A broadband X-ray study of the asynchronous polar: CD Ind

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ABSTRACT

A simultaneous broadband analysis of X-ray data obtained with XMM-Newton and NuSTAR observatories for the asynchronous polar source CD Ind is presented. The spin folded lightcurve in soft 0.3-3.0 keV band shows single broad hump-like structure superimposed with occasional narrow dips, indicating a single-pole accretion model with a complex intrinsic absorber. Lack of strong modulation in folded lightcurve above 3 keV reveals that emission from corresponding zone of post-shock region (PSR) remains in view throughout the spin phase. The broadband spectrum is modelled with a three-component absorbed plasma emission model and absorbed isobaric cooling flow model, both of which fit the data well with similar statistical significance. Presence of partial covering absorber is evident in the spectra with equivalent column density ~ 7 x 10^{22} cm^{-2} and a covering fraction of ~ 25%. Strong ionised oxygen Kα line emission is detected in the spectra. We notice spectral variability during spin phase 0.75-1.05, when there is a considerable increase in column density of overall absorber (from ~ 1 x 10^{20} cm^{-2} to ~ 9 x 10^{20} cm^{-2}). We required at least three plasma temperatures to describe the multi-temperature nature of the PSR. The shock temperature ~ 43.3^{+3.8}_{-3.4} keV, represented by the upper temperature of the cooling flow model, implies a white dwarf mass of ~ 0.87^{+0.04}_{-0.03} M_⊙. The iron Kα line complex shows a strong He-like and a weak neutral fluorescence line. We could not unambiguously detect the presence of Compton reflection in the spectra, which is probably very small and signifying a tall shock height.

Key words: novae, cataclysmic variables – white dwarfs – accretion, accretion discs – stars: individual: EUVE J2115-586 – stars: individual: RX J2115-5840

1 INTRODUCTION

Magnetic cataclysmic variables (mCVs) are a type of binary systems where the accreting material, coming from the Roche-lobe filling secondary star (typically late type main sequence star), falls on the primary white dwarf (WD) with supersonic velocities via the magnetic field lines of the WD (Warner 1995; Hellier 2001). Asynchronous polars (APs) are the type of mCVs which have spin periods (Ω) different than orbital periods (Ω), but very close to each other (with asynchronicity ≲ |Ω_Ω_ΩΩ| ≲ 3%). Though intermediate polars (IPs) also have differing spin and orbital periods, the degree of asynchronicity is much higher (for most IPs ≳ 90%, eg. Bernardini et al. (2012); de Martino et al. (2020)). The magnetic field strength of polars are high enough (≳ 10 MG), so that the field lines of the primary extend up to secondary and intertwines with field lines of the secondary, thus causing magnetic locking and resulting perfect synchronicity. IPs have weaker magnetic field (~ 1 – 10 MG) and unable to have magnetic locking, thereby posses high level of asynchronicity. APs have comparable magnetic fields as polars, and their spin periods gradually evolve towards the orbital period. The origin of asynchronicity in APs is still under debate. For one AP: V1500 Cyg, nova eruption (Honda et al. 1975; Stockman et al. 1988; Schmidt et al. 1995) is theorised to be a reason behind asynchronicity based on detection of nova shell around it. However, nova shells remain undetected around other APs (Pagnotta & Zurek 2016). The WD in AP rotates over a beat period (|1/Ω_Ω_ΩΩ - 1/Ω_Ω_ΩΩ|^{-1}) with respect to the secondary. Thus it provides insight about how the accretion properties vary in different intervals of beat cycle.

In magnetic CVs including APs, the supersonic accretion flow, channelled via magnetic field lines, form strong shock over WD surface near the pole region and produces X-rays. The material cools down in the post-shock region (PSR) primarily via bremsstrahlung emission in X-ray, and cyclotron emission in optical wavelength (Cropper 1990). The PSR of the accretion column thus represents multi-temperature zones of ionised plasma as it cools down at the bottom of the column i.e. the WD photosphere (Aizu 1973). The observed X-rays from the system carries the information about its interaction with the WD surface, accretion column, accretion disk or any other galactic intervening medium. A part of the X-rays from PSR can raise WD surface temperature and produce blackbody emission in very soft X-rays (few eVs to tens of eVs) to extreme UVs. A part of the interacting X-rays will undergo photoelectric absorption, the effect which is more pronounced as a reduction in soft X-rays (few hundreds of eVs to few keVs). There will also be fluorescence line emission, most notably the neutral Fe Kα line at 6.4 keV, followed by photoelectric absorption by WD surface. A part of downward emitting hard X-rays can undergo Compton reflection by the WD surface.
surface which will present itself as an excess (a hump like feature) in 10–30 keV (George et al. 1990). This last process is highly dependent on the parameters related to geometry of the accretion, like shock height and viewing angle of reflecting site. Also the strength of the reflection amplitude is correlated with the strength of the 6.4 keV line as they are believed to be originated from the same region of WD.

Our target CD Ind (also known as EUVE J2115-586, RX J2115-5840) is one of the asynchronous polars (other notable few V1432 Aql, BY Cam and V1500 Cyg) which has been first identified as polars by Craig et al. (1996); Vennes et al. (1996) via spectroscopic studies and estimating the magnetic field strength. Schwopa et al. (1997) updated the definition of CD Ind as an AP by intensive polarimetric study and signature of pole-switching was observed over a beat cycle. They also reported a magnetic field strength of 11 ± 2MG. Ramsay et al. (1999, 2000) stated that the accreting material follows same set of field lines over the full beat cycle, i.e., the materials travel around the azimuth of WD to connect to those field lines over certain beat phases and argued about the complex magnetic field structure with non-dipolar field geometry of the WD, where one pole is sufficiently stronger than other. Ramsay et al. (2000) also performed X-ray analysis using RXTE PCA data, taken over several days of a beat cycle and found that the hard X-ray spectra in 4-15 keV produces similar spectral parameters for both the accreting poles, whichever is active for accretion at different beat phases. Involving a far ultraviolet spectroscopic study, Araujo-Betancor et al. (2005) reported a galactic column density of $1 \pm 0.5 \times 10^{19} \text{ cm}^{-2}$ by measuring the absorption of a narrow interstellar Lyα line. Myers et al. (2017) revisited the source with extensive photometric campaign extended over a duration of 9 years and defined the spin and orbital periods along with the rate of change of spin period ($P_{\omega}$). Later Littlefield et al. (2019) used continuous TESS photometric data of 28 days and redefined the Myer’s identified period with $P_{\omega} = 6720$ s and $P_{\omega} = 6648$ s. They also claimed that $P_{\omega}$ is half of what Myer’s identified and updated the resynchronisation time scale ($\tau = |\frac{P_{\omega} - P_{\omega}}{P_{\omega}}|$) to be 13000 years, making it one of the slower achiever of synchronicity. Littlefield et al. (2019) reaffirmed that one accretion region is continuously visible during accretion over a spin phase, when the other pole undergoes self-eclipse and each pole accretes for nearly half of the beat cycle (~ 7.3 days). Using the TESS data, Hakala et al. (2019) studied the changes in accretion stream trajectory on to the two pole. The following year, also employing the TESS data, Mason et al. (2020) discussed the possible accretion scenario where four alternating and oppositely positioned accretion regions are present, with one accretion region being always in view. Sobolev et al. (2021) performed magnetohydrodynamic simulation of the flow structure under the assumption of shifted dipole configuration and predicted significant changes in flow structure depending on the pole-switching.

In this work, we present the study of the asynchronous polar source, CD Ind, for the first time, using the broadband X-ray data, obtained from XMM-Newton and NuSTAR telescope. We organise our paper as follows. In the next section (Sect. 2) we present the observations used and data reduction. Section 3 contains the results from the timing and spectral analysis of the source. In section 4 we discuss the results obtained from previous sections. The concluding section (sect. 5) describes the summary of the work.

2 OBSERVATIONS AND DATA REDUCTION

CD Ind was observed simultaneously with XMM-Newton (Jansen et al. 2001) and NuSTAR telescopes (Harrison et al. 2013) as a part of our proposal to perform a detailed broadband X-ray spectral study of APs. The hard X-ray imaging telescope NuSTAR is capable of extending our understanding till 79 keV with high sensitivity. Simultaneous observation with XMM-Newton, having excellent energy resolution, empowers us to probe the soft energy part till 0.3 keV. So, the availability of simultaneous broadband data provides us the superior opportunity to characterise the spectrum by accounting the absorption in lower end as well as probing the reflection in upper end, thereby constraining the multi-temperature continuum from PSR.

XMM-Newton telescope observed (Observation ID: 0870800101) the source for ~ 36.8 ks on source time, starting at 2020-11-09 T12:32:16 and NuSTAR observed (Observation ID: 30601018002) for ~ 56.5 ks, starting at 2020-11-09 T12:11:09. The high resolution reflection grating spectrometer, RGS (den Herder et al. 2001) on-board XMM, covering 0.35–2.5 keV energy band, can resolve the prominent emission lines present in the source.

2.1 NuSTAR

The two focusing imaging telescope modules of NuSTAR, namely FPA1 and FPA2, can bring the hard X-rays (3.0–79.0 keV) to its focus and record with high sensitivity. We have selected a circular source region of 40 arcsec radius centering the source, and a circular source free region of 80 arcsec radius as the background from the same detector. We have used NuSTARDAS version 2.1.1 for data reduction. The latest calibration files are used (v20210701), nuproducts command has been used to produce final science data products like lightcurve and spectrum files and necessary detector response files. We have performed the barycentric correction during product extraction. We have rebin the NuSTAR spectra with minimum 25 counts in each bin using grppha to utilize the $\chi^2$ minimization for spectral fitting.

2.2 XMM-Newton

XMM-Newton observation of the source was taken in large window mode using thin filter for both the PN (Strüder et al. 2001) and MOS detectors (Turner et al. 2001) of the European Photon Imaging Camera Instrument (EPIC). We have used XMMAS v19.1.1 for the data reduction. The calibration files used, are obtained from SAS current calibration files repository, latest at the time of analysis. We have followed the SAS analysis thread for data reduction. We have used SAS tools epproc and emproc to produce calibrated event files. Our data are contaminated heavily by high background flares due to XMM-Newton’s highly elongated eccentric orbit. The flaring is prominent during later part of observation in PN and MOS data. To get rid of this flaring, we discarded the data using time selection criteria Time<721326500 in our good time interval (GTI). Unfortunately, this aggressive but essential filtering leaves us with only initial ~ 11.2 ks and ~ 13.1 ks of data from PN and MOS respectively. We have also checked for pile-up using epatplot tool but did not find any significant presence of it. The flaring free event files are then used for science products extraction with barycentric correction. We have chosen a circular source region with 25 arcsec radius centering the source, and a circular background region with 50 arcsec radius from the same CCD to extract our final lightcurve.

1 https://www.cosmos.esa.int/web/xmm-newton/current-calibration-files
2 https://www.cosmos.esa.int/web/xmm-newton/sas-threads
spectrum and detector response files. The spectra have been rebinned with spacegroup tool to minimum 25 counts for using $\chi^2$ statistic to test goodness of spectral fit.

For RGS data extraction we have used rgsproc tool. Though we found that RGS data are not contaminated to that hefty extent as that of EPIC, yet background flaring peaks are present, for which we have used rate selection criteria RATE$=\theta$ .125 in the corresponding good time interval. We managed to get $\sim$ 30.9 ks of the exposure time for the spectra obtained from RGS detectors for our analysis. Spectra were rebinned with minimum 25 counts like before.

3 DATA ANALYSIS AND RESULTS

3.1 Timing Analysis

The data obtained from NuSTAR observation is $\sim$ 96 ks including the actual on-source time of $\sim$ 56.5 ks, gaps due to earth occultation and South Atlantic Anomaly (SAA) passage. These gaps result in difficulties to find the exact periods of the system with high precision and to distinguish between the spin (6648s) and orbital periods (6720s) which are closely spaced. However, given the total duration of NuSTAR data, we can get roughly $\sim$ 14 cycles to probe the timing properties of the system. On the other hand, flaring corrected EPIC data cover only $\lesssim$ 2 cycles. For spin and orbital period, we have followed Littlefield et al. (2019) who defined the periods based on nearly 28-days long continuous TESS data. The background subtracted cleaned lightcurves from both observatories have been plotted in the Figure 1.

We performed power spectral analysis on background subtracted PN and FPMA lightcurves that showed broad peaks at 6286 $\pm$ 917s and 6545 $\pm$ 111s respectively. These values agree with the literature values of rotational periods of the system, but our data could not resolve the spin and orbital periods.

3.1.1 Spin Folded Lightcurves

To fold the lightcurve based on the spin period, we have used the ephemeris $\nu (BJD) = 2458326.46492(17) + 0.0769522(11) \times E$ following Littlefield et al. (2019). They updated the derivative of spin period ($P = +1.75 \times 10^{-10}$) from the value given by Myers et al. (2017) which was two times faster. The time when our observation was made (BJD=2459163.00774), the spin period has changed only by $\sim 0.0126s$ i.e $\sim 0.0002\%$ from the reported value in Littlefield et al. (2019).

We have shown the background subtracted spin folded XMM-Newton PN lightcurves in Fig. 2 for different energy bands (0.3-10 keV, 0.3-3.0 keV, 3.0-10.0 keV). The soft X-ray band (0.3-3.0 keV) exhibit a strong pulse fraction (PF) of modulation, 62 $\pm$ 2%, using the definition $PF = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$ where $I$ denotes the count rate. It shows a single broad hump like structure with occasional narrow dips in between. However, it is difficult to comment about all the dips individually due to the limitation of the data, which cover $\lesssim$ 2 cycles. In 3-10 keV band of PN, the broad hump-like profile is not visible, and the count rate fluctuates around a mean value of 0.673 counts/s. The hardness ratio-1 plot ($HR1 = I_{10-30 \text{keV}}/I_{3-10 \text{keV}}$) in the bottom panel of Fig. 2 shows a strong peak in phase 0.75 $\pm$ 1.05, denoting a significant spectral variability during that phase.

Background subtracted spin folded NuSTAR lightcurves in different energy bands (3-40 keV, 3-10 keV, 10-40 keV) are plotted in Fig. 3. We have chosen 3-40 keV band from NuSTAR, since the background starts dominating beyond 40 keV. The folded lightcurve in 3-40 keV band in top panel of Figure 3 statistically represents a flattened profile with an average value $\sim$ 0.343 counts/s. We observe a similar flattened profile with fluctuating count rates in both the constituent energy bands, 3-10 keV and 10-40 keV. For the profile in 3-10 keV and 10-40 keV band, a constant model can fit reasonably well with an amplitude of $\sim 0.258 \pm 0.004$ counts/s ($\chi^2/\text{DOF} = 1.149(87)$) and $0.081 \pm 0.002$ counts/s ($\chi^2/\text{DOF} = 0.873(87)$) respectively. Also, the hardness ratio-2 ($HR2 = I_{10-40 \text{keV}}/I_{3-10 \text{keV}}$) in the bottom panel of Figure 3, show a flat profile with an average value

Figure 1. Background subtracted clean lightcurves from XMM-EPIC in 0.3-10.0 keV (top) and NuSTAR in 3-40 keV (middle). Background lightcurves are also shown in those panels for reference. In the bottom panel, cleaned lightcurves are shown in the common 3-10 keV band where both telescopes have coverage. The lightcurves from both the modules of NuSTAR are co-added and averaged to improve statistics. Same is done for XMM-Newton EPIC-MOS. The start time is chosen to be NuSTAR observation start time. The PN counts/s is scaled by 0.3 in top and bottom panel for comparison. The bin size is 200s in top panel and 400s for middle and bottom panel.
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Spin folded lightcurves in different energy bands along with hardness ratio using XMM-EPIC PN data. Bin size in each panel is \( \sim 150\)s.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Spin folded lightcurves in different energy bands along with hardness ratio using co-added and averaged lightcurves from both the FPMA and FPMB modules of NuSTAR. Bin size in each panel is \( \sim 150\)s. The red dotted line represents mean counts rate by fitting a constant model.}
\end{figure}

\( \sim 0.312 \), indicating there is no significant spectral variability above 3 keV over the full spin period.

The orbit folded lightcurves, using period 6720s (Littlefield et al.
2019), produce similar pattern in all energy bands as well as the hardness ratios, as observed in the spin folded lightcurves.

3.2 Spectral Analysis

We have used X-ray spectral fitting package, XSPEC (Arnaud 1996) version 12.12.0, to analyse the spectra. The spectral models used in this paper are available in the package. The errors on the spectral parameter values are quoted with 90\% confidence throughout the paper. Abundance table in our analysis was set after Wilms & McCray abundance table (Wilms et al.
2000) along with photoelectric absorption cross section defined after Verner et al. (1996).

3.2.1 Phenomenological fit to NuSTAR spectra

We have first utilised only the NuSTAR data for our phenomenological fit to get the idea about shock temperature and reflection amplitude. Both the FPMA and FPMB spectra (3.0-40.0 keV) were fitted simultaneously to improve the signal to noise ratio. The equivalent column density of galactic absorber (modelled after \textsc{tbabs} ) was fixed at \( 10^{19} \) cm\(^{-2}\) (Araujo-Betancor et al.
2005) as NuSTAR data can not constrain it. Ionised plasma emission model \textsc{mekal} has been used for modelling the emission from the post-shock region. The switch parameter for the emission model was set at 2 to determine the spectrum based on updated line emission code \textsc{AtomDB v3.0.9}

To incorporate the multi-temperature nature of the post-shock region of the accretion column, we have used two \textsc{mekal} components, where the upper temperature gives indication of the shock temperature.

The iron line complex (neutral fluorescence at 6.4 keV, He-like at \( \sim 6.7\)keV and H-like at \( \sim 6.97\)keV) is not separately resolved by NuSTAR, and was modelled using a \textsc{gaussian} component. The combined model (including absorption, emission and \textsc{gaussian}) produced an upper temperature \( 30.7^{+19.7}_{-9.1} \) keV with a \( \chi^2(\text{DOF}) = 411(459) \). Next we convolved the \textsc{reflect} model (Magdziarz & Zdziarski 1995) with the emission components, to find out the effect of the Compton reflection which should manifest itself as an excess or hump in \( \sim 10 \) to \( 30 \) keV energy range. We have kept the parameters of \textsc{reflect} other than reflection amplitude fixed at their default values (viewing angle set at \( \mu = 0.45 \), the abundance parameters were linked between reflection and emission component and were kept frozen at 1). The fit statistics didn’t have any significant change (\( \chi^2(\text{DOF}) = 409(458) \) i.e \( \Delta \chi^2 \sim 2 \) for 1 less DOF), indicating redundancy of reflection component in the fitting. However, NuSTAR-only fitting can not detect the lower temperature of the PSR, as well as presence of any extra absorber, which affects the soft X-rays, mostly below NuSTAR’s coverage. So, we need to incorporate the simultaneous data obtained from XMM-Newton for a global description of the spectra.
Figure 4. Modelling the iron K$_\alpha$ line complex using an absorbed bremsstrahlung continuum along with three gaussian component in 5-9 keV. The top panel shows the spectrum, and the bottom panel shows ratio (data/model) plot.

3.2.2 Phenomenological fit to XMM-Newton spectra

To build up the description of the soft X-ray part of the spectrum, we have looked into the XMM-Newton EPIC (0.3-10.0 keV) and RGS (0.45-2.0 keV) data. Owing to good spectral resolution of the EPIC, we can distinguish the K$_\alpha$ line complex. In order to quantify the contribution of those three lines, we have modelled them after three gaussian on top of a thermal bremsstrahlung continuum with fixed galactic absorption ($10^{19}$ cm$^{-2}$) using 5.0-9.0 kev data. The resultant best fit parameters are quoted in Table 1 and corresponding spectral plot is shown in top panel of Fig. 4. The width ($\sigma$) of all the gaussian components are consistent with the EPIC resolution limit (~130 eV at 6.5 keV), hence fixed at zero, thus indicating that the lines are narrow. The line centers appear at expected energies within error bar. Fluorescent line is the weakest (equivalent width ~ 71 eV) whereas the He-like line is the strongest (equivalent width ~ 137 eV) among the three lines.

Next we have fitted the full EPIC spectra (PN, MOS1 and MOS2) in 0.3-10.0 keV to estimate the lower temperature and absorption parameters. A simple model like an absorbed single temperature ionised plasma emission (mekal) model with gaussian component for narrow 6.4 keV line produced a mediocre fit with $\chi^2$(DOF) = 549(401) and a plasma temperature of 24.4$^{+2.6}_{-2.4}$ keV. But the fit has issues like extremely low value of column density of the absorber ($\sim 10^{10}$ cm$^{-2}$) unbounded at lower limit and with upper limit reaching ~ 2 x $10^{19}$ cm$^{-2}$ (close to the galactic $n_H$ value of $10^{19}$ cm$^{-2}$), and the excess around 0.6 keV and 1 keV indicating line emissions like oxygen and iron-L shell from low temperature plasma. Fixing the $n_H$ to $10^{19}$ cm$^{-2}$ and adding one more plasma emission component resulted in a somewhat improved fit statistic ($\chi^2$(DOF) = 527(400)) with low temperature coming around 0.17$^{+0.02}_{-0.03}$ keV representing an optically thin cold plasma. In order to evaluate the column density of any absorber present at the source, we included an photoelectric absorber model phabs, with $n_{H,ph}$ of galactic absorber tbabs fixed at $10^{19}$ cm$^{-2}$ and found a better fit-stat ($\chi^2$(DOF) = 518(399)) with $n_{H,ph} = 1.18^{+0.69}_{-0.67}$ x $10^{20}$ cm$^{-2}$. Guided by the presence of multiple narrow dips in our spin folded lightcurve, which possibly indicating presence of inhomogeneous absorber, we applied an extra partial covering absorber model, implemented by partcov*phabs on top of the overall absorption. This readily improved the fit to a significant amount ($\chi^2$(DOF) = 464(397) i.e $\Delta \chi^2 = 52$ for 2 less DOF) with a column density of partial absorber, $n_{H,pcf} = 10.7^{+3.6}_{-2.5}$ x $10^{22}$ cm$^{-2}$ and a covering fraction of 0.27$^{+0.07}_{-0.05}$. However, the model now define the lower energy part better, with the high temperature plasma emission component detecting a smaller value 10.5$^{+3.6}_{-2.5}$ kev. The model underestimated the observed data in harder X-ray (beyond 7 keV), resulting in excess in residual. This motivated us to add one more plasma emission model, which produced an improved fit statistic of $\chi^2$(DOF) = 429(394) with maximum temperature of 36.2$^{+32.9}_{-31.1}$ keV. F-test probability corresponding to the third mekal component is 8.75 x 10$^{-7}$, signifying its necessity. Though this temperature is not very well constrained due to absence of extended hard X-ray data for XMM Newton EPIC, yet clearly accounts for the excess residual beyond 7 keV, and is in agreement with the upper temperature we obtain from NuSTAR-only fit.

We have also looked into the grating spectrometer data, RGS in 0.45-2.0 keV band. We have used an absorbed thermal bremsstrahlung continuum model for fitting the data, with column density of absorber as a free quantity. The upper limit of the continuum temperature became unbounded, so kept fixed at fit value 4.95 keV. We see clear line emissions at ~ 0.57 keV and 0.65 keV, corresponding to the ionised oxygen K$_\alpha$ emission lines (O VII and O VIII respectively) in the spectra. We added two gaussian components to model those emission features. This produced a fit statistic

| Parameter | Unit | Value |
|-----------|------|-------|
| $n_H^{fr}$ | $10^{19}$ cm$^{-2}$ | $l_{fr}$ |
| $T_C$ | keV | 32.8$^{+67.8}_{-14.5}$ |
| $N_C^{fr}$ | $10^{-3}$ | 2.2$^{+0.29}_{-0.08}$ |
| $\text{Line}_{\text{E}}^{d}$ | keV | 6.43$^{+0.04}_{-0.03}$ |
| $\sigma_{\text{E}}^{f}$ | eV | 0$_{fr}$ |
| $\text{eqw}_{\text{E}}^{f}$ | eV | 71$^{+37}_{-30}$ |
| $N_{\text{E}}^{fr}$ | $10^{-5}$ | 0.90$^{+0.32}_{-0.32}$ |
| $\text{Line}_{\text{E}}^{d}$ | keV | 6.70$^{+0.02}_{-0.02}$ |
| $\sigma_{\text{E}}^{f}$ | eV | 0$_{fr}$ |
| $\text{eqw}_{\text{E}}^{f}$ | eV | 137$^{+46}_{-43}$ |
| $N_{\text{E}}^{fr}$ | $10^{-5}$ | 1.67$^{+0.38}_{-0.37}$ |
| $\text{Line}_{\text{E}}^{d}$ | keV | 6.97$^{+0.04}_{-0.03}$ |
| $\sigma_{\text{E}}^{f}$ | eV | 0$_{fr}$ |
| $\text{eqw}_{\text{E}}^{f}$ | eV | 83$^{+46}_{-33}$ |
| $N_{\text{E}}^{fr}$ | $10^{-5}$ | 0.93$^{+0.35}_{-0.35}$ |
| $\chi^2$(DOF) | 81.40(89) |
| $\chi^2_{fr}$ | 0.9146 |
of $\chi^2 (DOF) = 161(163)$. The corresponding best fit parameter values are listed in Table 2 with the best fit spectrum plot in Fig. 5. We noticed that the O VIII line is narrow, for which the width ($\sigma$) parameter couldn't be constrained and reaching value lower than instrument resolution, so we fixed it to 0. The width ($\sigma$) of O VII line was allowed to vary, however its best fit value reached almost the instrument resolution limit. The O VII line is composed of fine atomic transition lines (resonance, intercombination and forbidden lines), which are not resolved in the RGS spectra. The clear appearance of ionised oxygen K$_\alpha$ lines agrees with the presence of strong excess around 0.5-0.7 keV in EPIC spectra. Each of the gaussian components improve the fit w.r.t absorbed continuum by $\Delta \chi^2 \sim 31$ for 2 less DOF, indicating strong statistical significance of the two lines. The grating spectra doesn't show presence of other such strong lines, so modelling them using gaussian components are not statistically significant.

This phenomenological fit of XMM-Newton EPIC data now guides us to construct the final model in the next subsection for broadband spectral analysis of simultaneous data, obtained from both the observatories.

### 3.2.3 Broadband spectra fitting using XMM-Newton EPIC and NuSTAR

We have used the absorbed multi-temperature hot plasma emission model, as developed during phenomenological fits, for modelling the broadband data in 0.3-40.0 keV range. We used model cons*tbabs*phabs*(partcov*phabs)*(mekal+mekal+mekal+gauss) (model M1) to fit the broadband data, producing a resultant fit statistic $\chi^2 (DOF) = 839(857)$. The best fit parameters are quoted in Table 3 with the spectra shown in Figure 6. The fit can describe spectra perfectly by incorporating a total and a partial covering absorber, signifying complex absorption and with clearly detected atleast three plasma temperatures. Best-fit parameters agree with phenomenological fits, but with better error constraints.

We have also tried adding one more plasma emission component (mekal), resulting in a marginal improvement of fit statistic ($\chi^2 (DOF) = 835(855)$). The corresponding F-statistic probability is 0.094. So, we didn't find a strong incentive to keep this extra fourth component.

At this stage our spectral modelling of broadband data constrains plasma emission parameters as well as column density parameters of absorption components. Next, in order to check the effect of Compton reflection, we have convolved the reflect model with the plasma emission components using the broadband data. The abundance parameters in mekal and reflect were linked and kept free. Similar to NuSTAR-only fit, there is no improvement to fit statistics with negligibly small reflection amplitude ($\sim 10^{-5}$).

To check the robustness of the parameters obtained from our simple yet effective three temperature plasma emission model (M1), we have also modelled our spectra using isobaric cooling flow model for ionised plasma, mkcfow (Mushotzky & Szymkowiak 1988; Mukai et al. 2003). This model considers multi temperature nature of spectra by using the emissivity function as inverse of bolometric luminosity. The redshift parameter of mkcfow was kept fixed at $5.53 \times 10^{-8}$ according to the GAIA DR3 distance of 237 $\pm$ 4pc (Gaia Collaboration et al. 2021). The switch parameter was set at 2. We have used model cons*tbabs*phabs*(partcov*phabs)*(mkcfow+mekal+gauss) (model M2) for the broadband fit ($\chi^2 (DOF) = 839(858)$) and best-fit parameters are quoted in Table 3 with ratio plot in Fig. 6. We noticed the absorption parameter values agree with model M1, thus independent of choice of the model. We required the extra optical thin plasma emission component to consider the excess around 0.6 keV. Fixing low temperature of cooling flow component at 0.0808 keV could not consider the excess around 0.6 keV and actually gave poorer fit statistic. So, we kept the lower temperature parameter of cooling flow component free, which detects some mean temperature near the base of the PSR where mat-

![Figure 5](image-url)

**Figure 5.** Modelling the ionised oxygen lines (O VII and O VIII) using an absorbed bremsstrahlung continuum along with two gaussian component in 0.45-2.0 keV. The top panel shows the spectrum, and the bottom panel shows ratio (data/model) plot.

| Parameter | Unit  | Value    |
|-----------|-------|----------|
| $n_H^a$   | $10^{20} \text{ cm}^{-2}$ | $4.68_{-1.89}^{+1.97}$ |
| $T_C^b$   | keV   | $4.95_{-0.12}^{+0.11}$ |
| $N_C^c$   | $10^{-3}$ | $1.44_{-0.12}^{+0.11}$ |
| LineE$^d_{\text{He-like}}$ | keV | $0.569_{-0.002}^{+0.002}$ |
| $\sigma_y^e$ | eV | $3.9_{-1.3}^{+2.5}$ |
| $\text{eqw}^{f}_{\text{He-like}}$ | eV | $42_{-15}^{+15}$ |
| $N_{\text{H-like}}^y$ | $10^{-5}$ | $10.28_{-3.56}^{+4.39}$ |
| LineE$^d_{\text{H-like}}$ | keV | $0.654_{-0.001}^{+0.008}$ |
| $\sigma_y^e$ | eV | $0_{-0}^{+0}$ |
| $\text{eqw}^{f}_{\text{H-like}}$ | eV | $17_{-5}^{+5}$ |
| $N_{\text{H-like}}^y$ | $10^{-5}$ | $3.51_{-1.09}^{+1.34}$ |

$\chi^2 (DOF) = 161(163)$

$\chi^2 = 0.9877$

| $a$ | Overall column density |
| $b$ | $c$ | Temperature and normalisation of bremsstrahlung continuum |
| $d$, $e$, $f$, $g$ | Line energy, $\sigma$, equivalent width, and normalisation in terms of photons cm$^{-2}$ s$^{-1}$ |
| $fr$ denotes the parameter is fixed |

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**Table 2.** Best fit parameters from fitting oxygen K$_\alpha$ lines (0.45-2.0 keV RGS data)
3.2.4 Phase-resolved spectroscopy

The HR1 (bottom panel of Fig. 2) shows excess during the spin phase ~ 0.75 – 1.05 indicating spectral variation. However, HR2 (bottom panel of Figure 3) doesn’t indicate any such strong variation during the entire spin phase. The spin phase-resolved spectra in Figure 7, noticeably exhibit that the lower energy part of the spectra (below ~ 3 keV) is more absorbed during the phase 0.75-1.05 compared to phase 0.05-0.75, thereby explaining the excess in HR1 plot. To evaluate the spectral parameters, we have considered the broadband phase-resolved spectra in 0.3-40.0 keV range, and fit with the same models as phase-averaged spectra. The obtained best fit parameters are tabulated in the Table 3. Using the spectral model M1, the equivalent column density of overall photoelectric absorber comes out to be $8.78^{+2.96}_{-3.45} \times 10^{20}$ cm$^{-2}$ during phase 0.75-1.05, much higher than $1.23^{+0.68}_{-0.69} \times 10^{20}$ cm$^{-2}$ during phase 0.05-0.75. The best fit values of equivalent column density of partial covering absorber and covering fraction for the phase 0.05-0.75 are $11.2^{+4.2}_{-3.2} \times 10^{22}$ cm$^{-2}$ and $0.23^{+0.05}_{-0.03}$ respectively. The same parameters for the phase 0.75-1.05 have values $5.3^{+2.9}_{-2.0} \times 10^{22}$ cm$^{-2}$ and $0.33 \pm 0.07$ respectively. The above mentioned two parameters have slightly different best fit values but with overlapping error bars. Similar parameter values are obtained with model M2. The temperature of cold plasma emission component has an upper limit of ~ 0.1 keV in phase 0.75-1.05, but the lower limit is unconstrained (reaching the minimum temperature ~ 0.0808 keV, allowed by the model). This temperature could be mimicking the temperature near the bottom of the PSR. The upper temperature was getting poorly constrained in the phase 0.75-1.05, because of the reduced count statistics of NuSTAR data in that phase. So, we kept that temperature fixed at the corresponding value of best fit temperature obtained from phase-averaged spectra.

4 DISCUSSION

We have carried out the broadband X-ray timing and spectral analysis of the asynchronous polar CD Ind. The implication of the timing and spectral results are discussed in this section.

4.1 Spin modulations in folded lightcurves

The spin folded lightcurve in 0.3-3.0 keV band (Fig 2) shows strong pulse profile with a single broad hump with multiple narrow dips and a pulse fraction of 62 ± 2%. The single broad hump picture nicely fits into the earlier reporting of one pole accretion at any specific beat phase (Littlefield et al. 2019; Myers et al. 2017; Ramsay et al. 2000). The dips represent the scenario where the X-ray emission passes through the inhomogeneous and complex accretion stream, undergoing photoelectric absorption. The minima at phase ~ 0.94 can be envisaged as when the corresponding emitting region is moving away from the line of sight and the emission is reaching us after passing through the intrinsic absorber. The broad hump like structure is missing in 3.0-10.0 keV band of PN, but the features of absorption dips are present (Fig 2). It indicates the corresponding X-ray emitting region of the PSR remains visible during the entire spin cycle, but still passes through the inhomogeneous accretion stream. Also, spin folded NuSTAR lightcurve in the 3.0-10.0 keV band, as well as 10-40 keV band (Fig 3) lack strong modulation. The lack of strong modulation in hard X-rays suggests corresponding zones of the PSR remain in the view throughout the spin phase. This scenario is representative of a tall PSR and a small angle between spin axis and magnetic axis (eg. ~ 10°, Ramsay et al. (2000)).

4.2 Multi-temperature nature of the accretion column

Our spectral analysis of the spin-average broadband spectra reveals the multi-temperature nature of the post-shock plasma. It is represented by three plasma temperatures in our spectral modelling. The upper temperature is close to the shock temperature. The lower temperature, coming from the optically thin cold plasma, indicates the scenario near the bottom of the PSR. The middle-temperature plasma designates the cumulative contribution from remaining temperature zones of the PSR. It is to be mentioned that in Aizu model, PSR consists of multiple temperature zones with gradually decreasing...
temperature with most of cooling occurring near bottom of the PSR (Fig. 2 of Mukai (2017)), and there is no distinct division among them. Our three-component plasma emission model is a simple yet useful picture to represent the PSR, with averaged contribution of plasma emissivity from different zones. A more extensive approach to represent the multi-temperature nature of PSR is by cooling flow models (Mukai et al. 2003). However, the lower temperature of cooling flow model in our fit does not necessarily indicate the lowest temperature at bottom of the PSR and possibly detects some mean value of temperature near the base of the PSR where the plasma is rapidly cooling. The requirement of an additional optically thin plasma to incorporate the excess due to emission features present in soft X-ray is also evident in cooling flow model.

The importance of having highly sensitive spectral data in hard X-rays is to measure the shock temperature accurately, thereby constraining the mass of the WD. The upper temperature of the cooling flow model represents the shock temperature more accurately than the three-component plasma emission model. This is because, cooling flow model considers the temperature gradient of the PSR using multiple grid points according to emissivity function of the emitting plasma, whereas the three-component plasma emission model represents the whole PSR using three plasma temperatures. Thus the upper temperature for three component plasma emission model is more likely to be an average value of temperature profile from the region below the shock. Using the relation between the shock temperature, mass and radius of the WD (Mukai 2017), and incorporating the WD mass-radius relation (Nauenberg 1972), we quote a mass value \( M_{WD} = 0.87^{+0.04}_{-0.03} M_{⊙} \) for a shock temperature of 43.3$^{+3.8}_{-3.4}$ keV (obtained from model M2, see Table 3). The corresponding radius is \( R_{WD} = 6.42^{+0.27}_{-0.28} \times 10^{8} \) cm ($\sim$ 0.009 \( R_{⊙} \)). Ramsay et al. (2000) measured a WD mass of \( M_{WD} = 0.79^{+0.12}_{-0.11} M_{⊙} \) using RXTE PCA spectra in 4-15 keV. Our measured mass, obtained using broadband spectra, matches with theirs, but with better error constraint.

The line of sight orbital velocity of the WD comes out to be \(~ 90 \) km/s, calculated using the following parameters: the mass of WD (obtained in this work \(~ 0.87 M_{⊙} \)), mass of M6V secondary (Littlefield et al. 2019), typical mass \(~ 0.21 M_{⊙} \), binary period \(~ 6720 \) s (Littlefield et al. 2019), and inclination angle of \(~ 65° \) (Mason et al. 2020).

We obtain an unabsorbed bolometric (0.3-40.0 keV) flux of \( 22.2^{+0.4}_{-0.3} \times 10^{-12} \) erg cm$^{-2}$ s$^{-1}$ of which \(~ 64% \) is contributed from 0.3-10.0 keV band and the remaining is from 10-40 keV band. The corresponding luminosity from the source is \( L = 1.49^{+0.08}_{-0.07} \times 10^{32} \) erg s$^{-1}$ (using \( L = 4\pi F d^{2} \) where \( d \) is the distance to the source \(~ 237 \pm 4 \) pc (Gaia Collaboration et al. 2021)).

The relation between accretion luminosity \( (L_{acc}) \), mass, radius and mass accretion rate of the WD \( (M_{WD}, R_{WD} \text{ and } M) \) respectively is given by (Frank et al. 2002),

\[
L_{acc} = \frac{GM_{WD} M}{R_{WD}}
\]

Assuming accretion luminosity is mostly emitted in X-rays, we
calculate a mass accretion rate of $\dot{M} \sim 8.24 \times 10^{14} \text{ g s}^{-1} \sim 1.30 \times 10^{-11} M_\odot \text{ yr}^{-1}$ using our obtained values of mass, radius and luminosity.

### 4.3 Iron and Oxygen K$_\alpha$ line emissions

The asynchronous polar CD Ind showed strong Fe K$_\alpha$ line emission, and XMM-Newton could resolve the three lines i.e. fluorescence, He-like and H-like lines. The line diagnostic shows that all the three Fe K$_\alpha$ lines in CD Ind have central energies at their expected positions within 90% confidence level, and the lines are narrow, which is expected from the radial velocity of the emitting pole of the WD. The intensity and equivalent width of the He-like Fe line are the strongest among the three lines. On the other hand, the neutral Fe K$_\alpha$ line is weakest among all, carrying an equivalent width of $71^{+37}_{-30}$ eV.

According to Ezuka & Ishida (1999), the observed equivalent width of the neutral Fe-line could be a sum of contribution from various components, like absorbing material and the cold surface of the WD. However, within the current limitation of the data, it is not possible to distinguish between these contributions, therefore we observe a total equivalent width. The Compton reflection is also originated from the similar region of the WD when the hard X-ray emission hits cold material at surface (van Teeseling et al. 1996).

Our data could not unambiguously detect the presence of reflection, which might be very small in the spectra. If the shock height is very large, the emitted hard X-rays can subtend only a very small solid angle to the WD surface, thereby producing a negligible reflection.

In addition to the Fe K$_\alpha$ line in EPIC spectra, the RGS grating spectra show presence of strong ionised oxygen K$_\alpha$ lines, appearing with equivalent width of $42 \pm 15$ eV (O VII) and $17 \pm 5$ eV (O VIII). These lines come from the cooler bottom region of the PSR. Presence of these lines with such strength indicates that the bottom temperature of the PSR is low enough to produce them. This fits with our prediction about tall shock height in CD Ind, so that the PSR gets sufficient time to cool down while reaching WD photosphere.

Previous study of CD Ind from XMM-Newton also reported presence of a strong Ni K$_\alpha$ line at 7.4 keV (Joshi & Pandey 2019). However, we did not find any such emission feature in our XMM-Newton data.

### 4.4 Excess absorption during spin phase 0.75-1.05

Our phase-resolved spectroscopy of CD Ind clearly identified the increased absorption in the soft X-rays below 3 keV during 0.75-1.05 spin phase as indicated by the HR1 of spin folded lightcurves. The column density of overall photoelectric absorption, which affects the low energy part increased by almost an order of magnitude. The partial covering absorber, however, did not change significantly. Due to more absorption, the absorbed flux value obtained in 0.3-3.0 keV band during phase 0.75-1.05 $(3.89^{+0.15}_{-0.18} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1})$ is less than the flux in same band during phase 0.05-0.75 $(5.50^{+0.06}_{-0.09} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1})$. The absorbed flux values in 3-40 keV band during both phases remained similar.

### 5 SUMMARY

Our study using simultaneous broadband X-ray data has enabled us to extend the understanding of the accretion properties of the asynchronous polar CD Ind. Here, we summarise our results:

- Our X-ray observation supports single-pole accretion model where one accretion region is active and remains visible throughout the spin phase. This fits with the existing picture of pole-switching scenario of the source where alternatively two poles become active during two different phases of a beat cycle.
- Presence of complex absorber is indicated in our study. The emitted X-rays pass through the inhomogeneous accretion stream, causing several narrow dips in the folded lightcurve. We also notice a significant increase in column density of the overall absorber for certain spin phase, affecting the soft X-rays below ~ 3 keV.
- We constrained the mass of the WD to be $0.87^{+0.04}_{-0.03} M_\odot$. This is directly measured from the shock temperature using the extended hard X-ray data from NuSTAR, and thus an improvement from the earlier measured masses.
- We could not unambiguously detect the Compton reflection, which may be small and might not have revealed itself in our spectra. We predict a possible scenario where the shock height is large.
- The bottom of the PSR cools down sufficiently, as supported by the presence of strong ionised oxygen K$_\alpha$ lines in the spectra.

In this X-ray broadband study of CD Ind, there are certain limitations. We could only look into a part of the beat phase using our joint simultaneous data. Also our observation from XMM-Newton in 0.3-10.0 keV only covers a small subset of NuSTAR observation which includes 10-40 keV. Ramsay et al. (2000) didn’t find significant difference in X-ray spectra between two different phases of a beat cycle, when two different poles were accreting, but their observation was based on limited 4-15 keV band of RXTE-PCA. Considering the complex variability of accretion mechanism in the source (as predicted in recent works eg. Mason et al. (2020); Sobolev et al. (2021)), a future monitoring X-ray campaign for simultaneous broadband data covering several beat phases, and possibly in several beat cycles (for improved count statistics in hard X-rays) will bring out a clearer impression about the change in accretion properties over a complete beat phase.

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### DATA AVAILABILITY

The data used for analysis in this article are publicly available in NASA’s High Energy Astrophysics Science Archive Research Center (HEASARC) archive (https://heasarc.gsfc.nasa.gov/docs/archive.html) and XMM-Newton Science archive (http://nxsa.esac.int/nxsa-web/#search). The observation IDs are mentioned in Sect. 2.
Aizu K., 1973, Progress of Theoretical Physics, 49, 1184
Araujo-Betancor S., Gainsicke B. T., Long K. S., Beuermann K., de Martino D., Sion E. M., Szkody P., 2005, ApJ, 622, 589
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V. p. 17
Bernardini F., de Martino D., Falanga M., Mukai K., Matt G., Bonnet-Bidaud J. M., Masetti N., Mouchet M., 2012, A&A, 542, A22
Craig N., Howell S. B., Sirk M. M., Malina R. F., 1996, ApJ, 457, L91
Cropper M., 1990, Space Sci. Rev., 54, 195
Ezuka H., Ishida M., 1999, ApJS, 120, 277
Frank J., King A., Raine D. J., 2002, Accretion Power in Astrophysics: Third Edition
Gaia Collaboration et al., 2021, A&A, 649, A1
George I. M., Nandra K., Fabian A. C., 1990, MNRAS, 242, 28P
Honda M., et al., 1975, IAU Circ., 2826, 1
Joshi A., Pandey J. C., 2019, Bulletin de la Societe Royale des Sciences de Liege. 88, 240
Jansen F., et al., 2001, A&A, 365, L1
Mukai K., 2017, PASP, 129, 026001
Mukai K., Kinkhabwala A., Peterson J. R., Kahn S. M., Paerels F., 2003, ApJ, 586, L77
Mushotzky R. F., Szymkowiak A. E., 1988, in Fabian A. C., ed., NATO Advanced Science Institutes (ASI) Series C Vol. 229, NATO Advanced Science Institutes (ASI) Series C. p. 53, doi:10.1007/978-94-009-2953-1_6
Myers G., et al., 2017, PASP, 129, 044204
Nauenberg M., 1972, ApJ, 175, 417
Pagnotta A., Zurek D., 2016, MNRAS, 458, 1833
Ramsay G., Cropper M., Harrop-Allin M. K., 1999, MNRAS, 303, 96
Ramsay G., Poter S., Cropper M., Buckley D. A. H., 1999, MNRAS, 316, 225
Schwope A. D., Buckley D. A. H., O’Donoghue D., Hasinger G., Truemper J., Voges W., 1997, A&A, 326, 195
Sobolev A. V., Zhitkln A. G., Bisikalo D. V., Buckley D. A. H., 2021, Astronomy Reports, 65, 392
Schmidt G. D., Liebert J., Stockman H. S., 1995, ApJ, 441, 414
Strüder L., et al., 2001, A&A, 365, L18
Venners S., Wickramasinghe D. T., Thorstensen J. R., Christian D. J., Bessell M. S., 1996, AJ, 112, 2254
Verner D. A., Ferland G. J., Korista K. T., Yakovlev D. G., 1996, ApJ, 465, 487
Warner B., 1995, Cataclysmic Variable Stars. Cambridge Astrophysics, Cambridge University Press, doi: 10.1017/CBO9780511586491
Wilms J., Allen A., McCray R., 2000, ApJ, 542, 914
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