X-ray and optical studies of black-hole X-ray transients

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Hard X-ray lags in GRO J1719–24


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Abstract

We have used the Fourier cross spectra of GRO J1719–24, as 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 in the interval 0.002–0.488 Hz. 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 non-uniform clouds around the central source.

3.1 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 five days after first detection, and was remarkable for the stability of its hard X-ray emission on a time scale of days; its hard X-ray flux declined at a rate of ~0.3 ± 0.05% per day (Harmon et al. 1993c). GRO J1719–24 was detected above the BATSE 3σ one-day 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, indicative of quasi-periodic oscillations (QPOs) in the time series, whose centroid frequency 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 frequency scale of which is being stretched during the outburst. The total power in each PDS, integrated over corresponding (but relatively scaled) frequency intervals, remained constant throughout the outburst. 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 time scale of which becomes shorter, but the fractional amplitude of which is invariant. This may be related to the strong anticorrelation of the break frequency and power density at the break observed in the PDSs of several black-hole candidates (Belloni & Hasinger 1990a). Méndez & van der Klis (1997) suggest a correlation with mass accretion rate may exist, i.e., the break frequency increases (and the power density decreases) with increasing mass accretion rate.

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 1995 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. 1998a).

A possible optical counterpart to the X-ray source was discovered by Della Valle, Mirabel & Rodriguez (1994), 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 three 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 black-hole candidate on the basis of its X-ray and radio analogies 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 calculated lags between the 20–50 and 50–100 keV energy bands of the 1.024 sec 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. 1997a; Crary et al. 1998) and GRO J0422+32 (Grove et al. 1997; van der Hooft et al. 1998b).

### 3.2 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 80 days following first X-ray detection on 1993 September 25. Fast Fourier Transforms were created for 524.288 sec long time intervals (512 time bins of 1.024 sec each);
The complex Fourier cross spectra were created from the Fourier amplitudes in a way identical to that described by van der Hooft et al. (1998b). 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 \( \phi_j = \text{arctan}[\text{Im}(C_j^{12})/\text{Re}(C_j^{12})] \), and the corresponding time lag \( \tau_j = \phi_j/2\pi \nu_j \), with \( \nu_j \) the frequency in Hz 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. 1998b). 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 3.1. The time lags are displayed on a logarithmic scale. Time lags at frequencies above 0.5 \( \nu_{Nyq} \) are displayed but not not taken into account to our analysis, as 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 consistent with zero (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 days intervals are similar to those averaged over the entire 80 day outburst. The time lags of GRO J1719–24 decrease with frequency as a power law, with index 1.04 ± 0.13 for frequencies ≥ 0.01 Hz. The extrapolation of this power law for frequencies smaller than 0.01 Hz is well above the measured time lags.
3.3 Discussion

The 20–100 keV energy spectrum steadily softened during the entire X-ray outburst of GRO J1719−24 in 1993; the photon index increased from 2.0 to 2.3 ± 0.05 during the rise to peak intensity, beyond which the spectrum softened more gradually. No marked changes in the spectral shape were observed during the sudden decrease in X-ray flux in 1993 December (van der Hooft et al. 1996). It is not possible, on the basis of 20–100 keV BATSE observations alone, to distinguish between black hole source states. However, observations at low X-ray energies during the decay of the X-ray light curve of GRO J1719−24, suggest that the source was most likely in the low (or hard) state. The 2–300 keV X-ray spectrum, obtained about 30 days after first detection of GRO J1719−24 by combining SIGMA data with quasi-contemporaneous data taken by TTM on board Mir-Kvant, was quite similar to the low state spectrum of Cyg X-1. The 2–300 keV spectrum of GRO J1719−24 then had a power-law shape without a soft component, and a cut off at energies above 100 keV (Revnivtsev et al. 1998). Therefore, these observations indicate that 30 days after the X-ray outburst had started, GRO J1719−24 was in the low state. The lack of significant changes in the hard X-ray properties (van der Hooft et al. 1996) of GRO J1719−24, suggest that this conclusion applies to the entire 1993 outburst.

Recently, Crary et al. (1998) and van der Hooft et al. (1998b) have studied lags between the X-ray flux variations in 20–50 and 50–100 keV BATSE data of the black-hole candidates Cyg X-1 and GRO J0422+32. Cui et al. (1997a) measured hard X-ray time lags in 2–60 keV RXTE data of Cyg X-1, obtained during 1996. Crary et al. (1998) studied Cyg X-1 for a period of almost 2000 days, during which the source was likely in both the low, and high or intermediate state. They found that the lag spectra between the X-ray variations in the 20–50 and 50–100 keV energy bands of Cyg X-1 do not show an obvious trend with source state. They grouped the phase lag data according to the squared fractional rms amplitude of the noise, integrated in the frequency interval 0.03–0.488 Hz. The average phase lags of Cyg X-1 are reproduced in Figure 3.2. They find that at the lowest frequencies the phase lag is consistent with zero. For higher frequencies the phase lag increases to a maximum of 0.04 rad near 0.20 Hz, and decreases again to near zero at the Nyquist frequency.

Crary et al. (1998) showed that binning effects decrease the observed hard X-ray time lags to zero at the Nyquist frequency. Therefore, time lags obtained for frequencies between 0.5 \( \nu_{\text{Nyq}} \) and \( \nu_{\text{Nyq}} \) may be affected by data binning. The Cyg X-1 X-ray variations in the 50–100 keV band lag those in the 20–50 keV band over the 0.01–0.20 Hz frequency interval by a time interval proportional to \( \nu^{-0.8} \). The time lags in the Cyg X-1 hard X-ray data are reproduced as a function of frequency in Figure 3.3.

Cui et al. (1997a) studied Cyg X-1 during its 1996 spectral transitions. The observed period can be divided into a transition from the hard state to the soft state, a soft state, and a transition from the soft state back to the hard state. The lag spectra obtained by Cui et al. (1997a) cover the frequency range 0.01–100 Hz. They find that during the state transitions the time lags between energy bands with average energy \( E_0 \) and \( E_1 \), scale with photon energy roughly as \( \log(E_1/E_0) \). Such a scaling is consistent with the predictions of thermal Comptonization in the corona (see, e.g., Payne 1980; Hua & Titarchuk 1996; Kazanas, Hua & Titarchuk 1997). In the soft state, the time lags become much smaller. This implies that in the soft state the size of the corona becomes much smaller.

Van der Hooft et al. (1998b) 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. 1998b). They averaged the phase lags of GRO J0422+32 over a 30 day interval following 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. The 30 day averaged phase lags of GRO J0422+32 are shown in Figure 3.4. They find that at the lowest frequencies the phase lag of GRO J0422+32 is consistent with zero (0.014±0.006 rad, 0.001–0.02 Hz). At frequencies ≥ 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 (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 index ~ 0.9 for ν > 0.01 Hz (van der Hooft et al. 1998b). The 30 day averaged time lags of GRO J0422+32 are shown in Fig. 3.4. 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 ν⁻¹ up to about 10 Hz. At frequencies of ~ 0.01 Hz, hard time lags as large as 0.3 sec 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. (1998b).

The phase lags of GRO J1719−24 are very similar to those of GRO J0422+32 and Cyg X-1. At the lowest frequencies the phase lags are consistent with zero, at frequencies of ~ 0.10 Hz the variations in the 50–100 keV band lag those in the 20–50 keV band. 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.

Figure 3.2: Phase lags between 20–50 and 50–100 keV data for various daily averaged squared rms levels, s, of Cyg X-1. All data with s > 0.03 (a), 0.03 < s < 0.05 (b), 0.05 < s < 0.07 (c), and s > 0.07 (d). Figure taken from Crary et al. (1998).
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-ray radiation lags the soft X-ray radiation by as much as $\sim 0.1$−$1$ sec at low frequencies. The time lags are strongly dependent on the Fourier frequency, and decrease roughly as $\nu^{-1}$. The $\nu^{-1}$ 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 of the order of milliseconds.

However, 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 non-uniform 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 both in magnitude ($\sim 0.1$ sec at 0.10 Hz) and frequency dependence ($\nu^{-1}$). 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.

**Figure 3.3**: Time lags of Cyg X-1 as a function of frequency. Solid circles denote the values obtained by averaging over all data with fractional rms values greater that 0.03. The dashed line is the time lag obtained from a fit to the lag model including binning effects. The dotted line is a power law with parameters determined from a model fit, without including binning effects. Figure taken from Crary et al. (1998).
Figure 3.4: Average phase (left) and time (right) lags of GRO J0422+32 between the 20–50 and 50–100 keV energy bands (hard lags appear as positive angles). These averages cover 30 days following first X-ray detection of the source. The frequency scale has been logarithmically rebinned into 34 bins. Upper (lower) limits are indicated by triangles. Figure taken from van der Hooft et al. (1998b).

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