Cyclotron Lines in Binary X-ray Pulsars

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1. Introduction

Cyclotron Resonant Scattering Feature (CRSF) is a powerful tool to accurately determine the pulsar magnetic fields. The relation between the field strength and the fundamental cyclotron resonance energy Ea_1 is described as,

$$Ea_1 = 11.6 \times B_{12}\ (\mathrm{keV}).$$

Here, B_{12} is the magnetic field strength in unit of 10^{12} Gauss. Using this spectral feature, the surface magnetic fields of ~15 pulsars have been accurately measured by several X-ray observatories (e.g. RXTE, Suzaku and Integral). According to recent studies, several pulsars show luminosity dependence changes in the cyclotron resonance energy. In the case of two transient pulsars, 4U0115+63[1,2] and X0331+53(V0332+53)[3,4], the cyclotron resonance energy has been found to correlate negatively with the source luminosity. On the other hand, the positive correlation is reported from the results of Her X-1[5]. In this poster, we report on the change of the cyclotron parameters of CRSF sources observed with RXTE, and discuss the possible interpretations of the luminosity dependence behavior.

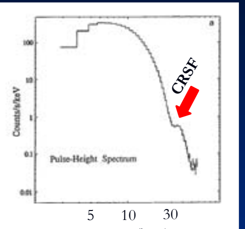

Fig. 1 Ginga/LAC spectrum of X0331+53.
(Makishima et al. 1990)

2. Sources and representative spectra

We have selected 12 cyclotron sources (4U0115+63, 4U1907+09, 4U158-52, Vela X-1, Cen X-3, X0331+53, MXB0656-07, Cep X-4, Her X-1, 4U1626-67, GX301-2, and A0535+26). So far, a number of the observations were performed by RXTE. Here, we utilized all pointing observations to investigate the change of the luminosity dependent CRSF parameters. As widely known, the continuum spectra of the accretion powered pulsars can be described by a power-law modified by exponential cutoff. Here, we employed a much improved one so-called NPEX[1,6] model. In addition, to evaluate the CRSF parameters, we employ the cyclotron absorption (CYAB) factor[1,6] which is described as,

$$\mathrm{CYAB}(E) = \exp\left(\frac{-D_i\,(W_i\,E/\,Ea_i)^2}{(E-Ea_i)^2 + W_i^2}\right) \quad (i = 1,2,3,,,),$$

where the Ea_i is the resonance energy, W_i is the resonance width, D_i is the resonance depth, and i is the cyclotron harmonic number. Using this model set, we fit all of the source spectra, and the representative ones are shown in Figure 1. Although some of the data left some residuals, most of the data can be reproduced with our model set at the various luminosity state. As results, we obtained the CRSF parameters at the various luminosity state.

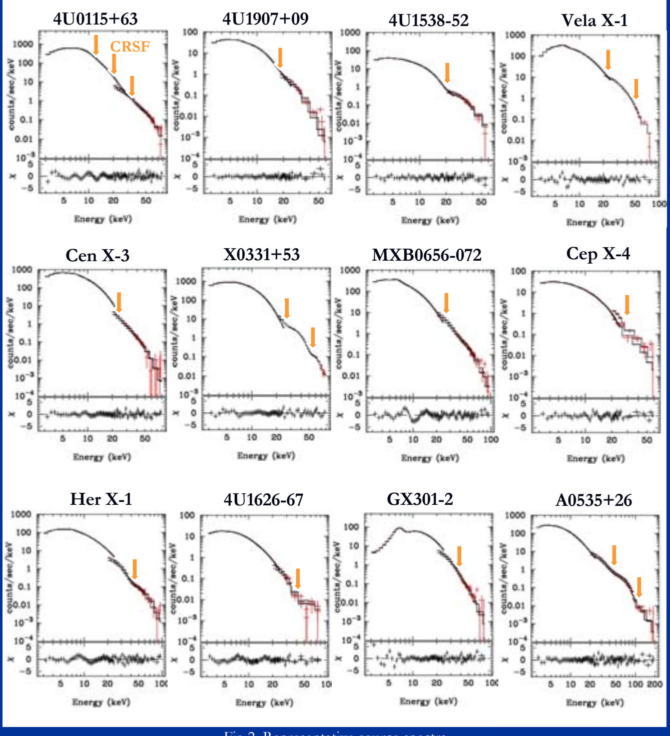

Fig 2. Representative source spectra

3. Cyclotron resonance energy change

Our spectral analysis provides the opportunity to compare the behavior of the CRSF energy changes of 12 sources. Figure 3 shows the fundamental cyclotron resonance energies of the 12 sources against the 3-50 keV luminosities. From this figure, we confirmed that 4U0115+63 and X0331+53 exhibited the negative correlation as mentioned in several papers. In addition, some sources show slight change. This negative luminosity-dependent change can be explained by the change of the accretion column height. Assuming that the pulsar has dipole magnetic filed, the observed Ea_1 depends on the distance from the pulsar. Using the height of the CRSF forming region h_r (see Fig. 4), Ea_1 can be described as, $Ea_1 \propto (R_{NS}+h_r)^{-3}$, where R_{NS} is the neutron star radius. Hence, we can estimate the height of the CRSF forming region with the observed Ea_1, as $h_r/R_{NS} \propto (Ea_1/E_0)^{-1/3}$ -1, where E_0 is the resonance energy to be observed on the neutron star surface. Fig 5 shows the estimated h_r/R_{NS} values of the two sources. This positive relation is consistent with the theoretical work[7], but the different luminosity dependence is found between the two sources. This difference might be caused by the shape of the accretion column and the angle between the rotation axis and the magnetic axis.

Comparing with the other sources, we confirmed that Her X-1 is the only source which exhibited the positive correlation. According to the previous study[5], this positive relation is to be observed when the source is in the sub-Eddington regime. The reason why the other sources do not exhibited the positive relation at the various luminosities is not understood.

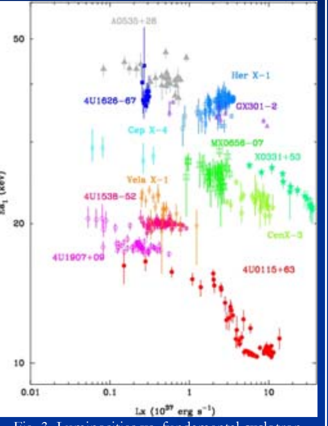

Fig. 3 Luminosities vs. fundamental cyclotron resonance energies.

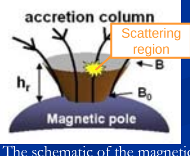

Fig. 4 The schematic of the magnetic pole of the pulsar.

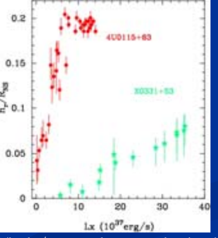

Fig. 5 The h_r/R_{NS} vs. the source luminosity.

4. Luminosity vs. cyclotron resonance depth

In addition to the Lx-Ea_1 relation, we investigated how the fundamental cyclotron resonance depth D_1 change together with the source luminosity. Figure 6 shows the relation between the source luminosities and the cyclotron depths. Although the plotted data have relatively large errors, most of the sources exhibited the same trend that the depths increase toward the low-luminosity state. This phenomenon might be explained by so-called "two photon effects"[8]. The second resonance will act as pure absorption, because the electron excitation and deexcitation occurs as shown in Fig. 7. In this case, the emitted photons of energies ~E_1 will fill up the fundamental resonance. Then this effect might occur when the source become bright.

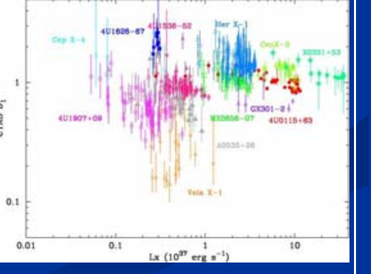

Fig. 6 Luminosities vs. Fundamental cyclotron line depths.

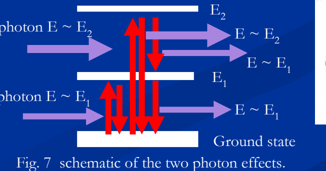

Fig. 7 schematic of the two photon effects.

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