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The Evolution of the Phase Lags Associated with the Type-C Quasi-periodic Oscillation in GX 339–4 during the 2006/2007 Outburst

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Abstract

We present the evolution of the phase lags associated with the type-C QPO in GX 339–4 during the rising phase of the 2006/2007 outburst. We find that the phase lags at the QPO frequency are always positive (hard) and show very different behavior between QPOs with frequencies below and above ~1.7 Hz: when the QPO frequency is below ~1.7 Hz, the phase lags increase both with QPO frequency and energy, while when the QPO frequency is above ~1.7 Hz, the phase lags remain more or less constant. When the QPO frequency is higher than ~1.7 Hz, a broad feature is always present in the lag–energy spectra at around 6.5 keV, suggesting that the reflection component may have a significant contribution to the phase lags. Below ~1.7 Hz, the QPO rms first decreases with energy and then turns to almost flat, while above ~1.7 Hz, the QPO rms increases with energy. During the transition from the low-hard state to the hard-intermediate state, the second harmonic and subharmonic of this QPO appear in the power density spectra. The second-harmonic and subharmonic phase lags show very similar evolutions for their centroid frequencies. However, the energy dependence of the second-harmonic and subharmonic phase lags are quite different. Our results suggest that, at different phases of the outburst, different mechanisms may be responsible for the phase lags of the QPO. We briefly discuss the possible scenarios for producing the lags.

Key words: accretion, accretion disks – black hole physics – X-rays: binaries

1. Introduction

Most of the known black hole X-ray binaries are transient systems (black hole Transients, BHTs) that usually go through several distinct temporal and spectral states during a complete outburst. Following the classification of Homan & Belloni (2005), these states are the low-hard state (LHS), hard-intermediate state (HIMS), soft-intermediate state (SIMS), and high-soft state (HSS; see Belloni 2010; Belloni et al. 2011 for reviews; for a different classification scheme of the black hole states, see Remillard & McClintock 2006). In the LHS, typically seen at the beginning and the end of an outburst, the energy spectrum is dominated by a hard power-law component ($\Gamma \sim 1.5$) with a high-energy cutoff around ~100 keV. The hard component is attributed to Compton up-scattering of soft photons by hot electrons in a corona (Gilfanov 2010). In the HSS, usually observed in the middle of the outburst, the energy spectrum is dominated by a thermal component associated with an optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973). Two additional states, HIMS and SIMS, have been identified between the LHS and HSS (Belloni et al. 2005). During these states, the power-law component becomes softer than that in the LHS and the contribution from the disk component gradually increases.

The X-ray spectrum of BHTs also shows a reflection component, produced via the hard X-ray photons in the corona irradiating the inner part of the accretion disk (Fabian & Ross 2010). The most prominent feature of the reflection spectrum is the fluorescent Fe Kα line at around 6.4 keV, which is often broadened by Doppler effects, light bending, and gravitational redshift (Fabian et al. 1989). Another important feature is the reflection hump between 10 and 30 keV due to Compton back-scattering (Ross & Fabian 2005; see Miller 2007 for a review).

Low-frequency quasi-periodic oscillations (QPOs) with centroid frequencies ranging from a few mHz to ~30 Hz have been observed in the power density spectra (PDS) of most BHTs. These QPOs can be classified into three categories, dubbed type-A, -B, and -C, based on the quality factor, fractional rms, noise component, and phase lag properties (e.g., Casella et al. 2005). The energy dependence of the QPO amplitude shows that QPO emission is associated with the power-law component (Gierliński & Zdziarski 2005; Belloni et al. 2011; Gao et al. 2014). Type-C QPOs are the most common type of QPOs in BHTs, and occur mostly in the LHS and HIMS. These QPOs are characterized by a strong, narrow peak with variable frequency, superposed on a band-limited noise continuum. A second harmonic and a subharmonic peak are sometimes present in the PDS. Here we will focus our study on the type-C QPO.

There is still no general agreement about the physical nature of the type-C QPOs, but increasing evidence suggests that they may have a geometric origin, with Lense–Thirring precession of the entire inner flow being the most promising model (e.g., Ingram et al. 2009). For instance, Heil et al. (2015) and Motta et al. (2015) found that the amplitude of the type-C QPO depends on the orbital inclination of the system in which they are observed. This confirms the prediction in the precessing ring model proposed by Schnittman et al. (2006) that the QPO should be stronger in high-inclination systems.

Based on phase-resolved spectroscopy analysis, the iron line equivalent width in GRS 1915+105 and the iron line centroid energy in H 1743–322 have been found to be modulated with

QPO phase (Ingram & van der Klis 2015; Ingram et al. 2016). Additionally, Ingram et al. (2017) found that the reflection fraction also changes with QPO phase. These results strongly point to a geometric QPO origin, and they are consistent with the idea that the QPO is produced by Lense–Thirring precession (Stella & Vietri 1998; Schnittman et al. 2006; Ingram et al. 2009).

Phase lags between different energy bands are a powerful tool to study the fast X-ray variability. Recently, van den Eijnden et al. (2017) made a systematic analysis of the phase lag in 15 BHTs and found that the phase lags at the type-C QPO frequency strongly depend on inclination. Low-inclination sources display hard lags (hard photons lag the soft ones) at high QPO frequencies, while high-inclination sources display soft lags, except GRS 1915+105 which shows both positive and negative lags. This is consistent with previous results from individual sources: XTE J1550–564 (Remillard et al. 2002), XTE J1859+226 (Casella et al. 2004), and XTE J1752–223 (Muñoz-Darias et al. 2010). Such an inclination dependence provides strong constraints on the physical mechanism that produces the phase lags. It is also very important to mention the peculiar source GRS 1915+105, which exhibits a very different phase-lag behavior. As QPO frequency increases, the phase lags decrease and change sign from positive to negative when the QPO is at around 2 Hz (Reig et al. 2000). Furthermore, the energy-dependent phase lags change with QPO frequency: for QPOs with a low frequency (<2 Hz), the phase lags increase with energy; for QPOs with a high frequency (>2 Hz), the phase lags decrease with energy (Reig et al. 2000; Qu et al. 2010; Pahari et al. 2013).

GX 339–4 is a recurrent low-mass X-ray binary (LMXB), which harbors a black hole with a mass function of $f(M) = 5.8 \pm 0.5\, M_\odot$ (Hynes et al. 2003). The distance to this system is between 6 and 15 kpc (Hynes et al. 2004). Due to the lack of eclipses and absorption dips (Cowley et al. 2002), the inclination of GX 339–4 must be less than $\sim 60°$, and a lower limit of $\sim 40°$ can be set by assuming that the black hole mass should not exceed 20 $M_\odot$ (Muñoz-Darias et al. 2008). GX 339–4 has undergone frequent outbursts and displayed all the black hole states (e.g., Méndez & van der Klis 1997; Belloni et al. 1999; Belloni et al. 2005; Dunn et al. 2008) in the past thirty years, making it one of the most studied BHTs. Among these outbursts, the 2006/2007 outburst was the brightest one, and contains a large quantity of low-frequency QPO phenomena. Detailed studies on the evolution of the low-frequency QPOs and spectral parameters during this outburst have been carried out by Motta et al. (2009), Motta et al. (2011). A systematic analysis of the reflection spectrum and the phase lags of the broadband noise component in GX 339–4 has been done by Plant et al. (2014) and Altamirano & Méndez (2015), respectively.

Tracing the evolution of rapid X-ray variability along an outburst can help us understand the physical changes of the accretion flow and the origin of the variability. Such crucial information can be obtained through studying the energy dependence of the variability properties, like QPO amplitude and phase lags. Therefore, in this paper, we study in detail the evolution of the phase lags associated with type-C QPO in GX 339–4 during the rising phase of the 2006/2007 outburst. We measured these phase lags at different Fourier frequency ranges: QPO fundamental, second harmonic, and subharmonic. We then produced a frequency-dependent phase lag spectrum for each observation and a energy-dependent phase lag spectrum for each Fourier component. In addition, we also calculated the energy-dependent QPO amplitude to investigate the QPO origin. We describe the observations and data analysis methods in Section 2. We present the results of our study in Section 3 and discuss them in Section 4. Conclusions follow in Section 5.

2. Observations and Data Analysis

We analyzed 23 *RXTE* public archival observations of GX 339–4 covering the rising phase of its 2006/2007 outburst. For our study, we selected only the observations that, according to Motta et al. (2009), have shown a type-C QPO. Due to the low count rate and signal-to-noise ratio, it is hard to study the energy dependence of the QPO properties during the fall of the outburst. Therefore, we only considered the observations during the rise. Table 1 lists the log of *RXTE* observations used in this work.

For the timing analysis, we used the software GHATS version 1.1.1 under IDL.[6] For each observation, we computed an average PDS in the full energy band (2–60 keV). We used 128 s long intervals and 1/1024 s time resolution, corresponding to a Nyquist frequency of 512 Hz. The Leahy normalization was used (Leahy et al. 1983) and the contribution due to the photon counting noise was subtracted (Zhang et al. 1995). We fitted the averaged PDS with a sum of Lorentzian functions using XSPEC v 12.9. In all PDS, a strong band-limited noise with one or more peaks was present, which is typical for the type-C QPO. Following Motta et al. (2015), we excluded from our analysis features with a significance of less than 3σ. When more than one peak was present in the PDS, we identified the fundamental based on the QPO evolution along the outburst. We identified the peaks near half and twice the fundamental frequency as the subharmonic and second harmonic, respectively. We calculated the fractional amplitude (rms) of the QPO fundamental in six energy bands (2–5.7 keV, 5.7–7.7 keV, 7.7–10.6 keV, 10.6–15 keV, 15–20.6 keV, and 20.6–44 keV) to make an rms spectrum (rms as a function of energy).

We also produced a frequency-dependent phase lag spectrum (lag–frequency spectrum) between the 2–5.7 and 5.7–15 keV energy bands for each observation, following the method described in Vaughan & Nowak (1997) and Nowak et al. (1999). To calculate the phase lags, $\Delta\phi$, at the QPO fundamental and (sub)harmonic, we averaged the phase lags over the width of each Fourier component, around its centroid frequency, $\nu_0 \pm \mathrm{FWHM}/2$, where ν_0 is the centroid frequency of the fundamental or the (sub)harmonic and FWHM is its full-width at half-maximum obtained from the Lorenzian fits. Throughout this paper, a positive phase lag means that the hard photons lag the soft photons. No correction for the dead-time-driven cross-talk effect (van der Klis et al. 1987) was done because this effect was found to be negligible. The corresponding time lag, $\Delta\tau$, at a frequency ν is $\Delta\tau = \Delta\phi/2\pi\nu$.

In addition to the lag–frequency spectrum, we also calculated the energy-dependent phase lag for both the QPO fundamental and its harmonics (lag–energy spectrum), following the procedure described in Uttley et al. (2014). The phase lags were calculated for the energy bands 4–5.7 keV,

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[6] GHATS, http://www.brera.inaf.it/utenti/belloni/GHATS_Package/Home.html.