first three observing cycles (see Table 1). We choose four sources: Cyg X-1 and GX 339−4, which are thought to contain black holes (Tanaka & Lewin 1995), and 4U 0614+09 and 4U 1705−44, which are atoll sources showing X-ray bursts and therefore contain neutron stars. In these observations, the BHXBs are in the low state and the atoll sources are in the island state. They have similar Fourier power spectra which can be fitted by a broken power law, with break frequencies of 0.18, 0.07, 1.8, and 3.6 Hz for Cyg X-1, GX 339−4, 4U
TABLE 1
RXTE Observations

| Source     | Start Time (UTC) | Duration (ks) | $T_{res}$ (μs) | $N_{chan}$ |
|------------|------------------|---------------|---------------|------------|
| Cyg X-1   | 1996 Feb 12 12:45| 3.1           | 16            | 16         |
| GX 339-4  | 1997 Feb 3 15:56 | 13.1          | 125           | 128        |
|           | 1997 Feb 10 15:40 | 11.8          | 125           | 128        |
|           | 1997 Feb 17 18:17 | 7.9           | 125           | 128        |
| 4U 1705-44| 1997 Apr 1 13:26 | 12.0          | 125           | 64         |
| 4U 0614+09| 1996 Apr 22 19:19 | 26.9          | 125           | 64         |
| 4U 1705-44| 1998 Aug 28 19:30 | 13.6          | 125           | 64         |

Note.—Listed are the start time (in Universal Time, Coordinated) of each observation and the duration of data used. We use Event mode data from the PCA with time resolution $T_{res}$ and a number of channels $N_{chan}$.

1705-44, and 4U 0614+09, respectively, and rms fractions of 29%, 36%, 22%, and 31% (2–9 keV, 0.01–100 Hz). The mean count rates are 4973, 586, 580, and 228 counts s$^{-1}$ (2–9 keV, background subtracted for the whole PCA), with small long-term variability.

To quantify the difference in variability between two energy bands, we use the cross spectrum defined as $C(j) = X_1(j) \ast X_2(j)$, where the $X$s are the measured complex Fourier coefficients for the two energy bands at a frequency $ν$ (van der Klis et al. 1987; for information on cross-correlation analysis, see Vaughan et al. 1994; Vaughan & Nowak 1997; Nowak et al. 1999). The phase lag $φ$ between the signals in the two bands is given by the argument of $C$ (its position angle in the complex plane). The corresponding time lag at Fourier frequency $ν$ is simply $φ/2πν$. We calculate an average crossvector $C$ by averaging over multiple spectra and binning in frequency, and then find $φ$. We calculate the error in $φ$ from the observed variance of the $C$ values in the real and imaginary directions. The resulting error is similar to, but slightly larger than, that derived from counting statistics (Vaughan et al. 1994; Cui et al. 1997) or (equivalently) from the coherence function uncorrected for counting statistics (Nowak et al. 1999).

We calculate cross spectra from data intervals of 256 s and use a Nyquist frequency of 2048 Hz, which is high enough to avoid binning effects that dominate at frequencies above half the Nyquist frequency (Crary et al. 1998). Since the resulting $φ$ depends somewhat on the choice of energy band, becoming larger for wider energy separations, we choose the energy bands to be closely similar. We choose two energy bands defined as effectively 2–9 keV and 9–33 keV. These bands correspond to PCA channels 0–35 and 36–127 for the Cyg X-1 observations and channels 0–25 and 26–87 for the other data, which were taken after a detector gain change in 1996 March. We correct for dead-time effects by subtracting from $C$ an average value obtained from 800 to 1024 Hz where Poisson noise dominates (van der Klis et al. 1987). This correction is close to negligible.

A positive value of $φ$ corresponds to a lag of the hard band relative to the soft band, a result we have confirmed by analyzing test signals and looking at data from the accreting millisecond X-ray pulsar SAX J1808.4–3658.

3. RESULTS

The results of the phase delay analysis are summarized in Figure 1. In all four sources the hard photons lag the soft photons significantly. Even in 4U 0614+09, where the statistics are the worst, the lag is detectable with a significance greater than 5 σ in the 1–10 Hz range. Averaging over the 0.01–100 Hz range, the $φ$ values are $0.077 ± 0.003$, $0.093 ± 0.003$, $0.092 ± 0.011$, and $0.067 ± 0.016$ rad for Cyg X-1, GX 339–4, 4U 1705–44, and 4U 0614+09, respectively. In 4U 1705–44 and 4U 0614+09, the lags are significant only above 1 Hz: over the range 0.01–1 Hz, $φ$ is $0.030 ± 0.014$ and $0.047 ± 0.021$ rad, respectively.

The significance of the phase lags is a factor of 3–10 better for the BHXBs than for the atoll sources. In Cyg X-1 this is

![Fig. 1. Phase delays between signals in the 2–9 and 9–33 keV bands for two black hole candidate binaries in the low state (left) and two neutron star binaries in the island state (right). The dotted lines show constant time delays of 10 ms. Measurements that are less than 1 σ significant are plotted as 95% confidence upper limits.](image-url)
Fig. 2.—Poisson noise–corrected coherence functions between the energy bands 2–9 and 9–33 keV

because of the high count rate. In GX 339–4 it is a result of the high rms fraction of the noise and long integration time. We calculate the expected significances, which are a function of the rate, rms fraction, observing time, and coherence (Nowak et al. 1999). Compared to 4U 0614+09, the significances should be better by factors of 13, 14, and 3 in Cyg X-1, GX 339–4, and 4U 1705–44, respectively, similar to what we have observed. There is structure visible for $\phi$ as a function of frequency in the BHXBs (Miyamoto et al. 1992); in particular, $\phi$ increases somewhat with frequency. The lags are not, however, consistent with a constant time lag as shown by the dotted lines in Figure 1.

In addition to the phase delay, we measure the coherence, defined by $\gamma^2 = \langle |X(j)|^2 \rangle \langle |Y(j)|^2 \rangle / \langle |X(j)|^2 \rangle \langle |Y(j)|^2 \rangle$ (Vaughan & Nowak 1997). The angle brackets represent averages over multiple cross spectra and Fourier frequencies. If the cross vectors have the same phase angles, $\gamma^2$ is unity; if the phases are random, $\gamma^2$ is zero. We corrected $\gamma^2$ for the contribution from Poisson noise (see Vaughan & Nowak 1997); this correction significantly changes the calculated values. We calculate the error of the noise-corrected $\gamma^2$ according to the prescription of Vaughan & Nowak (1997) in the high-coherence, high-variability regime applicable to our data below 100 Hz. Figure 2 shows the results. The coherence is consistent with unity for all sources.

4. DISCUSSION

We have presented the first measurements of phase lags and coherence in the band-limited noise below 100 Hz in accreting neutron stars. We find that the phase lags of the atoll sources 4U 1705–44 and 4U 0614+09 in the island state are very similar to those of BHXBs in the low state as reported here and by previous authors (Page et al. 1981; Miyamoto et al. 1988; Miyamoto et al. 1992; Nowak et al. 1999; Pottschmidt et al. 1998). In the noise at frequencies between 0.01 and 100 Hz, hard X-rays lag soft X-rays. The average phase delays that we measure in this frequency range are 0.09 and 0.07 rad for 4U 1705–44 and 4U 0614+09 and 0.08 and 0.09 rad for the low-state BHXBs Cyg X-1 and GX 339–4. The lags are not consistent with a constant time delay.

We discuss our results within the framework of the idea that the X-ray photons in the power-law spectral component are the result of Compton upscattering of low-energy seed photons, probably produced in the accretion disk, by a very hot electron gas. This implies that the energy emitted in X-rays first resides in energetic electrons, which subsequently lose part of their energy to low-energy photons in the scattering processes. In this Comptonization model, a low-energy photon on average gains energy in each scattering event. Higher energy photons, on average, are the result of more scatterings. Therefore, the higher energy photons emerge later than the lower energy photons produced simultaneously, since the total path length they traverse is larger due to more scatterings. The measured unity coherence in all sources argues for such a model, as opposed to scenarios in which signals at different energies are produced in disconnected regions (Vaughan & Nowak 1997).

In simple versions of Compton scattering in a uniform cloud, one expects a constant time lag between photons in different energy bands independent of frequency (Wijers, van Paradijs, & Lewin 1987), i.e., the phase lag $\phi$ is expected to increase proportionally to the Fourier frequency $\nu$, at least when the Fourier period is larger than the typical time delay. This is inconsistent with the data, as noted previously. The recent work of Kazanas, Hua, & Titarchuk (1997) and Hua, Kazanas, & Titarchuk (1997), however, shows that a scattering medium with a radial density gradient can produce phase lags roughly constant in frequency.

We also note that in the atoll sources there are also quasi-periodic oscillation signals in excess of 1000 Hz, which are thought to originate very close to the neutron star. The upper limits to any hard phase lags in these signals is small (Vaughan et al. 1997, erratum). For a medium that induces constant time delays, the measured lags of these fast signals should have been large.
The size of the Comptonizing region is large. Our measurements of a 0.02 s lag at 1 Hz for the neutron stars and 0.2 s at 0.1 Hz for the black holes correspond to a size of order 10^9 km for moderate optical depths. Even in the Kazanas et al. (1997) and Hua et al. (1997) models with nonconstant density, the scattering medium extends up to at least 10^9 R_s, where R_s is the Schwarzschild radius. At the same time, a large fraction of the total luminosity is released in hard X-rays which are apparently produced by the Comptonizing medium. Relative to the flux in the 0.1–100 keV band, in our observations Cyg X-1 emits 65% of its energy above 9 keV; in 4U 1705–44, this fraction is 25%. The question then arises, How can a substantial fraction of the emitted X-ray luminosity, which must originate from the conversion of gravitational potential energy into heat close to the compact object, reside in hot electron gas at distances of order 10^9 R_s away from the compact object? Energy production around accreting neutron stars was considered early on (Zeldovich & Shakura 1969). The energy problem discussed above has been raised by recent authors (e.g., Stollman et al. 1987).

For the black hole systems, one might argue that the energy budget in hot electron gas at distances of order 10^9 cm is sufficient to account for a substantial part of the observed X-ray luminosity via Compton upscattering. The required mass accretion rate then has to be of order 10^{-7} M_\odot, i.e., several orders of magnitude above the value inferred from the observed X-ray luminosities of \~10^{37} erg s^{-1}. The consequence of this is that the accretion flow within \~10^9 cm of the black hole must have a very low radiative efficiency, which suggests that it is advection dominated (see, e.g., Narayan & Yi 1994). In this picture it would be the advection-dominated accretion flow itself that provides the site for Comptonization. (Note that at 10^9 cm the virial temperature is already \~200 keV, in principle sufficient for the formation of a hard power law).

However, a similar advection-dominated accretion flow picture cannot apply to the atoll sources. These sources cannot have such a high accretion rate, since they have no way of hiding the corresponding photon luminosity liberated near the neutron star surface. The energetics is a problem for disk configurations in which the losses from Comptonization are expected to exceed the energy locally available from gravitational release or radiative heating (Shibazaki et al. 1988). Kazanas et al. (1997) suggest that the Comptonizing region is a quasispherical flow preheated by radiation from a central region (references in Kazanas et al. 1997; Zeldovich & Shakura 1969), perhaps a hot boundary region (Titarchuk, Lapidus, & Muslimov 1998). Transporting a large fraction of energy to large radii may also be accomplished by a wind blown from the inner disk (B. A. Achterberg 1998, private communication). Magnetic fields offer another possibility for transporting energy from near the compact star to larger radial distances (Stone et al. 1996). To maintain the Comptonizing region in the neutron star system, a large fraction (at least 25%) of the total accretion power must be efficiently transported from its point of release, within a few tens of kilometers of the neutron star, out to distances of order 10^9 cm.

To summarize, we have shown that the phase delays and coherences measured in X-ray binaries that contain neutron stars are the same as those that likely contain black holes. If these lags are from Comptonization, the size of the scattering medium is large, which may pose a problem for the energetics. Delays generated by processes other than Comptonization may have to be considered, as has been done recently (Böttcher & Liang 1999; Poutanen & Fabian 1998). The correct model must describe both accretion onto black holes and neutron stars.

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