MEASURING MAGNETIC FIELD OF NEUTRON STAR 4U 0115+63 WITH CYCLOTRON FEATURES

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We analyze the 3-80 keV spectrum of X-ray pulsar 4U 0115+63 taken by Rossi X-ray Timing Explorer(RXTE) on April 22nd, 2008. Two absorption features at ~ 13.5 keV and ~ 20.5 keV are detected by using cyclotron scattering feature profiles to fit the spectrum, ignoring the inadequate photons of the analyzed data. The fundamental feature is just right between ~ 11 and ~ 16 keV. It seems implausible to interpret these absorption lines as cyclotron features because of their inharmonic behavior, even when relativistic effect has been taken into account. But it is possible that the main region where first harmonic line forms is slightly different from the fundamental one.

Keywords: Pulsar; magnetic field of neutron star; X-ray observation.

1. Introduction

Magnetic field strength is one of the most important physical parameters of neutron star(NS). Since its first detection in 1976,¹ cyclotron lines have been considered to be the most accurate and the only direct way to measure magnetic field near the surface of NSs. Soon after the first detection, cyclotron lines were treated as harmonic lines caused by electron's transition between Landau energy levels, corresponding to a non-relativistic relation $E_{\text{cyc},n} \sim 11.6nB_{12}(1+z)^{-1}$, where n is the energy level, B_{12} is magnetic field in unit of 10^{12}G and z the gravitational redshift. The subsequent observation² of X-Ray Transient 4U 0115+63 showed the line feature in the spectrum appeared as absorption in 11.5 keV and 23 keV. It is suggested that the cyclotron re-emitting processes is equal to scattering and one might expect Cyclotron Resonant Scattering Features(CRSF) as absorption in the spectrum. This is consistent with the observations during the past decades which can be fitted well using absorption features depending on a proper continuum model, though only less than thirty sources, including one isolated,³ have shown credible CRSFs so far. Some of these sources, their spin period, orbital period, fundamental CRSF $E_{\text{cyc},1}$ and references related are shown in Table 1.

Though some progresses have been made,¹⁴ the theoretical model for X-Ray binary pulsar's emission is far from complete. The continuous spectra of accreting sources are usually fitted with the power-law component representing the mixture

Table 1. X-Ray Pulsars with CRSFs.

Object	P_{spin} (s)	P_{orbit} (day)	$E_{\text{cyc},1}$ (keV)	$B(1+z)^{-1}$ (10^{12}G)	Reference
4U 0115+63	3.6	24.3	11.5	1	Ref. 2
4U 0352+309	837	250	28.6	2.5	Ref. 4
4U 1538-52	529	3.73	20.7	1.8	Ref. 4
4U 1626-67	7.67	0.0298	39.3	3.4	Ref. 4
4U 1907+09	439	8.37	18.3	1.6	Ref. 4
Vela X-1	283	8.96	23.3	2	Ref. 5
Cen X-3	4.8	2.09	30.4	2.6	Ref. 4
V0332+53	4.37	34.25	25.2	2.2	Ref. 6
Cep X-4	66.3	20.8	30.7	2.6	Ref. 7
Her X-1	1.24	1.7	34.7	3	Ref. 8
A0535+26	103	111	48.5	4.2	Ref. 9
GX 301-2	690	41.5	42.2	3.6	Ref. 4
J1946+274	15.8	169.2	34.9	3	Ref. 4
MXB 0656-072	160.4	—	32.8	2.8	Ref. 10
J1409-619	500	—	21	1.8	Ref. 11
GX 304-1	275.5	132.5	53.7	4.6	Ref. 12
J16493-4348	1069	6.78	33	2.8	Ref. 13

of blackbody, bremsstrahlung radiation, and an exponential cutoff at high energy possibly representing thermal comptonization in accretion column, while for the line features, both Gaussian and Lorentz profiles are employed. See Ref. 15 for details about X-Ray binary pulsar spectrum fitting.

Among the sources with CRSFs, 4U 0115+63 is one of the most studied X-Ray pulsar, and CRSFs were observed up to the fifth.¹⁶ And the energy of fundamental feature varies from ~ 11 keV at its maximum luminosity throughout the outburst to ~ 16 keV at the end of outburst.¹⁷ In this short work, we analyze the RXTE observation of 4U 0115+63 on April 22nd of 2008 and try to find CRSFs on its spectrum.

2. Data Analysis and Results

We concentrated on the observation on April 22nd, 2008 (*Observation ID*: 93032-16-02-01) because of its long observing time, giving totally ~ 38 ks of exposure time. Standard 2 data of Number 2 Proportional Counter Unit(PCU) in Proportional Counter Array(PCA) on board RXTE is considered since other PCUs were not always working during the observation. We only extracted data from the top layer of PCU for its highest signal to noise ratio. The data reduction employed the HEASoft version 6.11.1 with standard procedure, and the spectral fitting were performed with XSPEC version 12.7.0.

To describe the continuous spectrum, we use the combination of a powerlaw and high-energy cutoff.² Adding only one CRSF with Lorentz profile¹⁵

$$\exp \left[-D \frac{(WE/E_{\text{cyc}})^2}{(E - E_{\text{cyc}})^2 + W^2} \right] \quad (1)$$

Fig. 1. *Top panel:* PCA spectrum (cross) and best-fit model (histogram). *Bottom panel:* Residuals in terms of sigmas with error bars of size one.

Table 2.

Model Parameter	Value
Photon index	0.363 ± 0.013
$E_{\text{cutoff}}(\text{keV})$	13.81 ± 0.30
$E_{\text{fold}}(\text{keV})$	5.59 ± 0.53
D_1	0.94 ± 0.16
$E_{\text{cyc},1}(\text{keV})$	13.63 ± 0.33
$W_1(\text{keV})$	4.80 ± 0.38
D_2	0.59 ± 0.18
$E_{\text{cyc},2}(\text{keV})$	20.59 ± 1.06
$W_2(\text{keV})$	5.29 ± 2.27

results in $\Delta\chi^2 \approx 1.39$, showing a line feature at ~ 14 keV. To get a better result, we added another CRSF at 28 keV as first harmonic line which turned into a worse fit ($\Delta\chi^2 \approx 1.42$). Then, with all D , E_{cyc} and W of two CRSFs left free, the fit is significantly improved to $\Delta\chi^2 \approx 1.08$ (Fig. 1), which shows the first absorption line appears at 13.6 keV and the second at 20.6 keV (see Table 1 for the best-fit parameters).

These inharmonic features may not be interpreted as cyclotron lines because they scale too far from 1 : 2 even when the relativistic effect has been taken into account. The analysis of the data on April 9th, 11th, 13th, 15th and 18th showed that the luminosity of the source has been reducing from April 9th to 22nd. And the insufficiency of the detected photons can affect the analysis. But it is possible, if it is not for the inaccuracy of data, that the inharmonic behavior may be caused when the main region where the first harmonic line forms is slightly different from the fundamental one. Considering the conservation of magnetic moment $BR^3 \approx \text{const}$, these two regions are ~ 1 km apart. This still needs the support from more study about the radiation mechanism and geometry in accretion column.

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