THE CROSS SPECTRAL TIME LAG EVOLUTION ALONG BRANCHES IN XTE J1701-462

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ABSTRACT

We investigate the cross spectrum of XTE J1701-462 in various types of neutron star low-mass X-ray binary subclasses during its 2006–2007 outburst. We analyze the relation between the time lags and temporal variabilities. We find that the hard time lags accompany horizontal branch oscillations (HBOs) and the soft time lags dominate the noise in the low frequency range 0.1–10 Hz on HB. In the Cyg-like phase, the time lags decrease on the middle normal branch (NB) from HB/NB vertex to NB/FB vertex, whereas the time lags are roughly invariant in the Sco-like source. We discuss the fact that the Compton upscattering by the corona introduces the soft lag in low-frequency noise. We suggest that the variation of the Comptonization component from the disk emission leads to the HBOs’ time lag evolutions along the Z tracks. We also report the rms amplitude spectrum and phase lag spectrum for the normal branch oscillation (NBO). A ~160° phase lag is found. We find that the rms amplitudes of both the Cyg-like and the Sco-like NBOs linearly increase with the photon energy in low energy bands, and drop in the highest energy band.

Key words: binaries; general – stars: individual (XTE J1701-462) – stars: neutron – X-rays: binaries – X-rays: individual (XTE J1701-462) – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) are binary systems that contain a neutron star (NS) accreting material from a low-mass companion star (see van der Klis 2006 for review). Based on their correlated X-ray spectral and timing properties, they can be divided into two subclasses: Z sources with near-Eddington luminosities (~0.5–1 $L_{\text{edd}}$) and atoll sources with much lower luminosities (~0.0001–0.5 $L_{\text{edd}}$). The color–color diagram (CD) and hardness–intensity diagram (HID) of Z source have three branches, from top to bottom, which are called the horizontal branch (HB), the normal branch (NB), and the flare branch (FB); Hasinger & van der Klis (1989), respectively. However, the CDs/HIDs of atoll sources are obviously different from those of Z sources. A CD/HID of atoll sources also has three branches: the extreme island state, the island state, and the banana state. Usually, a complete track of the Z sources lasts from hours to days, whereas that of atoll sources lasts from weeks to months.

In terms of the orientation of branches, Z sources are classified into Cyg-like Z sources (Cyg X-2, GX 5-1, and GX 340+0) with a horizontal HB ("Z"-shaped track) and Sco-like Z sources (Sco X-1, GX 17+2, and GX 349+2) with a vertical HB ("v"-shaped track). A fast Fourier transform (FFT) algorithm was applied in order to obtain the power density spectra (PDSs) of LMXBs. In some Z sources (e.g., Cyg X-2, GX 5-1, GX 340+0, GX 17+2), the HB quasi-periodic oscillation (QPO) signals, which vary with frequencies in the range from 13 Hz to 55 Hz, are observed in the power spectra. Almost all Z sources have 5–7 Hz QPOs on the NB and a few of them have ~20 Hz QPOs on the FB. The radiation hydrodynamic model (Lamb 1989; Fortner et al. 1989; Miller & Lamb 1992) was proposed to explain the ~6 Hz normal branch oscillations (NBOs). In this model, the NBOs of Z sources arise from the optical depth oscillation of an inflowing medium near the NS scattered by the outgoing X-ray flux. This model also explained a minimum in the NBO rms amplitude spectrum when the phase lag spectrum showed a 180° phase jump. In Cyg X-2, a 150° phase jump was observed around 6 keV, which was defined as pivot energy (Mitsuda & Dotani 1989; Dieters et al. 2000). Moreover, the same phase jump was observed around 3.5 keV in GX 5-1. Both of these Cyg-like sources displayed a minimum around pivot energy in the NBO rms amplitude spectrum. However, Sco X-1, which is a Sco-like Z source, did not exhibit a phase jump on the NB. The near-180° phase jumps observed in Cyg X-2 and GX 5-1 but not in Sco X-1 are consistent with the classification of Z sources.

Two kinds of time lags were observed in LMXBs. First, Lei et al. (2008) applied a cross-correlation function to Cyg X-2 during its low-intensity states and detected both an anticorrelation and a positive correlation with hectosecond soft and hard time lags. An anticorrelation and time lags were also observed in the HB and upper NB of GX 5-1 (Sriram et al. 2012) which implied a truncated accretion disk in LMXBs. Second, van der Klis et al. (1987) used a Fourier cross-spectrum technique to study Cyg X-2 and GX 5-1. They found tens of milliseconds of hard time lags (i.e., hard photons lag behind soft photons) in horizontal branch oscillations (HBOs) and NBOs and soft lags in low-frequency noise. Kaaret et al. (1999) discovered millisecond soft lags in the atoll source 4U 1636-536. Qu et al. (2001) found that Cir X-1 presents a hard lag on the HB and a soft lag on both the NB and FB. In order to explain both soft and hard lags in LMXBs, several mechanisms including a shot model (Vaughan et al. 1994), a uniform Comptonization model (Cui et al. 1997a), a two-layer corona model (Nobili et al. 2001; Qu et al. 2001), and a disk propagation model (Uttley et al. 2011) have been proposed.

XTE J1701-462 is a unique LMXB source observed by the Rossi X-Ray Timing Explorer (RXTE) during its outburst in 2006–2007 (Remillard et al. 2006). At high luminosity, XTE J1701-462 switched between a Cyg-like Z source and a Sco-like Z source and at low luminosity; a transition from...
Z source to atoll source was observed (Homan et al. 2007; Lin et al. 2009; Homan et al. 2010). During these states, the shape of the CDs/HIDs, the X-ray timing behavior, and the X-ray spectra also changed. This provides us with a great opportunity to understand NBO behavior, the time lag spectrum, and the rms amplitude spectrum, between Cyg-like and Sco-like phases. We also utilize the cross-spectrum to study the time lag evolution along with branches from Z sources to atoll sources.

In Section 2 we describe the observations and analysis techniques, and our results are reported in Section 3. In Sections 4 and 5, we present the discussion and conclusions.

2. OBSERVATIONS

We analyzed all 866 observations of the LMXB XTE J1701-462 from its 2006–2007 outburst collected with the Proportional Counter Array (PCA) instrument on board RXTE. During the outburst, the source showed X-ray spectral and timing behaviors of a Z source and an atoll source.

For all observations, we employed the following standard data selection criteria, a source elevation of \( > 10^\circ \), a pointing offset of \(< 0.01\) and a South Atlantic Anomaly exclusion time of 30 minutes. We utilized the Heasoft 6.12 to extract background-subtracted light curves with a 16 s time resolution from the “Standard 2” mode data and no dead-time correction was applied. Only data from PCU 2 were used. In order to obtain the CDs/HIDs from the light curves, we define the soft color as 4.5–7.4 keV/2.9–4.1 keV (channels 10–17/6–9) count rate ratios and the hard color as 10.2–18.1 keV/7.8–9.8 keV (channels 24–43/18–23) count rate ratios, then defined the intensity as count rates covering the energy range 2.9–18.1 keV (channels 6–43). Our data selection is listed in Table 1, and the CDs/HIDs are displayed in Figure 1. Intervals I and II belong to the Cyg-like source, and Intervals III and IV belong to the Sco-like source.

We used the single-bit and science event model data with 32 s segments and a 2−9 s time bin to create PDSs in the frequency range 1/32 Hz–128 Hz. We studied HBOs in the energy range \( \sim 2–60\) keV and NBOs in the energy range \( \sim 7–60\) keV because the NBOs were more apparent in \( \sim 7–60\) keV than in \( \sim 2–60\) keV (Homan et al. 2007). No background-subtraction or dead-time correction were applied. We employed the power spectral normalization of Miyamoto et al. (1991). Then we fitted the power spectral normalization using a multi-Lorentzian function (Nowak 2000; Belloni et al. 2002) for Intervals I–IV. All parameters were set free (Pottschmidt et al. 2003; van Straaten et al. 2005). We obtained the centroid frequency \( \nu_c \), the FWHM \( (\Delta \nu, \text{FWHM}) \), and the fractional root-mean-squared (rms) of HBOs. We plotted the power spectra in the power times frequency representation \((\nu P_{\nu}, \text{in units of rms}^2)\) where each power spectral density \(P_{\nu}\) is multiplied by its Fourier frequency \(\nu\).

We also extracted five energy bands, i.e., 2.06–4.49 keV (channels 0–10, CH1), 4.9–7 keV (channels 11–16, CH2), 7.4–9.4 keV (channels 17–22, CH3), 9.8–14.8 keV (channels

![Figure 1. CDs (upper panels) and HIDs (lower panels) for each of the four intervals in Table 1. Each dot represents 16 s of background-subtracted data from PCU 2. From left to right, are Intervals I–IV.](image)
23–35, CH4), and 15–65 keV (channels 36–149, CH5) to compute cross-spectra. The cross-spectrum (Nowak et al. 1999) is defined as \( C(j) = S(j) ∗ H(j) \), where \( S(j) \) and \( H(j) \) are the measured complex Fourier coefficients at a given frequency \( ν_j \) for soft and hard energy bands, respectively. The phase lag between two energy band light curves is the Fourier phase \( φ(j) = \arg[C(j)] \). The time lag is constructed from \( φ(j) \) by dividing by \( 2πν_j \), i.e., \( τ(ν_j) = φ(j)/2πν_j \). A positive time lag indicates that the hard photons lag the soft photons. The cross-spectra of XTE J1701-462 show that the phase lag above 100 Hz is consistent with \( π \). This is a dead time effect which should be corrected for by subtracting a cross-vector, averaged over 100–128 Hz (van der Klis et al. 1987; Vaughan et al. 1999). Hectohertz QPOs and kHz QPOs were observed in XTE J1701-462 (Homan et al. 2010; Sanna et al. 2010); the subtracted cross-vector might be combined with the white noise and signal. However, the signal above 100 Hz can be dismissed compared with the noise amplitude. We computed the time lags of CH2–CH5 relative to the CH1 of NBOs and investigated the time lag evolution along with the HB between 9.8–14.8 keV and 2–4.5 keV.

To investigate the correlation between the data position in the HID and the temporal properties, we introduce a rank number \( S \), defined by Hasinger et al. (1990). In Figure 2, we set the \( S \) of Boxes 12 and 24 as 1 and 2, respectively. The rank numbers of other boxes are decided by spline interpolation (Dieters & van der Klis 2000; Lin et al. 2012).

3. RESULTS

3.1. Time Lag Evolution along the HB in the Cyg-like Phase

We calculate the PDSs and average cross-spectra for XTE J1701-462 in the Cyg-like Z phase (Figures 3 and 4) and in the Sco-like Z phase (Figure 5). Positive lags indicate that the hard photons (9.8–14.8 keV) lag behind the soft photons (2–4.5 keV). In Figure 3, the cross-spectra of Interval I show hard lags (red “+”) during the QPO frequency range on the HB. The red noises below 10 Hz display soft time lags (black “o”) on the HB. The time lags of the NB are dominated by hard lags. In Figure 4, the HBOs and cross-spectra of Interval II are present. The time lags of Intervals I and II on the HB have similar behaviors. In Figure 5, the hard lags are accompanied by QPOs and the soft lags are observed at less than 10 Hz on HB. Meanwhile, we plot the phase lag versus frequency in Figures 3–5, which clearly show the intrinsic phase lag coupled with QPOs.

In order to investigate the correlation between \( S \), and temporal variabilities, we average the time lags of QPOs over the frequency between \( ν_c − Δν/2 \) and \( ν_c + Δν/2 \). In Figure 6, we display the QPO centroid frequencies, the time lags, and the rms of the HBOs as a function of \( S \) in Interval I. The centroid frequencies of HBOs increase from 12 Hz to 53 Hz, but the time lags and rms of HBOs decrease when \( S \) is below 0.5, then remain constant when \( S \) is larger than 0.5. As a contrast,
Figure 4. Power density spectra (top panels) and cross-spectra (middle panels) as well as phase lags (bottom panels) on the upturn, the left HB, the middle HB, the right HB, and the HB/NB vertex of Interval II. The selected energy channels are the same as in Figure 3. The PDSs and the cross-spectra of the NB and FB are not provided here because the data are not dense enough.

(A color version of this figure is available in the online journal.)

Figure 5. Power density spectra (top panels), cross-spectra (middle panels), and phase lags (bottom panels) on the HB of Interval III.

(A color version of this figure is available in the online journal.)

we provide the same temporal variabilities of Interval II in Figure 7. We note that the centroid frequencies and the rms of HBOs are similar to those in Interval I. However, The time lags rapidly decrease when $S_z$ is less than 0.5, then the time lags slowly increase with $S_z$. All time lags are hard lags with several milliseconds.

For different HIDs, the intensities of the HB/NB vertex and the NB/FB vertex were considered as reference values for the accretion rate $\dot{m}$. In order to study the time lag–accretion rate connection, we also calculate the time lag between 7.4–9.4 keV and 2–4.5 keV in the HB/NB vertex region of Intervals I–IV. In Figure 8, the QPO centroid frequency positively correlates with time lag. Both are followed by a decrease in source intensity, that is, the accretion rate decreases (Lin et al. 2009). We should note that the source intensity difference between Intervals I and II is small (upper panel in Figure 1) and the time lags are also extremely close.

3.2. Time Lag Evolution of the Z Phase on the NB

In Figure 9, we show the variation of NBOs in Interval I. The centroid frequencies of NBOs are around 6 Hz which is consistent with other Z sources. In order to study the time lags along the NB, we average the time lags with a fixed frequency range 6 ± 2 Hz, between 7.4–9.4 keV and 2–4.5 keV.

In Figure 10, we display the time lag evolution from the HB/NB vertex to the NB/FB vertex of Interval I. The time lags
are nearly constant on the upper NB ($1 \leq S_z < 1.2$) and the lower NB ($1.7 \leq S_z \leq 2$) and reduce from $\sim 45$ ms to $\sim 70$ ms on middle NB ($1.2 < S_z < 1.7$).

In Figure 11, the time lags as a function of $S_z$ on the NB and the FB of Interval III are reported. Between the HB/NB vertex and the NB/FB vertex, the time lags averaged over 4–8 Hz are nearly constant around 50 ms.

3.3. The Time Lag Spectrum and rms Amplitude Spectrum of NBOs in the Cyg-like Phase and the Sco-like Phase

We extracted the Cyg-like phase and the Sco-like phase NBOs with five energy band light curves, 2.06–4.49 keV (channels
Figure 11. Average time lags on the NB and FB of Interval III. The energy channels and frequency range selection are the same as in Figure 10.

Figure 12. Time lag spectrum (left panel) and rms amplitude spectrum (right panel) for the NBOs on the lower NB of Interval I.

Figure 13. Time lag spectrum (left panel) and rms amplitude spectrum (right panel) for the NBOs on the lower NB of Interval III.

Figure 14. Time lag spectrum (left panel) and rms amplitude spectrum (right panel) for the NBOs on the lower NB of Interval IV.

amplitude spectrum of Interval IV (right panel in Figure 14) but with a weak tendency.

4. DISCUSSION

The LMXB source XTE J1701-462 transitioned from a Z source to an atoll source during its outburst. We used an FFT to compute the PDS of XTE J1701-462. For the Cyg-like observations (Intervals I and II), the centroid frequencies of HBOs increased from 12 Hz to 53 Hz, while the amplitude of HBOs became weaker. The cross-spectra of HBOs were computed as well. In Figures 3 and 4, we found that the time lags of low-frequency noise less than 10 Hz are dominated by soft lags. Moreover, the soft lag increases toward low frequency. When QPOs appeared, the XTE J1701-462 showed hard lags, i.e., high energy photons lag soft photons. For the NB observations of the Cyg-like phases and the Sco-like phases, hard lags were also observed in the HBO frequency range. These also appeared in other Z sources (van der Klis et al. 1987; Vaughan et al. 1994; Qu et al. 2001, 2004). We also study the time lag evolution along the NB in Z sources. In Interval I, the time lags averaged between 4 Hz and 8 Hz decreasing on the middle NB as a function of rank number $S_z$ (Figure 10). This could be the centroid frequency and rms amplitude variation of the NBO (Figure 9). In Interval III, the time lags of NBOs remained nearly 50 ms (Figure 11). For the HB/NB vertex regions in the Z sources, the time lag increased with decreasing source intensity, which is a trend of decreasing accretion rate.

Regardless of CH5, the rms amplitude of NBOs linearly correlates with energy in the range 2–15 keV (i.e., the signal strength of QPOs is proportional to the photon energy) of Intervals I and III (right panels in Figures 12 and 13). The rms energy dependence was also observed in Sco X-1 (Wang et al. 2012). Because of the low count rates and low signal-to-noise ratio in the highest energy band, the rms of NBOs has large error bars. A drop in the rms amplitude in the highest band was observed. A pivot energy in 4.9–7 keV appears in the rms
(Uttley et al. 2011), and Comptonization models (Cui et al. 1997b; Kazanas et al. 1997). The shot model mathematically explained the observed power spectra in LMXBs (Alpar & Shaham 1985), the soft lag in the low-frequency noise (Shibazaki et al. 1988), and the hard lag in the HBO (Vaughan et al. 1994). HBOs are the signature of intensity modulation and low-frequency noise is regarded as the power spectral signature of shots when the accretion matter falls onto the NS surface. The observed soft lag of low-frequency noise could be interpreted if the shot envelopes in the soft energy band lag behind those in the hard energy band. Meanwhile, the hard lag in the HBO may originate from a particular delay of QPO production in the high energy band without distinct interference from low-frequency noise.

The time lag in the hard state of BH-LMXBs, which displays a hard lag in low-frequency noise, shows the exact opposite of our results (Nowak et al. 1999; Pottschmidt et al. 2003; Uttley et al. 2011). Nowak et al. (1999) investigated the hard state time lag in Cyg X-1 and found that both the energy dependence of the hard lag in low-frequency noise and the hard lag increase with decreasing low Fourier frequency. This seems contradictory to the uniform and compact Comptonization corona model. Uttley et al. (2011) pointed out that the observed hard lag in GX 339-4 corresponds to the viscous propagation of mass accretion instabilities through the disk. The emission of BH-LMXBs contains two parts: the power law dominant in the high energy band and the disk blackbody dominant in the low energy band. When mass accretion fluctuations occur, the variabilities of disk blackbody emission lead to the power-law emission variations on timescales of seconds. If the low-frequency noise comes from these two component variations, then the hard lag appears. For the soft lag, it may be caused by the power law illuminating the blackbody on timescales of milliseconds, where the power-law emission regions locate about tens of $R_G$ from the disk.

However, XTE J1701-462 shows a more complicated emission mechanism than BH-LMXBs (Lin et al. 2009; Ding et al. 2011). On the HB, the energy spectrum of XTE J1701-462 is composed of the multi-color blackbody from the disk, the blackbody from the NS surface, and the cutoff power law from the corona above the disk, which dominate the emission in several keV, tens of keV, and the hard tail, respectively. On the NB and FB, the cutoff power-law component becomes too faint to be detected. We indicate that three possible lag mechanisms exist: Compton upscattering by the corona (Kotov et al. 2001; Arévalo & Uttley 2006), propagation of the accretion rate instabilities in the disk (Uttley et al. 2011), and disk illuminating by the blackbody from the NS surface in XTE J1701-462. However, the soft lag introduced by the NS X-ray illuminating is likely the timescale of light travel from the NS to the disk, which is too low ($\sim$0.1 ms) compared to our calculations. The propagation of the accretion rate instabilities in the disk only produce a hard lag in low-frequency noise which does not conform to the soft lag in XTE J1701-462.

The uniform Comptonization models (Payne 1980; Kazanas et al. 1997) cannot interpret the energy dependence of hard and soft time lags in LMXBs. In order to explain the soft lags and time lag evolution of QPOs, a Comptonization model with a two-layer corona was proposed (Nobili et al. 2001; Qu et al. 2001). When photons pass through the two-layer corona, the photons encounter inverse Compton scattering by hot electrons and gain energy. If the inner layer is hot and the optical depth is $<1$, the hard photons are scattered more than the soft photons and hard time lags are observed. If the inner layer is optically thick, the photons are efficiently upscattered. When the harder photons pass through the outer part of the corona with lower temperature, they lose energy and soft lags appear.

Qu et al. (2001) explained that the change in accretion rate along branches leads to Cir X-1’s time lag evolution. From multiwavelength campaigns of Cyg X-2, a monotonic increase in $m$ from the HB, via the NB, to the FB was reported (Hasinger et al. 1990; Vrtilek et al. 1990). If the accretion rate of XTE J1701-462 rises from the HB to the NB, the hot electrons in the inner layer corona are cooled by photons from the disk. This process shrinks the inner layer of the corona and the observed HBO time lags become smaller. Lin and co-workers (Lin et al. 2009; Homan et al. 2010; Lin et al. 2012) concluded that the accretion rate did not vary significantly along the Z tracks but did along secular change, i.e., $m$ decreases from a Z source to an atoll source. The time lag–QPO relation of the HB/NB vertex could be explained by the accretion rate decreasing (Figure 8). However, for the time lag evolution of XTE J1701-462 on the HB, when the source intensity increased, the disk luminosity which was mainly contributed by Comptonization ascended simultaneously (see Figure 20 in Lin et al. 2009).

When the luminosity of the disk component increases from the up turn to the HB/NB vertex, the temperature of the inner layer of the corona cools down through Compton emission and then leads to a smaller radius layer. Because the photons contributing to the HBOs came from the disk, a decrease in the time lags of HBOs as a function of S was also observed. In a Z track, the time lag of HBOs increasing toward high source intensity can be explained by the accretion rate increasing and the Comptonization component variations. Jackson et al. (2009) and Balucinska-Church et al. (2010) suggested an opposite direction for the increasing accretion rate, i.e., from the NB to the HB, which could not reasonably explain the time lag evolution of XTE J1701-462.

A near-180° phase lag and a dip in the rms amplitude spectrum were observed in Cyg X-2 and GX 5-1 but not in Sco X-1. Dieters et al. (2000) provided two explanations for the NBOs’ behavior for Cyg X-2, GX 5-1, and Sco X-1. First, they may have different viewing angles. Second, with the radiation-hydrodynamic model of QPOs, the QPOs of GX 5-1 and Sco X-1 are determined by optical depth oscillations while the QPOs of GX 5-1 are determined by luminosity variation, where the NS of GX 5-1 has a weaker magnetic field. XTE J1701-462 changes from a Cyg-like Z source, via a Sco-like Z source, to an atoll source with in two years. The binary inclination and the strength of the NS magnetic field are invariant on such a short timescale (Kuulers et al. 1994; Psaltis et al. 1995). The accretion rate dominates the whole process. We found a near-160° phase lag of NBOs in both the Cyg-like and Sco-like phases which is consistent with Cyg X-2 and GX 5-1. However, no pivot energy in the rms amplitude spectrum was observed in the Cyg-like phase. This cannot be explained by the radiation-hydrodynamic model (Fortner et al. 1989). Wang et al. (2012) suggested that the NBO and the rms energy dependence in Sco X-1 originate from the transition layer. The similar behaviors of the time lag spectrum and rms amplitude spectrum between the Cyg-like sources and the Sco-like sources indicate that the NBOs are irrelevant to the luminosity variation in XTE J1701-462.

5. CONCLUSIONS

We investigated the cross-spectra and QPOs for the Cyg-like and Sco-like phases of XTE J1701-462. The QPOs increase from 12 Hz to 53 Hz on the HB and remain at $\sim$6 Hz on the
NB. This is consistent with other Z sources. We also computed the time lags and HBOs for the HB/NB vertices (Intervals I–IV). A two-layer corona Comptonization model can explain the soft lag in low-frequency noise and hard lag in HBOs. Both the increasing accretion and the Comptonization component variation can produce the evolution of the HBO’s time lag. For an NS-LMXB, we could not deduce its direction of increasing accretion rate along branches in the HID solely from the time lag variation. The spectral states should be analyzed simultaneously. This will be discussed in our future work.

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