Change of Cyclotron Resonance Energies of Binary X-ray Pulsar X0331+53

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Abstract

We report on the further analysis results of the cyclotron-resonance energy changes of X0331+53 (V0332+53) observed by RXTE in 2004-2005 outburst. This source is known to have the prominent fundamental cyclotron resonance, and that resonance energy increased from $\sim$ 22 to $\sim$ 27 keV as the source luminosity changed from 3.5×10^{38} ergs/s to 1.0×10^{38} ergs/s. Although the behavior of the fundamental resonances have been examined by several authors so far, the detailed analysis of the second cyclotron resonances were not performed due to the low statistics in higher energies. In order to reveal the behavior of the second cyclotron resonance, we have analyzed the whole 2004–2005 outburst data of X0331+53 with "flux-sorted analysis" method (Nakajima et al. 2006). As a result of our analysis, we clearly confirmed that the second cyclotron energy changed from $\sim$ 49 to $\sim$ 54 keV, implying a weaker fractional change as a function of the luminosity. The observed resonance energy ratio between the second and the fundamental cyclotron line was $\sim$ 2.2 when the source was most luminous, whereas the ratio decreased to the nominal value of 2.0 at the least luminous state. The change of the resonance energy ratio may result from the different heights of the cyclotron scattering in the accretion column.

Key words: pulsars: individual(X0331+53) — X-rays: binaries

1. Introduction

Cyclotron Resonant Scattering Feature (CRSF) provides the magnetic field strength on the pulsar surface. The relation between the field strength (B) and the fundamental CRSF energy E_{a1} is described as $E_{a1} = 11.6 \times \frac{B}{10^{12}\mathrm{G}}(1+z_g)^{-1}$keV. Here, z_g is the gravitational redshift. X0331+53 is one of the accretion-powered pulsar. This source is famous for having the multiple CRSFs in the X-ray spectrum (Makishima et al. 1990; Mihara et al. 1998; Kreykenbohm et al. 2005; Pottschmidt et al. 2005). In addition, the luminosity dependent changes of E_{a1} were reported by the *Ginga*, *INTEGRAL* and *RXTE* observations (Mihara et al. 1998; Mowlavi et al. 2006; Nakajima 2006; Tsygankov et al. 2006). This luminosity dependent E_{a1} change is explained by the accretion column model (Burnard et al. 1991, Mihara et al. 1998, Nakajima et al. 2006), and the luminosity dependent behavior of the fundametanl resonance have been studied so far. However, the change of the second harmonic CRSFs are poorly understood due to the low statistics at higher energies. In this paper, we describe the details of the second harmonic CRSFs analyzing the 2004–2005 outburst data continuously observed by *RXTE*.

2. Date Analysis and Results

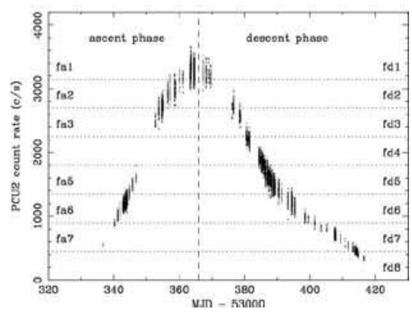

Fig. 1. The lightcurve of the 2004–2005 outburst of X0331+53.

During this outburst, *RXTE* performed total $\sim$ 100 pointing observations. In this paper, we utilized 86 pointing observations. The PCU2 which were operating throughout the observations and the HEXTE cluster-B data are utilized in this paper.

We divide the data into 8 intensity intervals, in references to Fig 1, and co-add those data which fall in the same flux range. The spectra of the accretion powered pulsars are well described with the power-law times exponential cutoff model. Here we employed NPEX model (Mihara 1995; Makishima et al. 1999). The data to the NPEX model ratios are shown in the middle panels of Figure 2.

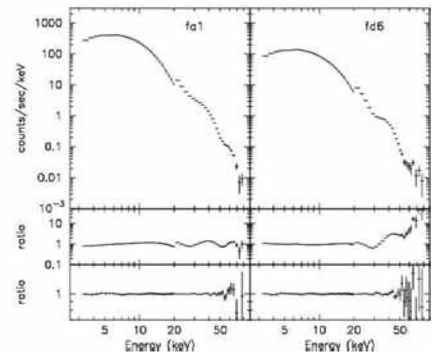

Fig. 2. The representative spectra of X0331+53. The top panel shows the PCU2 and HEXTE cluster B spectra, the middle panel shows the NPEX model ratios, and the bottom panel shows the best-fit NPEX×CYAB2×GABS model ratios.

Two CRSFs are clearly seen. To reproduce the spectra, we introduce one of the CRSF models, called CYAB model (Mihara 1995). As reported by Pottschmidt et al. (2005), the fundamental CRSF can not be reproduced by single cyclotron model. Thus, we utilized GASB model (Kreykenbohm et al. 2005) for the fundamental CRSF in addition to the CYAB model. We confirmed that the data are well reproduced by the NPEX×CYAB2×GABS model as shown in the bottom panel of Figure 2.

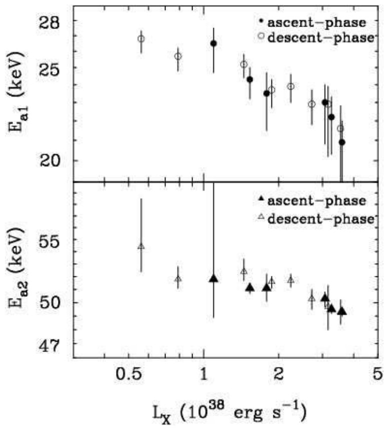

Fig. 3. The CRSF energies plotted against the 3–80 keV luminosity.

Figure 3 shows the CRSF energies plotted against the 3–80 keV luminosity. From this figure, we can clearly confirm that both of the fundamental (E_{a1}) and the second resonance (E_{a2}) energy show the luminosity dependent change. The change of the second resonance is weaker than that of the fundamental CRSF. Figure 4 shows the E_{a2}/E_{a1} ratio plotted against the 3–80 keV luminosity. That ratio becomes largest value when the source was most luminous state. The ratio decreased to the nominal value of 2.0 at the dim state.

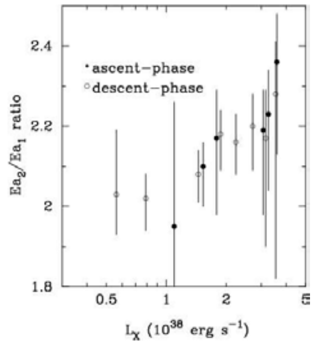

Fig. 4. The E_{a2}/E_{a1} resonance energy ratios plotted against the 3–80 keV luminosity.

3. Discussion

We confirmed that the observed resonance energy ratio between the fundamental and the second harmonic was ~ 2.2 when the source was most luminous, whereas the resonance energy ratio decreased down to the nominal value 2.0 at the least luminous state. Comparing with the fundamental and the second CRSF cross-sections, the cross-section of E_{a1} is ~ 10 times larger than that of the second CRSF (Araya et al. 1999). When we are looking down the accretion column, the second CRSF could be produced in the lower part of the accretion column than that of the fundamental CRSF. This might result in the less change of the second harmonics than the fundamental. And when the ratio reaches 2.0, the two CRSF might be occurring at substantially the same place such as the bottom of the accretion column. This behavior largely depends on the density profile of the accretion column and its change against the accretion rate (luminosity). In other wards, our observational results can give new information on the structure of the accretion column.

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