Detection of fundamental and first harmonic cyclotron line in X-ray pulsar Cep X-4

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ABSTRACT

We report the broad-band spectral properties of the X-ray pulsar Cep X-4 by using a Suzaku observation in 2014 July. The 0.8-70 keV spectrum was found to be well described by three continuum models - Negative and Positive power-law with Exponential cutoff (NPEX), high energy cutoff power-law and CompTT models. Additional components such as a cyclotron line at ~28 keV and two Gaussian components for iron lines at 6.4 and 6.9 keV were required in the spectral fitting. Apart from these, an additional absorption feature at ~45 keV was clearly detected in residuals obtained from the spectral fitting. This additional feature at ~45 keV was clearly seen in phase-resolved spectra of the pulsar. We identified this feature as the first harmonic of the fundamental cyclotron line at ~28 keV. The ratio between the first harmonic and fundamental line energies (1.7) was found to be in disagreement with the conventional factor of 2, indicating that the heights of line forming regions are different or viewed at larger angles. The phase-resolved spectroscopy of the fundamental and first harmonic cyclotron lines shows significant pulse-phase variation of the line parameters. This can be interpreted as the effect of viewing angle or the role of complicated magnetic field of the pulsar.

Key words: pulsars: individual (Cep X-4) – stars: neutron – X-rays: stars

1 INTRODUCTION

Cyclotron resonance scattering features (CRSFs) are generally seen in the hard X-ray spectrum (10-100 keV) of the accretion powered X-ray pulsars with surface magnetic field of ~10^{12} G. These are absorption like features which appear due to the resonant scattering of photons with electrons in quantized Landau levels (Mészáros 1992). The energy difference between these levels depends on the strength of magnetic field and expressed through the relation $E_{\text{cyc}} = 11.6B_{12} \times (1+z)^{-1}$ (keV) (without relativistic correction); where $B_{12}$ is the magnetic field in the unit of 10^{12} G and $z$ is the gravitational red-shift. Detection of fundamental CRSF in the spectra of accretion powered X-ray pulsars provides the direct estimation of local magnetic field of the neutron stars in line forming region. At the same time, the study of the harmonics (multiples of fundamental cyclotron line) gives crucial information about the optical depth of the line-forming region (Araya-Góchez & Harding 2000; Schönherr et al. 2007; Nishimura 2013). As of now, CRSF has been seen in about 20 accretion powered X-ray pulsars. However, the harmonics of the fundamental cyclotron line are detected only in a few cases (Pottschmidt et al. 2012 and references therein).

The transient X-ray pulsar Cep X-4 (GS 2138+56) was discovered at a position near the galactic plane with OSO-7 in 1972 (Ulmer et al. 1973). X-ray pulsations were detected in the source at ~66 s during its 1988 March outburst with Ginga (Makino et al. 1988; Koyama et al. 1991). A cyclotron absorption line feature at ~30 keV was discovered with the 2002 June RXTE observations of Cep X-4 (McBride et al. 2007). However, there was no significant changes in cyclotron line energy with source luminosity observed during these observations.

First observation was carried out near the peak of the outburst. The transient X-ray pulsar Cep X-4 (GS 2138+56) was discovered at a position near the galactic plane with OSO-7 in 1972 (Ulmer et al. 1973). X-ray pulsations were detected in the source at ~66 s during its 1988 March outburst with Ginga (Makino et al. 1988; Koyama et al. 1991). A cyclotron absorption line feature at ~30 keV was discovered with the 2002 June RXTE observations of Cep X-4 (McBride et al. 2007). However, there was no significant changes in cyclotron line energy with source luminosity observed during these observations. The pulsar was observed with NuSTAR during the 2014 June-July outburst. First observation was carried out near the peak of the outburst.

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burst whereas the second was at the declining phase of the outburst (Fürst et al. 2015). The 1-50 keV combined spectra from Swift/XRT and NuSTAR were described by Fermi-Dirac cutoff power-law (FDCUT) model along with an absorption component at $\sim 30$ keV. Addition of a simple absorption component or a pseudo-Lorentzian profile was failed to explain the cyclotron absorption feature properly because of the asymmetric nature of the line profile. Along with this asymmetry profile, an absorption like feature at $\sim 19$ keV was also detected in the spectrum. A marginal positive dependence of cyclotron line energy with the pulsar luminosity was seen during the NuSTAR observations.

In the present work, we used Suzaku observation of the pulsar during 2014 outburst to study its spectral properties. The broad-band coverage and low background capability (up to 70 keV) of detectors onboard Suzaku provided best opportunity to investigate cyclotron absorption line parameters in binary X-ray pulsars. Using Suzaku observation of Cep X-4, we detected a cyclotron line at $\sim 28$ keV along with another absorption like feature at $\sim 45$ keV. We interpret the absorption lines at $\sim 28$ keV and at $\sim 45$ keV as the fundamental and first harmonic cyclotron absorption lines, respectively. Details on the observations, analysis procedures, results and conclusions are presented in following sections of the paper.

2 OBSERVATION AND ANALYSIS

A Target of Opportunity (ToO) observation of Cep X-4 was carried out with Suzaku (Mitsuda et al. 2007) in July 01-02 during its 2014 June-July outburst. The pulsar was observed for exposures of $\sim 60$ ks with XIS-3 and $\sim 81$ ks with HXD during the decay phase of the outburst. Among three active XISs (XIS-0, 1 & 3), data from the XIS-3 was used in our analysis as XIS-0 and XIS-1 were exposed for $\sim 100$ s short durations. The XIS-3 was operated in “normal” clock mode with “1/4” window option yielding 2 s time resolution. The observation was carried out in “XIS nominal” position. We used publicly available data (Obs. ID: 909001010) in the present study. Calibration database (CALDB) files released on 2015 January 05 (XIS) and 2011 September 13 (HXD) were applied during reprocessing of data in Heasoft (version 6.16) analysis package.

The ‘aepipeline’ task of FTOOLS was used to reprocess the unfiltered XIS and HXD events. Clean events generated after the reprocesing were used in our study. Barycentric correction was applied on these XIS and PIN clean events by using ‘aebarycen’ package. XIS data were checked for the attitude and pile-up effects by applying S-lang scripts (aetcorr.s1 and pile_estimate.s1), respectively. We found a pile-up of $\sim 8\%$ at the centre of XIS-3 that was reduced to $\lesssim 4\%$ by choosing the events only from an annulus region with inner and outer radii of 10$''$ and 180$''$, respectively. The source light-curves and spectra from XIS-3 were extracted by using XSELECT package of FTOOLS. Background light-curves and spectra for XIS-3 were created from a circular region away from the source. Response matrix and effective area files for XIS-3 were generated from the command in XSELECT. Source light curves and spectra for PIN were extracted from cleaned event data by using XSELECT. However, HXD/PIN background light curves and spectra were accumulated in a similar manner from simulated non-

![Figure 1. Pulse profiles of Cep X-4 obtained from XIS-3 and HXD/PIN light curves during the Suzaku observation in 2014 July. The presence of absorption dip in soft X-ray pulse profile in 0.4-0.5 phase range can be seen. The error bars represent 1σ uncertainties. Two pulses in each panel are shown for clarity.](image)

3 RESULTS

Source and background light curves with 2 s and 1 s time resolution were extracted from the barycentric corrected XIS-3 and PIN event data, respectively. The $\chi^2$-maximization technique was used to estimate the pulse period of the pulsar. The pulsation was detected at a period of 66.334±0.004 s from background subtracted light curves of XIS-3 and PIN. Above pulsation period was used to generate pulse profiles in soft (0.5-10 keV) and hard X-rays (10-70 keV) and are shown in Fig. 1. Strong energy dependence of pulse profiles with energy can be seen in the soft and hard X-rays pulse profiles. A dip like feature in soft X-rays (top panel) in 0.4-0.5 phase range disappeared from the hard X-ray pulse profile. Therefore, it is interesting to investigate spectral properties of the pulsar at different pulse phases.

3.1 Spectral Analysis

3.1.1 Pulse-phase-averaged spectroscopy

To study the broad-band spectral characteristics of the pulsar, phase-averaged spectroscopy was carried out by using the source and background spectra accumulated from the XIS-3 and PIN event data. The procedure for spectral extraction was described earlier. The 0.8-70 keV spectra, obtained from XIS-3 and PIN data were simultaneously fitted by using XSPEC (ver. 12.8.2) package. Appropriate background spectra, response matrices and effective area files for corresponding detectors were used in the spectral fitting. Spectral data in 1.7-1.9 keV and 2.2-2.4 keV ranges were ignored in the fitting due to presence of known artificial emission features in the spectrum. XIS-3 spectrum was binned by a factor of 6, whereas PIN spectrum was binned by a factor of 2 up to 30 keV, a factor of 4 from 30 to 50 keV and a factor of 6 from 50 to 70 keV. All the spectral parameters were tied during the fitting, except the normalization constant of detectors which were kept free.
Continuum models used to describe spectra of accretion powered X-ray pulsars such as high energy cutoff power-law (White et al. 1983), cutoff power-law, NPEX (Makishima et al. 1999), FDCUT and CompTT (Titarchuk 1994) were used to fit the 0.8-70 keV spectrum of Cep X-4. Investigating the residuals, we added two Gaussian functions at 6.4 and 6.9 keV for iron emission lines in the source spectrum. As in case of Be/X-ray binary pulsars, a partial covering absorption component (Paul & Naik 2011 and references therein) was used in the spectral model along with the interstellar absorption component. A strong absorption like feature at ∼28 keV was clearly seen in the spectrum. Addition of a CRSF component at above energy was added to all continuum models. Simultaneous spectral fitting of XIS-3 and HXD/PIN data in 0.8-70 keV range showed that partial covering NPEX continuum model, partial covering high energy cutoff power-law model and partial covering CompTT model describe the spectrum well with acceptable values of reduced $\chi^2$ (<1.5).

Apart from ∼28 keV cyclotron line, we found an additional absorption like feature at ∼45 keV in the residues obtained from all three continuum models. This feature was clearly seen at same energy range and was model independent (third panel in Fig. 2). The inset in Fig. 2 shows the HXD/PIN spectrum of the Suzaku observation of the pulsar with background, without background and simulated PIN background spectrum. The absorption-like feature at ∼45 keV can be clearly seen in the background subtracted spectrum. The inclusion of additional CRSF component at this energy in the model fitted the XIS-3 and HXD/PIN spectra well with significant improvement in the values of $\chi^2$. Absorption feature at ∼45 keV can be considered as the first harmonic of the ∼28 keV cyclotron absorption line. Ideally, the ratio between the energy of first cyclotron harmonic and fundamental line is expected to be a value closer to 2. However, in present case, the ratio was estimated to be ∼1.7±0.1, which can be acceptable in current understanding of the cyclotron physics. Best-fit parameters obtained from simultaneous spectral fitting are given in Table 1. The energy spectra of the pulsar along with all three best-fitted model components resemble similar absorption features in the spectral residues. Energy spectra obtained from simultaneous fitting of the XIS-3 and HXD/PIN data are shown in Fig. 2. The second and fourth panels in figure show the residuals to the best-fit model with one and two cyclotron lines in the continuum model, respectively. As in case of NuSTAR observations, a weak absorption like feature can be seen at ∼19 keV in the spectral residue (third and fourth panels of Fig. 2). Addition of an absorption component at ∼19 keV, however, did not show any significant improvement in the spectral fitting. Negligible strength and width of the ∼19 keV line against other two absorption lines at ∼28 and ∼45 keV, therefore, makes it difficult to accept the earlier feature as the fundamental cyclotron absorption line. Therefore, we did not include any spectral component for this feature in our fitting.

To verify the ∼45 keV feature as additional absorption feature detected in Suzaku spectra, we fitted XIS-3 and HXD/PIN spectra with the spectral model (FDCUT model

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**Figure 2.** Energy spectrum of Cep X-4 in 0.8-70 keV range obtained from XIS-3 and HXD/PIN data, along with the best-fit model comprising a partial covering NPEX model, two Gaussian functions for iron emission lines and two cyclotron absorption components. The second and fourth panels show the contributions of the residuals to $\chi^2$ for each energy bin for the partial covering NPEX continuum model with one and two cyclotron absorption components, respectively. The third panel shows the residuals for FDCUT model with one GABS component. The inset shows the HXD/PIN spectrum of the pulsar with background, without background and the simulated HXD/PIN background spectrum.

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**Table 1.** Best-fitting parameters (with 90% errors) obtained from the spectral fitting of Suzaku observation of Cep X-4 in 2014 July. Model-1 & Model-2 consist of the partial covering NPEX and CompTT model with two Gaussian and two cyclotron lines, respectively. Model-3 is combination of FDCUT model with blackbody, two Gaussian and one gabs components.

| Parameter | Model-1 | Model-2 | Model-3 |
|-----------|---------|---------|---------|
| $N_\text{H}_1$ | 0.78±0.03 | 0.77±0.03 | 0.71±0.02 |
| $N_\text{H}_2$ | 3.7±0.6 | 2.6±0.3 | – |
| Cov. fraction | 0.28±0.06 | 0.41±0.08 | – |
| Photon index | 1.04±0.09 | – | 1.01±0.05 |
| BB temp. (keV) | – | – | 1.08±0.06 |
| BB norm. ($10^{-4}$) | – | – | 4.8±0.6 |
| $E_{\text{cut}}$ (keV) | 9.5±2.1 | – | 25.1±4.0 |
| $E_{\text{fold}}$ (keV) | – | – | 6.8±1.1 |
| CompTT $\alpha$ (keV) | – | 0.21±0.21 | – |
| CompTT $\beta$ (keV) | – | 11.6±2.3 | – |
| CompTT $\tau$ | – | 4.4±0.4 | – |
| $E_{\text{cyc}}$ (keV) | 6.41±0.03 | 6.41±0.03 | 6.42±0.03 |
| Eq. width (eV) | 32.8±4 | 27.7±4 | 34±8 |
| Energy (keV) | 6.97±0.16 | 6.98±0.22 | 6.95±0.14 |
| Eq. width (eV) | 13±6 | 9±6 | 14±7 |
| $\chi^2$ (dofs) | 254 (244) | 261 (244) | 303 (247) |

$a$: Equivalent hydrogen column density and $b$: Additional hydrogen column density (in $10^{22}$ atoms cm$^{-2}$); $c$: Absorption uncorrected flux (in $10^{-10}$ ergs cm$^{-2}$ s$^{-1}$); $*$: cyclotron parameters are given for gabs component.
along with black-body and Gaussian absorption (gabs) components as used by Fürst et al. (2015) to fit spectra obtained from Swift and NuSTAR observations of the source. Though the data shown in Fig. 2 of Fürst et al. (2015) were up to 50 keV, we used Suzaku data in 0.8-70 keV range to compare both the results. The spectral parameters obtained from our fitting were found to be comparable (within errors) with the parameters obtained from the NuSTAR observations and given in Table 1. While fitting Suzaku data with the model used by Fürst et al. (2015), an absorption like feature at \( \sim 45 \) keV was also seen (third panel of Fig. 2). A careful look at the trend of distribution of points at \( \sim 45-50 \) keV in the residuals obtained from the spectral fitting of Obs.1 data (second and third panels of Fig. 2 of Fürst et al. (2015)) indicates a hint of presence of an absorption-like feature.

Statistical significance of \( \sim 45 \) keV absorption feature was tested by using XSPEC script simftest as applied in case of IGR J17544-2619 (Bhalerao et al. 2015). Including systematic uncertainty of 0.3% (15-40 keV) and 1.9% (40-70 keV) in PIN background model, we simulated 1000 fake spectra for partial covering NPEX model and estimated the differences in \( \chi^2 (\Delta \chi^2) \) without and with \( \sim 45 \) keV cyclotron absorption line. The maximum value of \( \Delta \chi^2 \) from 1000 simulations was found to be 17.8 which is less than observed \( \Delta \chi^2 = 27.2 \) for three degree of freedom in real data. Corresponding to this, we confirmed the significant detection of \( \sim 45 \) keV absorption feature at \( > 4 \sigma \) level.

### 3.1.2 Pulse-phase-resolved spectroscopy

We performed phase-resolved spectroscopy to understand the change in cyclotron absorption line parameters with the pulse phase of the pulsar. Another motivation in doing phase-resolved spectroscopy was to study the presence of \( \sim 45 \) keV absorption line as well as its dependence on pulse-phases of the pulsar. Detection of absorption feature at \( \sim 45 \) keV at each pulse-phase bins can confirm the detection of first cyclotron harmonic in Cep X-4. For this, the phase-resolved spectroscopy was carried out by accumulating source spectra in 10 pulse-phase bins. XIS-3 and PIN phase-resolved spectra were extracted by applying phase filter in XSELECT. Using the same background, response and effective area files as used in phase-averaged spectroscopy, the phase-resolved spectroscopy was carried out in 0.8-70 keV range. Partial covering NPEX model with a cyclotron component at \( \sim 28 \) keV was used to describe the phase-resolved spectrum. While fitting, the normalization constants, equivalent hydrogen column density \( (N_{H1}) \), iron line parameters and cyclotron width were fixed to the corresponding phase-averaged values as given in Table 1.

Spectral residues obtained from fitting all phase-resolved spectra with above model are shown in Fig. 4. Presence of an additional significant absorption feature in \( \sim 40-50 \) keV range can be clearly seen in each phase intervals. Detection of the \( \sim 45 \) keV absorption line in phase-averaged as well as phase-resolved spectra ensures that this feature is not spurious and model dependent. This feature can be interpreted as the first cyclotron harmonic of the \( \sim 28 \) keV fundamental line. Inclusion of a CRSF at this energy improved the spectral fitting significantly as in case of phase-averaged spectroscopy. During the fitting, widths of both cyclotron lines were frozen at phase-averaged value to constrain the absorption features. Variation of best fitted cyclotron line parameters with pulse phase are shown in Fig. 4 along with hard X-ray source flux.

Cyclotron parameters such as depth and energy of both the lines were found significantly variable with pulse-phase with maximum values in 0.3-0.6 phase range. However, the peak values of these parameters were slightly phase shifted (0.1 phase) with the peaks of 10-70 keV pulse profile and source flux. Depth of fundamental line was variable in the range of 1.8 to 2.7 (\( \sim 20\% \) of the phase-averaged value). Depth of first cyclotron harmonic was found to be marginally variable with the pulse phase of the pulsar. The variation of the energy of the first harmonic was found to be
double (~8 keV) of that of the fundamental line (~4 keV). However, while computing the ratio between the energy of the first harmonic and the fundamental cyclotron line, it was found to be in ~1.6-1.8 range. Source flux in 10-70 keV range was found to follow similar pattern as the pulse profile in same energy band.

4 DISCUSSION AND CONCLUSIONS

We report the detection of first harmonic of the cyclotron absorption line in Cep X-4. Though the pulsar was observed with *NuSTAR* during same outburst, data from *Suzaku* observation with longer exposure (twice that of *NuSTAR*) confirmed the detection of the harmonic at ~45 keV. The harmonic feature was found to be model independent and also present in each bin of the phase-resolved spectra of the pulsar. Statistical tests on the *Suzaku* data also confirmed the detection of the harmonic of the cyclotron line at ~45 keV. Though *NuSTAR* has better effective area at ~50 keV than *Suzaku*, long exposure of the *Suzaku* observation detected the additional feature at ~45 keV.

Cyclotron absorption features in the broad-band X-ray spectrum originate due to the resonance scattering of photons with quantized electrons in the presence of magnetic field. Depending on the strength of the magnetic field, the states of electrons are quantized in harmonically spaced levels such that the first harmonic energy is expected to be at twice of the fundamental energy. In the present case of Cep X-4, however, the first harmonic is detected at an energy which is ~1.7 times that of the fundamental line which is less than the ideal coupling factor of 2. An-harmonic spacing between fundamental and harmonic lines has also been seen in a few other X-ray pulsars and described by considering the relativistic effects in photon-electron scattering for small changes in the energy ratio (Mészáros 1992; Schönherr et al. 2007). However, this may not be the only cause that can produce the anharmonicity in lines. Cyclotron absorption phenomena for fundamental and harmonic lines occurring at two different scale heights can have different optical depths and introduce the anharmonicity in the coupling factor or line energy ratio. In detailed studies of cyclotron lines, Nishimura (2005) and Schönherr et al. (2007) showed that the increase in magnetic field within a line forming region can result the line ratio less than 2, as seen in 4U 0115+63 (Heindl et al. 1999) and Cep X-4 (present work). At larger viewing angle $\mu=0.79$, the line ratio is expected to be 1.73 for polar cap radius of 1.5 km (Nishimura 2013). Such decrease in energy ratio (1.57-1.73) is possible for viewing angle of 0.52-0.79 where superimposition of large numbers of fundamental line emerging from different heights of line-forming region shifts the energy to higher side with nearly constant energy for first harmonic. In another scenario, the anharmonicity in the line ratio can be expected due to distortion or displacement from the dipole geometry of the magnetic field. In this case, both CRSFs are generated at two different poles of neutron star and produce a significant phase shift between both line parameters. Such phase-shift was not seen in Cep X-4 (Fig. 4).

For the first time, we present the detailed analysis of fundamental cyclotron line with previously unknown first cyclotron harmonic in Cep X-4. Numerous simulation works on cyclotron lines were done by considering certain sets of assumptions and geometry in line forming regions (Araya-Góchez & Harding 2000; Schönherr et al. 2007; Mukherjee & Bhattacharya 2012). These studies predicted that the cyclotron absorption line parameters are expected to show 10-20% variation over pulse phases depending on the viewing angle of the accretion column. However, more than 30% variation in cyclotron parameters can be explained by considering distortion in the magnetic dipole geometry of the pulsar (Schönherr et al. 2007; Mukherjee & Bhattacharya 2012). In Cep X-4, both cyclotron line parameters are varying within 20% over pulse-phase, which can be described in terms of the viewing angle or local distortion in magnetic field. Detailed modeling of the observed variations in cyclotron parameters would provide useful information about the neutron star magnetic field geometry, inclination and beaming or emission patterns. However, these works are beyond the scope of the paper.

In summary, we report the detection of the first harmonic of ~28 keV fundamental cyclotron absorption feature at ~45 keV in Cep X-4. This feature was clearly seen in the phase-averaged and phase-resolved spectra from the *Suzaku* observation in 2014 July. The values of the energy of first harmonic with fundamental line were found anharmonic with ratio of 1.7. Parameters of both the fundamental and first harmonic lines were variable within 20% with pulse-phase which is explained as the effect of viewing angle or local perturbation in magnetic field of line forming region.

We sincerely thank the anonymous referee for valuable comments which improved the paper significantly. This research has made use of *Suzaku* data obtained through HEASARC Online Service.

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