TIME LAGS OF Z SOURCE GX 5-1

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Abstract

We investigated the time lags and the evolution of the cross spectra of Z source GX 5-1, observed by the Rossi X-ray Timing Explorer (RXTE), when it is in the horizontal branch oscillations. We showed that the time lags of 3 horizontal branch oscillations are related to the position on the hardness intensity diagram. All of the three QPOs were shown to have hard time lags. However on the cross spectra, one is in a ‘dip’, one in a ‘bump’, the other has no so obvious characteristic. The time lags of two of the QPOs decrease with QPO’s frequency, while the other has a trend increasing with its frequency. Moreover, in the normal branch, we found no significant time lags in the present observational data.

Keywords: binaries: general — stars: individual (GX 5-1) — X-rays: stars

1. Introduction

The neutron-star low-mass X-ray binaries (LMXBs) can be divided into two types on the basis of pattern traced out in the X-ray intensity-hardness or color-color diagram (HID or CCD, respectively; Hasinger & van der Klis 1989). One is Z source which traced out a “Z” pattern on HID or CCD, the other is atoll source which traced out a “C” pattern on CCD. From the top to the bottom of the Z pattern, the three limbs of the pattern traced out on HID or CCD is called the Horizontal Branch (HB), Normal Branch (NB), and the Flaring Branch (FB), respectively. The temporal properties of Z source depend on the position on the Z pattern. On the HB and the NB, there are varying quasi-periodic oscillations (QPOs) with frequency less than 100 Hz, called horizontal branch oscillation (HBO) and normal branch oscillation (NBO).

Recently, Jonker et al. (2002) studied in detail the power-density spectra (PDS) of the Z source GX 5-1. They showed that there are four QPO components on the HB, which are HBO and its three harmonics. Using the EXOSAT data, van der Klis et al. (1987) had studied the time lags (or phase lags) of the HBO and the low frequency noise (LFN) by cross-correlation spectra, showing a complex timing behavior. There
are hard time lags decreasing with the HBO frequency and soft time lags in LFN increasing with the Fourier frequency. They argued that the hard time lags of HBO are due to Comptonization of soft photons, and the soft time lags of LFN due to the evolution of energy spectrum of the shot. Using the Ginga data, Vaughan et al. (1994) studied one harmonic with higher Fourier frequency and the relation between time lags of NBO and its energy, in which a jump at 3.5 keV was found. Their results are similar to that from van der Klis et al. (1987).

Thanks to the large effective collective area and high time-resolution of the Rossi X-ray Timing Explorer (RXTE), we can investigate the cross-spectrum and PDS of GX 5-1 in more details. In this paper, we report the time lags of HBO and its harmonics of GX 5-1 basing on the RXTE data. We found that the time lag behaviors are related to the HBO fundamental frequency. In section 2, we describe the method of data analysis. In section 3, the results are presented. We discuss the results briefly in the last section.

2. Observations and Analysis

GX 5-1 was observed for 11 times in 1997 with the Proportional Counter Array (PCA) on board the RXTE satellite. Because the energy channel bins changed during the different observation epochs, we only used data of 6 observations from May 30 to July 25, 1997. The data were always obtained in a mode with 16 s time-resolution and a high spectral resolution (129 energy channels covering the effective 2-60 keV range, the Standard 2 mode). For this epoch of observations we used Single-Bit mode, a high time-resolution data mode with $2^{-13}$ s time-resolution covering four energy bands (namely 2-5.1 keV, 5.1-6.6 keV, 6.6-8.7 keV, and 8.7-60 keV; absolutely RXTE energy channels 0-13, 14-17, 18-23, 24-249, respectively), to calculate PDS and cross spectrum.

We used standard 2 mode data to make an HID for GX 5-1. Because one detector was off sometimes, we only used data when all 5 detectors were on simultaneously. The hardness, or hard color, is defined as the 8.7-19.7keV/5.9-8.7keV (24-53/16-23) count rate ratio and the intensity is defined as the count rate in the 2-19.7 keV (0-53) band averaged in a 32 s.

The HID was showed in Fig.1, each point represents 32 s data length in the HID. The source was found on the HB and the NB. To investigate X-ray temporal properties of GX 5-1 along the Z track, we divided the HB into 6 boxes (see Fig.1), according to the point numbers of each box.

![Figure 1](image)

The HID of GX 5-1. Each point corresponds to 32 s of data.

The good quality of data with high time resolution allows us to calculate the power-density spectra for each energy band and the cross-spectra for two energy bands of data stretches of 32 s with 4 ms time bin in each box. All the spectra were logarithmically re-binned. The cross spectra of GX 5-1 show that time lags above 80 Hz are dominated
Table 1. The centroid frequencies and the Full Width at Half Maximum of 3 QPOs.

| Box No. | sub-HBO (Hz) | FWHM (Hz) | HBO (Hz) | FWHM (Hz) | harmonic (Hz) | FWHM (Hz) |
|---------|--------------|-----------|----------|-----------|---------------|-----------|
| 1       | 8.15±1.20    | 8.17±3.10 | 17.39±0.09| 3.74±0.28 | 31.34±1.19    | 8.17±2.63 |
| 2       | 10.29±1.13   | 8.78±3.78 | 22.99±0.22| 5.81±0.47 | 42.83±1.41    | 20.69±2.67|
| 3       | 11.96±1.37   | 12.30±3.21| 26.69±0.11| 5.04±0.50 | 50.85±1.28    | 22.51±3.13|
| 4       | 17.64±2.62   | 11.58±12.28| 32.37±0.18| 7.15±0.57 | 62.11±1.50    | 19.16±4.38|
| 5       | 19.68±1.65   | 2.31±18.87| 37.29±0.32| 8.62±1.07 | 72.35±3.78    | 19.38±11.03|
| 6       | 22.07±5.19   | 2.86±—    | 41.41±0.50| 10.52±2.01| 86.31±8.03    | 28.59±34.52|

by the dead-time effect, which was corrected by subtracting a cross vector, averaged over 80 to 128 Hz, from the cross spectrum (van der Klis et al. 1987; Qu, Yu & Li 2001). As an illustration, only the PDSs and the cross spectra of the highest energy band are shown in Fig. 2.

Figure 2. The PDSs for 8.7 – 60 keV (top panel) and cross spectra between 2 – 5.1 keV and 8.7 – 60 keV (bottom panel) of GX 5-1 on different boxes.

3. Results

Figure 2 (panel 1–6, top) presents that there exist two obvious QPOs, and their frequencies increase from ‘Box 1’ to ‘Box 6’. Jonker et al. (2002) showed that the PDS of GX 5-1 can be fitted well by a model consisting of 4 QPO components (Lorentzians) and a cut-off power-law component. We only used a model composed of three Lorentzians (i.e., 3 QPO components) and a cut-off power-law to fit the PDSs of GX 5-1, while the harmonic at high frequency has not been studied due to the low signal-to-noise ratio caused by the limited integration time. The QPO parameters were listed in table 1. Following Jonker et al. (2002), we call the low-frequency QPO as sub-HBO, and the strongest QPO as HBO, the higher frequency QPO as the harmonic. In Fig.2, QPOs’ position (QPO’s centroid frequency) were indicated by the dotted-lines. As an illustration, we plotted the HBO vs. sub-HBO and the harmonic in Fig.3. The results are consistent with those of Jonker et al. (2002).

The cross spectra (Fig.2; panel 1–6, bottom) show that the time lags of the noise less than 10 Hz are dominated by soft time lags (negative lags are represented by ‘−’ in the cross spectra of Fig.2). During QPOs’ frequency range, GX 5-1 shows hard time lags (positive lags are presented by ‘+’ in the cross spectra of Fig.2). The time lags of HBO and the harmonic decrease with their centroid frequencies (see Fig.4), but the time lag of HBO in box 6 has a trend increasing with QPO frequency. Those results are consistent with earlier works (van der Klis et al. 1987, Vaughan et al. 1994). However, the cross spectra of GX 5-1 also show finer timing behaviors. The time lags of the harmonic and the HBO may be in a bulge and a concave, which were named as ‘bump’ and ‘dip’ respectively in this paper, for convenience. For checking those characteristics in the cross spectra, we fitted the cross spectrum with a
quadratic and a Lorentzian around the centroid frequency of the harmonic and the HBO. We found that the centroid frequency of the HBO and the harmonic is linear with the fitted results of the cross spectra, with a slope near 1.0. We also calculated the average time lags of the HBO and the harmonic. In the first five boxes it is found that the time lag of the harmonic is higher than the HBO's with a significance level $\sim 4.1\sigma$, which is obtained from numerical simulations. Those results showed that the time lags of the HBO and the harmonic are in a dip and a bump respectively. Due to the contamination of the LFN, the behavior of the sub-HBO may also be different from the those of the HBO and the harmonics. The time lags of the sub-HBO has a trend increasing with its frequency (see bottom panel of Fig.5). We also calculated the cross spectrum of 'Box NB' on the NB and average the time lags in NBO frequency range. However, we didn’t find any significant time lags at 90% confidence level (average time lag of the NBO is 4.9±8.0 ms).

In order to study the relations between the time lags of different QPOs, we average the time lags over the frequency ranges from $\nu_{QPO} - 0.5\Delta\nu_{QPO}$ to $\nu_{QPO} + 0.5\Delta\nu_{QPO}$, where $\Delta\nu_{QPO}$ is the full width at half maximum (FWHM) of the QPO. The time lags of the HBO and the harmonic were plotted in Fig.4. The time lags of the sub-HBO were plotted in Fig.5(bottom panel). Because the sub-HBO was in the frequency range of the LFN, time lags of the LFN might have affected the sub-HBO. We fitted the real and imaginary parts of a cross vector between 1 and 5 Hz by Lorentzian and quadratic model respectively. Then the time lags of the LFN were corrected by subtracting a real and imaginary part from the cross spectra of the sub-HBO frequency range basing on the above models. The results were shown in top panel of the Fig.5.

**Figure 3.** The relations among HBO and sub-HBO (bottom panel) as well as the harmonic (top panel).

**Figure 4.** Time lags of HBO and the harmonic.

In order to discuss the thermal electron distribution near the neutron star, we used all the data from Box1~3 and calculated the coherence function which shows how the photons in the two energy bands are related. The results were shown in Fig.6. For clear, the coherence functions for high energy bands are offset by 1.0 and 2.0 respectively.

**Figure 5.** Time lags of sub-HBO. The top is the time lags corrected with LFN’s by subtracting a real and imaginary part from the cross spectra(see text).

**Figure 6.** The coherence function of GX 5-1 on the HB. The upper two panels are offset by 1.0 and 2.0 respectively.

For studying the energy dependence of the lags, the cross spectra between higher energy bands and 0-13 energy band was calculated in each box. The energy dependence of the HBOs was listed table 2. For
Table 2. The energy dependence of time lags of HBOs.

| Box No. | HBO  | FWHM | $E_2 = 5.78^{+0.64}_{-0.64}$ | $E_3 = 7.50^{+1.24}_{-0.92}$ | $E_4 = 11.1^{+1.50}_{-2.36}$ |
|---------|------|------|----------------------------|----------------------------|----------------------------|
| 1       | 17.39 | 3.74 | 0.53±0.11                  | 1.01±0.11                  | 1.58±0.12                  |
| 2       | 22.29 | 5.81 | 0.29±0.12                  | 0.74±0.12                  | 1.15±0.12                  |
| 3       | 26.69 | 5.04 | 0.19±0.09                  | 0.36±0.08                  | 0.83±0.09                  |
| 4       | 32.37 | 7.15 | 0.00±0.10                  | 0.17±0.10                  | 0.66±0.09                  |
| 5       | 37.29 | 8.62 | -0.27±0.19                 | 0.15±0.16                  | 0.47±0.13                  |
| 6       | 41.41 | 10.5 | 0.12±0.28                  | 0.12±0.24                  | 0.49±0.21                  |
| NB      | 5.69  | 4.0  | 1.76±7.94                  | 0.82±9.38                  | 4.90±7.99                  |

The unit of time lag and energy bands is ms and keV respectively.

$E_1 = 3.93^{+1.21}_{-3.82}$ (keV)

simple, only the energy dependence of time lags of 17 Hz QPO were shown in Fig.7.

Figure 7. The time lags of 17 Hz QPO as a function of energy compared to the lowest energy 2-5 keV(channel 0-13).

4. Discussion

We have performed the analysis of the RXTE/PCA data of GX 5-1 when it was on the HB and the NB. Beside that the soft time lags of the LFN and the hard time lags of QPOs were found to be similar to the results of Vaughan et al. (1994), we discovered some finer characteristics in the cross spectra around the centroid frequency of the QPOs. The time lag of the HBO is in a dip while the harmonic in a bump. The sub-HBO also shows a hard time lag. Due to the contamination of the LFN, the time lag of the sub-HBO increases with the centroid frequency of the sub-HBO. When the effect of the LFN was corrected, this trend disappear. The QPOs in the horizontal branch show hard time lag. In present RXTE data and energy bands, we didn’t find any significant time lags in the NBO’s frequency range. It may be caused by that the lowest energy channel for calculating cross spectra is above the jump energy (3.5 keV) of time lags (Vaughan et al. 1999).

If box series numbers in the HID represent the mass accretion rate of the source, the evolution of the cross spectrum along the track suggests that the cross spectrum should vary with the mass accretion rate.

There are several kinds of models proposed to interpret the time lags: 1) the Comptonization models, e.g., the uniform corona model (Payne 1980), 2) the non-uniform corona model (Kazanas, Hua, & Titarchuk 1997), and 3) the drifting-blob model (Böttcher & Liang 1999), they only explain the hard time lags and the energy dependence of the time lags. The soft time lags cannot be explained. However, those models have some problems physically. For example, for producing measured time lags in a static Compton cloud, a hot corona with a large ra-
dius (for example, for Cyg X-1, the radius extent of the hot corona exceeds $10^{10} r_g$), it is physically unrealistic (see the review by Poutanen 2000). The coherence function might reflect the dynamical properties of the corona in the corona models (Nowak et al. 1999a, 1999b, Ji et al. 2003). The loss of coherence in high energy channels might show that the corona of GX 5-1 is dynamical. This is consistent with the above suggestions.

To explain the soft time lags and the time lag evolution in GRS 1915+105 and neutron-star binary Cir X-1 (Cui 1999; Reig et al. 2000, Qu, Yu & Li 2001), a two-layer corona model has been proposed (Nobili et al. 2001, Qu, Yu & Li 2001). In this model, the evolution of time lags of GX 5-1 with mass accretion can be explained, but the increase of the time lag near the transition between the HB and the NB can not be explained.

Both shot profile properties and Comptonization of photons can introduce time lags. The numerical simulations showed that the energy-dependent shot profiles can produce low-energy phase lags in the cross spectrum at typical frequencies for the shot time scale (tenths of a Hz to a few Hz) without noticeably affecting the cross spectrum at higher frequencies (Shibazaki et al. 1988). The shots are thought to originate near or at the neutron star surface as material falls through the magnetosphere and onto the surface of the neutron star. The delays should be of the order of the free-fall time. But the free-fall time is not longer than 0.5 ms. Although the shot models can produce almost any time-delay spectrum like Comptonization models, they also have problems on physical grounds (see Vaughan 1994, Poutanen 2000, Qu et al. 2002).

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