The hard X-ray advance in the Centaurus X-3 and its X-ray emission mechanism

Takayoshi Kohmura

Rikkyo University, 3-34-1, Nishi-Ikebukuro, Toshima-ku, Tokyo, 171-8501

tkohmura@ess.sci.osaka-u.ac.jp

Abstract.

We present a study of aperiodic variability from the X-ray binary pulsar Centaurus X-3. We have analyzed all archival data of Cen X-3 observed with the *Rossi X-Ray Timing Explorer* (RXTE).

We extracted light curves both in the energy band which included the iron K lines ("iron-band") and in the continuum X-ray bands which did not include the iron K lines. Then, we calculated cross spectrum functions between the iron-band and the remaining continuum bands. We discovered the significant time delay of temporal variation of iron-band emission as compared with that of the other energy X-rays by (0.98±0.45) ms, (0.39±0.10) ms, (1.24±1.08) ms, and (0.52±0.20) ms (1-σ error). We also discovered the time difference showed a general trend such that the higher energy X-rays advanced in comparison with the lower energy X-rays with the exception of the iron-band.

1. Introduction

The accreting X-ray pulsars are thought to be magnetized neutron stars with a normal star companion, the majority of which are high mass, early type stars (Rappaport & Joss 1983; see Nagase 1989 for a review). X-ray observations has revealed the existence of the strong iron K lines emission from many X-ray binary pulsars, including Cen X-3 (Nagase et al. 1992; Ebisawa et al. 1996).

So far, many authors have investigated the origin of the iron K lines. In the case of Cen X-3, this line emission is not observed during the eclipse, it must originate near to the neutron star (Nagase et al. 1992; Ebisawa et al. 1996). Further, the iron emission region must cover a large solid angle near to the neutron star (although not the full 4π steradian) in order to explain the large equivalent width of the line (Nagase et al. 1992). Nagase et al. (1992) derived an upper limit for the distance, between the iron line emitter and the neutron star, of $\sim 3\times10^{10}$ cm, based on the *Ginga* observation that showed the 6.4 keV line intensity to drop by a factor of 20 in less than 10 min. If the iron K-lines originate from the magnetosphere and the magnetosphere covers a large fraction of the solid angle at the neutron star, the line photons must be delayed in comparison with the X-rays observed directly from the neutron star. If this iron K lines are considered to come from a re-processing matter around the neutron star, e.g. the Alfven shell, we expect that iron-band has a certain delay from the higher energy X-rays.

2. Analysis and Results

To detect a small delay time, *RXTE* is the best experiment, which provides us high time resolution data with excellent statistics and reasonable energy resolution.

Figure 1 shows the power spectral density of P20104 observation data. The QPO component (Takeshima et al. 1991) was confirmed with the center frequency of 41±3 mHz. The noise due to Poisson statistics component has been subtracted. The first, second, and higher order harmonics of the pulsed component were detected. Aperiodic time variation is significantly detected up to ∼25 Hz. We are attempting to analyze the aperiodic time variation rather than the coherent pulsations. The best method to use is the cross spectral analysis (van der Klis et al. 1987), since the cross spectra make it possible to distinguish the pulse component from the interesting aperiodic component.

We first made light curves of some energy bands. One energy band contained the iron lines and the other did not contained (e.g. 3.3–4.7, 4.7–5.8, 5.8–7.2, 7.2–8.7, 8.7–10.9, and 10.9–13.1 keV at P20104 observation). We refer to the light curve which contain the iron lines as the "iron-band". We calculate the cross spectra between the X-ray light curve in the iron-band and the other energy bands, and studied the coherence and the phase lag between them. (the detail of this analysis can be seen in Kohmura et al. 2001, 2002). Figure 2 shows an example of the coherence and phase lag of 10.9–13.1 keV band from the iron-band. Here we pay attention to the phase lag between 3 Hz and 15 Hz, where the coherence is high enough and the effect of the coherent pulse shape is small. If there is a constant time delay which is independent of frequency, the phase lag must be a linear function with no offset. The data between 3 Hz and 15 Hz was fitted with a linear function. The best fit lines is plotted in figure 2. Figure 3 shows the result of our cross spectral analysis as a function of the energy. We apply the simple linear function to this data, and the result is $-(2.6\pm0.4)\times10^{-4}$ E (keV) + $(1.3\pm0.4)\times10^{-3}$ s. The deviation of the iron-band data at 6.5 keV from this best-fit model is (0.39±0.10) ms, where error is the one sigma level. Therefore, we detected the delayed iron-band intensity variation with almost the four sigma confidence level.

We also applied this cross spectral analysis to the other observation data of Cen X-3, and we summarized of these results in Table 1.

3. Discussion

Using P20104 data, we derived a 0.39±0.10 ms time delay of the iron-band relative to that of the general trend of the other energy bands. However, this value may not necessarily represent an actual delay of the reprocessed X-rays for two possible reasons. The first reason is that the fraction of iron line photons in the iron-band is only ∼9 %, and the second is that the value is the deviation of the iron-band from the general trend and may not be the delay from the original temporal variation. For the first reason, we consider the effect of the mixture of the delayed and the non-delayed components. For the second reason, we calculate the mean time difference between non-reprocessed X-rays in the iron-band and the X-rays above the iron K absorption edge, because the photons responsible for iron fluorescence are those above the K-absorption edge. As a result, we derived 6.5±1.6 ms for the time delay of the temporal variation of the iron line from the average temporal variation in the energy band above the iron absorption edge. This result leads to a determination of $(2.0\pm0.5)\times10^8$ cm for the distance between the original X-ray source and reprocessor, which emits the iron lines. The radius derived from above discussion is consistent with the Alfven radius derived from QPO analysis (Kohmura et al. 2001, 2002) within a factor of two.

The advance of the hard X-ray variation was also discovered from all data of Cen X-3. We think this advanced trend of the continuum X-ray is related to the X-ray emission mechanism on the neutron star as follows (Kohmura et al. 2001, 2002). The short term intensity variation can be interpreted as being due to the variation of the amount of material falling onto the polar cap of the neutron star. The intensity must become high when the large amount of matter falls on the polar cap. The kinetic energy of the falling matter is converted into thermal energy almost instantaneously, resulting in an extremely high temperature plasma. This plasma must cool via radiation and conduction, and consequently the hard X-ray advance is expected. Although the quantitative consideration is beyond the aim of this paper, this discovery of the hard advance may be related to the interaction between the accretion matter and the neutron star.

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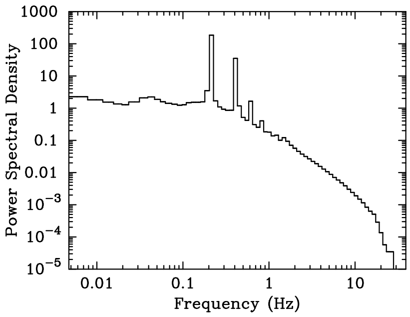

Figure 1:The power spectral density obtained for P20104 data in the energy range from 3.3 keV to 13.1 keV. The time resolution of the data is 15.625 ms. This was calculated by adding the 316 separate power spectral density derived from 256 s exposure. The Poisson statistics component has been subtracted.

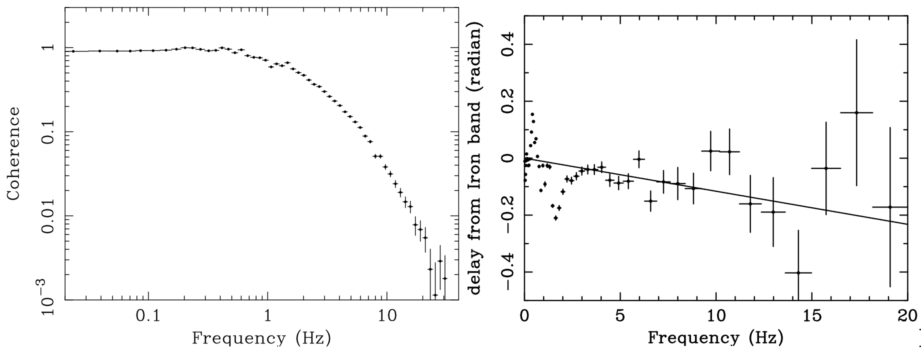

Figure 2: Left: The coherence, calculated between the iron-band and 10.9–13.3 keV band, is plotted as a function of the frequency. Right: The phase lags of time variations between iron-band and 10.9–13.3 keV band are plotted as a function of the frequency.

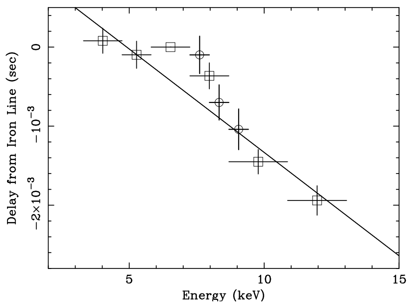

Figure 3: The time delay in the time variation from that of the iron-band as a function of the X-ray energy. The five squares are the data obtained from the original six energy bands and the line around 6.5 keV is marked for reference. The circles are the data derived by using more finely binned energy bands. Errors are one sigma levels. The straight line is the best fit model of the linear function. The positive direction of the vertical axis represents the delay from the variation of the iron-band.

Table 1. Summary of the Observations and Cross Spectral Analysis

Obs ID	Obs mid-time (MJD)	Delay time (ms)	$A \times 10^{-4}$[sec keV^{-1}]*
P10132	50301.7	-(0.98±0.45)	-(5.0±3.0)
P10134	50345.2	-(0.14±0.39)	-(1.0±1.0)
P20104	50508.9	-(0.39±0.10)	-(2.6±0.4)
P20105	50554.8	-(0.13±0.40)	-(2.7±2.5)
P20106	50720.7	-(1.24±1.08)	-(0.5±4.3)
P30083	50934.0	-(0.03±4.95)	-(6.3±10.3)
P30084	51043.0	-(0.52±0.20)	-(3.0±0.5)
P40072	51579.4	+(0.41±0.70)	-(2.9±1.6)

* The time difference is assumed to be a liner function with $A \times (E - 6.4[\mathrm{keV}])+$ constant.

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