HARD X-RAY LAGS IN GRO J1719−24

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ABSTRACT

We have used the Fourier cross spectra of GRO J1719−24, obtained with BATSE, to estimate the phase lags between the X-ray flux variations in the 20–50 and 50–100 keV energy bands as a function of Fourier frequency. Our analysis covers the entire ~80 day X-ray outburst of this black hole candidate, following the first X-ray detection on 1993 September 25. The X-ray variations in the 50–100 keV band lag those in the 20–50 keV energy band by an approximately constant phase difference of 0.07 ± 0.010 rad in the frequency interval 0.02–0.20 Hz. The peak phase lags in the interval 0.02–0.20 Hz are about twice those of Cyg X-1 and GRO J0422+32. These results are consistent with models for Comptonization regions composed of extended nonuniform clouds around the central source.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (GRO J1719−24) — X-rays: stars

1. INTRODUCTION

The soft X-ray transient GRO J1719−24 (= GRS 1716−249, Nova Oph 1993) was detected simultaneously with BATSE on board the Compton Gamma Ray Observatory and the SIGMA telescope on Granat on 1993 September 25 (Harmon et al. 1993b; Ballet et al. 1993). The source reached a maximum X-ray flux of ~1.4 crab (20–100 keV) within 5 days after first detection and was remarkable for the stability of its hard X-ray emission on a timescale of days; its hard X-ray flux declined at a rate of ~0.3% ± 0.05% per day (Harmon et al. 1993a). GRO J1719−24 was detected above the BATSE 3σ detection threshold of 0.1 crab (20–100 keV) for ~80 days following the start of the X-ray outburst (Harmon & Paciesas 1993). A time series analysis of the hard X-ray variability of GRO J1719−24, observed with BATSE in the 20–100 keV energy band, was presented by van der Hooft et al. (1996). They analyzed the entire 80 day X-ray outburst of GRO J1719−24 in the frequency interval 0.002–0.488 Hz. The power density spectra (PDSs) of GRO J1719−24 show a significant peak, indicating quasi-periodic oscillations (QPOs) in the time series, with a centroid frequency that increases from ~0.04 Hz at the start of the outburst to ~0.3 Hz at the end. Van der Hooft et al. (1996) discovered that the evolution in time of the PDSs of GRO J1719−24 can be described by a single characteristic profile. The evolution of the PDSs can be described as a gradual stretching by a factor of ~7.5 in the frequency of the power spectrum, accompanied by a decrease of the power level by the same factor, such that the integrated power in a scaled frequency interval remains constant. Therefore, it is likely that the X-ray variability during the entire outburst of GRO J1719−24 can be described by a single process, the characteristic timescale of which becomes shorter, but the fractional amplitude of which is invariant. This may be related to the strong anti-correlation of the break frequency and power density at the break observed in the PDSs of several black hole candidates (Belloni & Hasinger 1990). Méndez & van der Klis (1997) suggested that a correlation with the mass accretion rate may exist, i.e., that the break frequency increases (and the power density decreases) with increasing mass accretion rate. Two average PDSs (20–100 keV), corresponding to days 13–15 and 51–60 of the X-ray outburst of GRO J1719−24, are displayed in Figure 1.

GRO J1719−24 remained undetectable until 1994 September, when several X-ray flares were detected with both SIGMA and BATSE (Churazov et al. 1994; Harmon et al. 1994). Subsequent to strong X-ray flares in 1994 February (Borozdin, Alexandrovich, & Sunyaev 1995), a rapidly decaying radio flare was detected, followed by recurrent radio flaring activity (Hjellming et al. 1996). The relation between X-ray and radio events is similar to that observed in the superluminal radio-jet sources GRO J1655−40 and GRS 1915+105 (Hjellming et al. 1996; Foster et al. 1996): radio emission follows the peak, or onset to decay of X-ray flares observed with BATSE in the 20–100 keV energy band, by intervals ranging from a few to 20 days (Hjellming et al. 1996). GRO J1655−40 is a Galactic black hole candidate (BHC) with a dynamically determined mass of 7.0 ± 0.7 M⊙ (Orosz & Bailyn 1997; van der Hooft et al. 1998). Della Valle, Mirabel, & Rodríguez (1994) discovered a possible optical counterpart to the X-ray source, the photometric and spectroscopic properties of which suggest that GRO J1719−24 is a low-mass X-ray binary. The optical brightness of GRO J1719−24, measured during 3 weeks after first X-ray detection, is modulated at a period of 0.6127 days, thought to be the superhump period (Masetti...
et al. 1996). Quiescent (optical) photometry and/or spectroscopy of GRO J1719–24 has not been reported. The source is considered a BHC on the basis of its X-ray and radio similarities to dynamically proven BHCs.

We have investigated the phase (or, equivalently, time) lags in the hard X-ray variability of GRO J1719–24 during its 1993 X-ray outburst. We calculate the lags between the 20–50 and 50–100 keV energy bands of the 1.024 s time resolution BATSE data, and compare our results with those obtained in recent similar studies of the black hole candidates Cyg X-1 (Cui et al. 1997; Crary et al. 1998) and GRO J0422+32 (Grove et al. 1997; van der Hooft et al. 1999).

2. ANALYSIS

A time series analysis of the hard X-ray (20–100 keV) data of the entire 1993 outburst of GRO J1719–24 was presented by van der Hooft et al. (1996). These data were obtained in two broad energy channels (20–50 and 50–100 keV) with the large-area detectors of BATSE, collected during the 80 days following first X-ray detection on 1993 September 25. Fast Fourier transforms were created for 524.288 s time intervals (512 time bins of 1.024 s each); the corresponding frequency interval covered 0.002–0.488 Hz. The average number of uninterrupted 512 bin segments available with the source unocculted by the Earth was approximately 35 per day. See van der Hooft et al. (1996) for a detailed description of the reduction and analysis of these data.

The complex Fourier cross spectra were created from the Fourier amplitudes in a manner identical to that described by van der Hooft et al. (1999). These cross spectra were averaged daily. Errors on the real and imaginary parts of the daily averaged cross spectra were calculated from the
respective sample variances, and formally propagated when computing the phase and time lags. The phase lags, $\phi_j$, as a function of frequency were obtained from the cross spectra via $\phi_j = \arctan \left[ \Im \left( \frac{C_1}{C_2} \right) / \Re \left( \frac{C_1}{C_2} \right) \right]$, and the corresponding time lags from $\tau_j = \phi_j / 2\pi v_j$, where $v_j$ is the frequency in hertz of the $j$th frequency bin. With these definitions, lags in the hard X-ray variations (50–100 keV) with respect to the soft X-ray variations (20–50 keV) appear as positive angles.

Cross spectra for a large number of days must be averaged and converted to lag values in order to obtain sufficiently small errors (see, e.g., Crary et al. 1998; van der Hooft et al. 1999). Therefore, we averaged the phase and time lags between the 20–50 and 50–100 keV energy bands of the entire 80 day X-ray outburst of GRO J1719–24. These are presented in Figure 2. The time lags are displayed on a logarithmic scale. Time lags at frequencies above 0.5 $v_{\text{Nyq}}$ are displayed but not taken into account in our analysis, since Crary et al. (1998) have shown that data binning effects distort the shape of the cross spectra at these frequencies. These data show that at the lowest frequencies the phase lags are likely to be smaller than the high-frequency lags (0.021 ± 0.028 rad, average of 0.001–0.02 Hz; 9 bins). At frequencies above 0.02 Hz, the hard X-rays lag the soft by 0.072 ± 0.010 rad (average of 0.02–0.20 Hz; 94 bins). The phase lags averaged over two 40 day intervals are similar to those averaged over the entire 80 day outburst, being 0.0017 ± 0.028 rad and 0.041 ± 0.043 rad, respectively, for the 0.001–0.02 Hz interval, and 0.082 ± 0.013 rad and 0.061 ± 0.016 rad, respectively, for the 0.02–0.20 Hz interval.

The time lags of GRO J1719–24 decrease with frequency as a power law, with index $0.02$, respectively, for the 0.001 $v_{\text{Nyq}}$ above the measured time lags. This implies that in the soft state the size of the corona also becomes much smaller. This confirms what was derived from the source state.

Van der Hooft et al. (1999) determined lags in the hard X-ray variability of GRO J0422+32 during its 1992 outburst. Their time series analysis covered the entire 180 day X-ray outburst. GRO J0422+32 is a dynamically proven black hole candidate; during its 1992 outburst it was most likely in the low state (van der Hooft et al. 1999). They averaged the phase lags of GRO J0422+32 over a 30 day interval following the first X-ray detection of the source, and over a flux-limited sample of the remaining data (95 days). Statistically significant lags were derived for the shorter interval only. They find that at the lowest frequencies, the phase lag of GRO J0422+32 is consistent with zero (0.014 ± 0.006 rad, 0.02–0.20 Hz). At frequencies of $\geq 0.02$ Hz, the variations in the 50–100 keV band lag those in the 20–50 keV band by 0.039 ± 0.003 rad (with an average of 0.02–0.20 Hz).

The time lags of GRO J0422+32 during the first 30 days of its outburst decrease with frequency as a power law, with an index of $\sim 0.9$ for $v > 0.01$ Hz (van der Hooft et al. 1999). Grove et al. (1997) studied the time lags of GRO J0422+32 between the X-ray variations in the 35–60 keV band and 75–175 keV band with OSSE. They find that the hard X-ray emission lags the soft emission at all Fourier frequencies, decreasing roughly as $v^{-1}$ up to about 10 Hz. At frequencies of $\sim 0.01$ Hz, hard time lags of as large as 0.3 s are observed. The hard time lags of GRO J0422+32 obtained by Grove et al. (1997) are consistent with those obtained by van der Hooft et al. (1999).
The phase lags of GRO J1719–24 are very similar to those of GRO J0422+32 and Cyg X-1. At frequencies below 0.02 Hz, very small lags are observed (consistent with zero), while at frequencies of ~0.10 Hz the variations in the 50–100 keV band lag those in the 20–50 keV band. However, the phase lags of GRO J1719–24, averaged in the interval 0.02–0.20 Hz, are about twice as large as those detected in GRO J0422+32 and Cyg X-1.

These results show that the hard time lags observed in GRO J1719–24, GRO J0422+32, and Cyg X-1 are all very similar. The hard X-radiation lags the soft by as much as ~0.1–1 s at low frequencies. The time lags are strongly dependent on the Fourier frequency, and decrease roughly as $v^{-1}$. The $v^{-1}$ dependence of the hard time lags is very different from the lags expected from simple models of Compton upscattering of soft X-rays by a cloud of hot electrons near the black hole. In such a case, the energy of the escaping photons increases with the time they reside in the cloud. Therefore, higher energy photons lag the photons with lower energies by an amount proportional to the photon scattering time. If the hard X-rays are emitted from a compact region near the black hole, the resulting time lags should be independent of Fourier frequency and on the order of milliseconds.

Analysis of the hard time lags in the X-ray variability of black hole candidates can provide information on the density structure of the accretion gas (Hua, Kazanas, & Titarchuk 1997). Kazanas et al. (1997) argued that the Comptonization process takes place in an extended nonuniform cloud around the central source. They showed that such a model can account for the form of the observed PDS and energy spectra of compact sources. Hua et al. (1997) showed that the phase and time lags of the X-ray variability depend on the density profile of such an extended scattering atmosphere. Their Monte Carlo simulations of scattering in a cloud with a density profile proportional to $r^{-1}$ agree with our time-lag data in both magnitude (~0.1 s at 0.10 Hz) and frequency dependence ($v^{-1}$). The results presented here support the idea that the Comptonizing regions around the black holes in Cyg X-1, GRO J0422+32, and GRO J1719–24 are quite similar in density distribution and size.

However, the observed lags require that the scattering medium have a size of the order of $10^3$ to $10^4$ Schwarzschild radii. It is unclear how a substantial fraction of the X-ray luminosity, which must originate from the conversion of gravitational potential energy into heat close to the black hole, can reside in a hot electron gas at such large distances. This is a generic problem for Comptonization models of the hard X-ray time lags. Such models also do not specify the source of soft photons, nor do they account for the soft excesses and weak Fe lines seen in the energy spectra. Very detailed high signal-to-noise ratio cross-spectral studies of the rapid X-ray variability of accreting BHCs and combined spectro-temporal modeling may solve this problem.

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