Observation of variable pre-eclipse dips and disk winds in the eclipsing LMXB XTE J1710-281

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ABSTRACT
We report the first detection of highly ionized Fe species in the X-ray spectrum of the eclipsing and dipping Low Mass X-ray Binary XTE J1710-281. Using archival Chandra and Suzaku observations, we have carried out a spectro-timing analysis of the source during three different epochs. We compare the average orbital profile and obtain differences in pre-eclipse dip morphologies between different observation epochs. We observe an orbit to orbit evolution of the dips for the first time in this source in both the Chandra observations, reflecting changes in the structure of the accretion disc in timescales of hours. We further perform intensity resolved spectroscopy for both the Chandra and the Suzaku data to characterize the changes in the spectral parameters from the persistent to the dipping intervals. We find that the absorbers responsible for the dips, can be best described using a partially ionized partial covering absorber, with an ionization parameter, \( \log(\xi) \) of \( \sim 2 \). The photon index of the source remained at \( \sim 2 \) during both the Chandra and the Suzaku observations. In the 0.6-9 keV Suzaku spectra, we detect a broad 0.72 keV Fe L-alpha emission line complex and two narrow absorption lines at \( \sim 6.60 \) keV and \( \sim 7.01 \) keV. The highly ionized Fe line signatures, being an indicator of accretion disc-winds, has been observed for the first time in XTE J1710-281.

Key words: X-rays: binaries, (stars:) binaries: eclipsing, stars: neutron, accretion, accretion discs

1 INTRODUCTION

Accreting Low Mass X-ray Binary (LMXB) systems contain a compact object in a binary configuration with a mass-donating low-mass companion star (Lewin & Clark 1980). A small subset of the total LMXB population that have high inclinations (\( i \sim 70-90^\circ \)) are the dipping and eclipsing sources (Díaz Trigo et al. 2006). Out of the thirteen LMXB dipping sources (dippers from now) that host a neutron star, six systems show complete eclipses (D’Ai et al. 2014). These systems present a variety of spectro-temporal signatures that allow efficient means of probing the accretion disc, it’s atmosphere and possible structures on it.

Absorbers responsible for producing the intensity dips are understood to be vertical structures present on the outer accretion disc, with asymmetric azimuthal distribution (White & Swank 1982; Boyin et al. 2005). Spectroscopic studies in a set of six dippers (EXO 0748-676, 4U 1254-690, 4U 1624-490, MXB 1659-298, 4U 1746-371 and 4U 1915-05) revealed that the spectral continuum during dips could be well described by simple ionized absorber models (Díaz Trigo et al. 2006).

High inclination systems have also been found to exhibit X-ray disc winds that are an important aspect in understanding the process of accretion/ejection, particularly in LMXBs (Miller et al. 2011, 2015; Ponti, Muñoz-Darias & Fender 2014). Disc-wind outflow signatures have been detected in the form of high ionization Fe absorption lines with large outflow velocities, in the soft spectral state (Neilsen & Lee 2009; Ponti et al. 2012). The fact that these absorption lines are seen only in high inclination sources indicate that these absorbers have an equatorial distribution. In both black hole as well as neutron star binaries, equatorial disc-wind outflow

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signatures have been detected only in their soft spectral state (Miller et al. 2011; Neilsen & Lee 2009; Ponti et al. 2012; Ponti, Muñoz-Darias & Fender 2014). Díaz Trigo et al. (2006) detected highly ionized Fe absorption lines (Fe XXV and Fe XXVI) in six high inclination dippers. Our current study focuses on one such high inclination LMXB, XTE J1710-281, with an aim to bring out important timing and spectral features in the source.

XTE J1710-281 is a transient eclipsing LMXB that was discovered in 1998 serendipitously, with RXTE (Markwardt et al. 1998). It is a highly inclined binary system viewed edge on with an inclination angle $i \sim 75\degree - 80\degree$ (Younes, Boirin & Sabha 2009). It shows X-ray eclipses every 3.28 hours with an average eclipse duration of $\sim 420$ s (Jain & Paul 2011). This LMXB also exhibits X-ray intensity dips. The discovery of Type 1 thermonuclear bursts indicated that the compact object is a neutron star and the distance to the source was constrained using the Type 1 bursts to be between 15-20 kpc (Markwardt, Swank & Strohmayer 2001). The spectrum measured with RXTE PCA was consistent with a thermal bremsstrahlung ($kT = 14 \pm 3$ keV) or a power law (photon index $1.8 \pm 0.1$), with an absorption column density $N_H < 2 \times 10^{22}$ cm$^{-2}$ (Markwardt et al. 1998). Younes, Boirin & Sabha (2009) reported spectral changes during dipping intervals using XMM-Newton observations in 2004 and compared the partial neutral absorber and ionized absorber models. Absorption lines due to ionized species like Fe XXV and Fe XXVI observed in other dippers (for example EXO 0748-676; Ponti, Muñoz-Darias & Fender 2014) were not detected in their 2004 XMM-Newton observation.

XTE J1710-281 resembles a well studied eclipsing source, EXO 0748-676 in many ways. Both are high inclination LMXBs that show frequent thermonuclear X-ray bursts and intensity dips in their light curves. EXO 0748-676 has an orbital period of 3.82 hr and displays pre-eclipse dips that vary significantly within short time-scales (Parmar et al. 1986; Raman & Paul 2017). Jain & Paul (2011) carried out extensive eclipse timing studies for XTE J1710-281 and reported two orbital period glitches which are similar to the period glitches observed in EXO 0748-676 (Wolff et al. 2009).

In this work we have analyzed archival data from Chandra and Suzaku for XTE J1710-281 to study the accretion disc dynamics in the context of the dip evolution and continuum spectral changes from persistent to dipping intervals. We then compare it with the eclipsing LMXBs, EXO 0748-676 and AX J1745.6-2901.

2 OBSERVATIONS AND DATA REDUCTION

We have analyzed archival X-ray observations of XTE J1710-281 from Chandra and Suzaku observatories, a summary of which, is presented in Table 1.

2.1 Chandra

XTE J1710-281 was observed with the Chandra X-ray Observatory (CXO; Weisskopf et al. 2002) on the 23rd of July and on the 7th of August, 2011. The archival data for each Obs ID (12468 and 12469) had an exposure of $\sim 75$ ks with the ACIS-S detector using the High Energy Transmission Grating Spectrometer (HETGS; Canizares et al. 2000). The data was processed using the CIAO software version 4.7. A level 2 dataset was produced using the chandra_repro script. The ACIS light curve and spectra were extracted within a source region of 4 arc seconds. The pile-up for Chandra observations were computed using the web PIMMS version 4.8. The ACIS-camera suffered from heavy photon pile-up ($\sim 65\%$) for the zeroth order and so the zeroth order data are not used for further analysis for these two Obs-IDs. All the subsequent analysis are done with Chandra first order HETG. The HETG first order grating spectra, arf and rmf were produced during the level 2 processing using the chandra_repro script. The combine_grating_spectra tool was used to produce a co-added grating spectrum for the plus and minus first order spectra of the HETG. The corresponding arf and rmf files were averaged. The spectra were rebinned to obtain a minimum of 50 counts per bin.

2.2 Suzaku

The X-ray Imaging Spectrometer (XIS) aboard Suzaku covers the energy range of 0.2-12 keV (Koyama et al. 2007). The three operational XIS detectors: XIS0, XIS1 and XIS2 have been used for this current analysis. The Suzaku obs-id 404068010 had a useful exposure of $\sim 75$ kilo-seconds. The XIS detectors were operated in the standard data mode with normal window operation that provided a timing resolution of 8 s. The unfiltered event files were reprocessed with the CALDB version 20160607 and HEASoft version 6.16. The XIS event files were checked for pile-up using the ftool ‘pileest’ and were found to be free from photon pile-up (less than 0.01%). The reprocessed event files were used to extract light curves and spectra from a circular region of 240 arc seconds around the source centroid. A circular region of the same size far away from the source centroid was selected for the background. Corresponding response file was generated using the ftool ‘xisresp’ using the CALDB mentioned above. In the case of Suzaku spectra, the spectra from the front illuminated CCDs (XISs 0 and 3), and the back illuminated CCD (XIS-1) were fit simultaneously in the energy range of 0.6-9 keV keeping the instrument normalizations free. Due to artificial structures in the XIS spectra around the Si and Au edge, the energy range of 1.7-2.3 keV was neglected. The XIS spectra were rebinned to contain 100 counts per bin.

1 http://cxc.harvard.edu/toolkit/pimms.jsp
Table 1. Table detailing the different observations used in the current analysis.

| Observatory | Obs-ID | Instrument | Date of Observation (MJD) | Exposure (ks) | No. of type-1 X-ray bursts |
|-------------|--------|------------|---------------------------|--------------|----------------------------|
| Chandra     | 12468  | HETG       | 23-07-2011 (55765)        | 75.1         | 7                          |
| Chandra     | 12469  | HETG       | 07-08-2011 (55780)        | 75.1         | 5                          |
| Suzaku      | 404068010 | XIS       | 23-03-2010 (55278)        | 76.1         | 6                          |

3 TIMING ANALYSIS

3.1 Light curve and average orbital profile

Since the ACIS zeroth order light curve was heavily piled up, we extracted HETG first order plus and minus arms light curves. Background subtracted and energy dependent (described in detail in section 3.3) first order light curves between 0.5 to 10 keV for *Chandra* Obs-IDs 12468 and 12469 were extracted with a bin size of 1.74 s and are plotted with a 200 s binning (Figure 1 top left and right panels). The light curves display more than 6 orbital cycles with sharp X-ray eclipses. X-ray intensity dips are seen to occur at orbital phases prior to the eclipse. The depth and width of the dips are seen to vary from one orbital cycle to the next, as described in detail in the next subsection. The first order light curves from both the *Chandra* observations also exhibit 7 and 5 type-1 bursts, respectively, as mentioned in Table 1.

We also extracted light curve for the *Suzaku* observation in the 0.5-10 keV energy band with a time bin size of 8 s and plotted it with a bin size of 100 seconds (Figure 1 bottom panel). The light curve contains large data gaps, with incomplete sampling of persistent, dipping and eclipsing intervals. The light curve shows a total of six thermonuclear X-ray bursts during this observation.

In order to compare the average orbital profile, specially the dip features between the different observations, we folded the light curves with the orbital period of 11812.66 s (Jain & Paul 2011), at a reference epoch of MJD 55278.29, 55762.79 and 55766.895 for the *Suzaku* observation and *Chandra* Obs-IDs 12468 and 12469, respectively. In order to exclude the thermonuclear bursts, time filters were applied to the light curves. These time windows were ~ 100 s in duration. The average orbital profile is shown in Figure 2 with dips covering the phase range 0.6-0.9. The *Chandra* Obs IDs 12468, 12469 and *Suzaku* light curves show slightly different folded orbital profile features. The duty cycle of a dip is defined as the duration of the dip as a fraction of the total orbital period. The pre-eclipse dips for the *Chandra* Obs-ID 12468 and *Suzaku* have duty cycle of nearly 40%, while for the *Chandra* Obs-ID 12469 it is nearly 30%. Along with the pre-eclipse dips, the *Suzaku* profile shows a bump at around phase 0.3, while the *Chandra* Obs-IDs 12468 and 12469 profiles show a less intense secondary dip at phase ~0.4 (duty cycle 10%).

3.2 Orbit to orbit evolution of dips

While examining the *Chandra* data, an orbit to orbit evolution of dips is seen for the first time in the source (Figure 3). The evolution of the depth and width in each subsequent orbit is clearly visible for both the observations. The pre-eclipse dip is observed to be with and without sub-structures in different orbital cycles. An earlier study of the dips made by Younes, Boirin & Sabra (2009) in 2004 using *XMM-Newton* also reported presence of narrow absorption dips in one single orbital cycle alone. For both the observations, the duty cycle of the dips range from about 10% to nearly 50%, possibly indicating variable absorber azimuthal distribution above the disc plane. The depth of the dips vary between 20%-90%, signifying variable absorber column density along our line-of-sight between successive orbital cycles. Unlike the light curves from the *Chandra* observations, the *Suzaku* light curve has data gaps. We cannot therefore investigate the dips in the light curve in successive orbits.

3.3 Energy dependence of dips

To investigate the energy dependence of the dips, we extracted background subtracted light curves in two energy bands: 0.5-5 keV and 5-10 keV for all the observations. Figure 1 shows the energy dependent intensity variations in the light curves for the three observations. The soft X-ray light curve shows more prominent dips as compared to the hard-X-ray band. As a result, the hardness ratio increases during the X-ray dips, with the deeper troughs showing an increased hardness ratio compared to the shallower one. Although the *Suzaku* observation has periodic large data gaps, a periodic increase in the hardness ratio with interval same as the orbital period indicate it to be due to the dips in the same orbital phase range as the *Chandra* light curves. The increase in hardness ratio during dipping intervals has been observed before by Younes, Boirin & Sabra (2009) using *XMM-Newton* observations for this source, and for other dipping sources like 4U 1254-690, 4U 1323-62, 4U 2127+11 etc. (Ioannou et al. 2002; Boirin et al. 2003; Díaz Trigo et al. 2009).

4 SPECTRAL ANALYSIS

4.1 Time averaged spectroscopy

We performed spectroscopy of XTE 1710-281 averaged over the entire stretch of the observations for the *Chandra* and *Suzaku* data. Spectral fitting was performed using *XSPEC*
Figure 1. Light curves from the first order HETG Chandra Obs-ID 12468 (top-left), 12469 (top-right) with a bin size of 200 s and Suzaku (bottom) with a bin size of 100 s are shown. The light curves, extracted in two energy bands, soft (0.5-5 keV) and hard (5-10 keV) are shown along with the hardness ratio in the bottom panel for all the three Obs-IDs. An increase in the hardness ratio is observed during dipping. Type-1 thermonuclear X-ray bursts are also observed in all the light curves.

(Arnaud 1996) version 12.8.1. The photo-electric cross-sections of Wilms, Allen & McCray (2000) have been used to model the line-of-sight absorption by neutral gas with solar abundances (the ‘TBabs’ XSPEC model). The cross section for X-ray absorption by the ISM is computed as the sum of the cross sections for X-ray absorption due to the gas-phase ISM, the grain-phase ISM, and the molecules in the ISM.

At first all the spectra were fitted with a powerlaw with a single absorption component accounting for the foreground absorption which includes the line of sight interstellar absorption as well as absorption local to the source. Fitting a simple power-law model to the Chandra observation 12468 resulted in a reduced chi-squared value of ~0.65. We therefore re-binned the spectrum to at least 1 count per bin and applied C-statistic which is appropriate for the quality of the data. The spectral fit with an absorbed power-law provided an acceptable fit with a C-stat/dof of 2305/3841 (Figure 2 top left panel).

In the case of the other Chandra (Obs-ID 12469) and Suzaku observation, the fit with a simple absorbed power-law proved to be unsatisfactory with large systematic residuals particularly in the energy range 1.2 - 2.0 keV. To account for this we added another absorption component in the form of a partial covering absorber. This can be explained due to absorption by local structures in the accretion disc (causing the pre-eclipse dips). We tried to fit the spectra with both a partial covering neutral absorber (XSPEC model ‘pcfabs’) and partial covering ionized absorber (XSPEC model ‘zxipcf’, Reeves et al. 2008). For the Chandra Obs-ID 12469, the addition of partial covering neutral absorber improved the $\chi^2$ by 12.1 (\Delta d.o.f. of 2) and the addition of partial covering partially ionized absorber improved the $\chi^2$ by 79.5 (\Delta d.o.f. of 3). In the case of the Suzaku observation, the reduction in $\chi^2$ obtained by adding the partial covering neutral and ionized absorber models, was 37 (\Delta d.o.f. of 2) and 50 (\Delta d.o.f. of 3), respectively. The fit with the ionized absorber model proved to be better both in terms of absence of systematic structures in the residuals and a lower value of reduced $\chi^2$. A power-law model with a partially ionized partial covering absorber model was therefore chosen as the
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This is probably a complex due to unresolved Fe L shell lines. Two additional weak absorption lines are observed at 6.60±0.03 keV and 7.01±0.03 keV. These two absorption lines were modeled using gaussian absorption model. The addition of the 0.72 keV feature improved the $\chi^2$ by 31, with the addition of 3 new parameters for a ∆d.o.f of 3. Further addition of the two absorption features at 6.6 keV and 7.01 keV progressively improved the $\chi^2$ by 23 (∆d.o.f of 3), and 7 (∆d.o.f of 3), respectively. The 6.6 keV line is detected with an equivalent width of 4.28±0.47 eV. The 7.01 keV absorption line, being not statistically significant is detected with an equivalent width of only $\sim$0.58±0.49 eV. The best fits for the time-averaged spectra after adding all the components gives a reduced $\chi^2$ of 1.10 for 566 d.o.f. for the Chandra Obs-ID 12469 spectrum and 0.95 for 599 d.o.f for the Suzaku spectrum.

Although we do not detect the $\sim$6.6 keV feature in the Chandra HETG spectrum, we cannot rule out their presence in the corresponding spectra. This is because, for the count rate of XTE J1710-281, these lines would be below the detection threshold of HETG considering its lower effective area w.r.t the XIS. In order to examine if such a feature would be detectable in the Chandra spectrum, a gaussian absorption feature (the 'gabs' model in XSPEC) was introduced at 6.60 keV, with the line energy and width fixed to the parameter values obtained in the Suzaku spectra. This model is, however, not statistically preferred (∆$\chi^2$ of 0.11 for ∆d.o.f of 3) as an additional component over the continuum. We therefore do not include it in the spectral fit.

Table 2 shows the best fit parameters along with the fluxes measured for the Chandra and Suzaku observations. Figure 1 shows the best-fit average HETG first order spectra for Chandra Obs ID 12469, and the XIS0 Suzaku spectra. The derived absorbed fluxes (0.5-8 keV) for the Chandra (Obs-ID 12468 and 12469) and the Suzaku observations in order are $5.14±0.20\times10^{-11}$ ergs s$^{-1}$ cm$^{-2}$, $7.94±0.10\times10^{-11}$ ergs s$^{-1}$ cm$^{-2}$ and $4.10±0.07\times10^{-11}$ ergs s$^{-1}$ cm$^{-2}$, respectively. The Chandra Obs-ID 12469 shows a steeper power law index and larger flux compared to the Chandra Obs-ID 12468 and Suzaku observation.

4.2 Intensity resolved spectroscopy

In order to probe the changes in the spectrum from the persistent and dipping intervals, we carried out an intensity resolved spectral analysis of the Chandra and Suzaku observations. In order to perform this exercise, we first excluded the intervals corresponding to thermonuclear bursts and eclipses. We then defined persistent and dipping intervals based on the count rate from the light curves of the corresponding observations. For the Chandra observations the persistent emission is seen to have an average count rate of 0.25 counts/s (Figure 1). Time intervals that had intensities below 75% of the average persistent count rate were

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Figure 4. The time averaged best fit spectra for Chandra Obs-ID 12468 (top-left), Obs-ID 12469 (top-right) and Suzaku (bottom) are shown. For the Chandra Obs-ID 12468 spectrum, the plot has been re-binned for visual clarity. In the Suzaku spectrum, the residuals are indicated without (top residual panel) and with (bottom residual panel) the 0.72 keV, 6.59 keV and 7.01 keV lines modelled.

Table 2. Best fit spectral parameters for time-averaged Chandra (Obs-IDs 12468 and 12469) HETG spectra and Suzaku XIS0 spectra. The errors are quoted at 90% confidence interval.\textsuperscript{a} Flux is measured from 0.5-8 keV
considered as dipping intervals. We then extracted spectra corresponding to those intervals. The Chandra intensity resolved spectra were grouped to contain 50 counts per energy bin. We did not carry out intensity resolved spectral analysis for the Chandra Obs-ID 12468 due to statistical limitations.

Since the Suzaku light curve contained incompletely sampled dips, it was not possible to identify dipping time intervals from the light curve. Therefore a count rate cut of 75% of the average persistent count rate (about 2 counts/s), similar to what was used for the Chandra analysis, was adopted to identify the dipping intervals. The corresponding spectra for the persistent and dipping intervals were extracted. A different grouping scheme was adopted for the persistent (minimum of 120 counts per bin) and dipping (minimum of 100 counts per bin) intervals, as compared to the time-averaged Suzaku spectrum to have comparable statistics. The same background and response files that were used to fit the persistent spectra were taken for the fits.

We consider the cause of the dipping activity to be absorption due to the passage of the vertical structures obscuring our view to the source (White & Swank 1982; Diaz Trigo et al. 2006). In this case we may assume that the underlying continuum spectrum does not change during the duration of the observation, and the spectral changes during the dipping intervals are solely due to the passage of this absorbing material along our line of sight. In order to demonstrate this we fit the persistent and the dipping spectra simultaneously linking the parameters of the continuum emission, i.e. the powerlaw component. The absorption components are left free. The persistent emission is not used for constraining the ionized absorber properties. We fix the energy and width of the emission and absorption lines and edges in the Chandra and Suzaku spectra to the corresponding values obtained in the average spectra.

In the case of the intensity resolved spectral fit for the Chandra Obs-ID 12469, the line-of-sight neutral hydrogen column density was fixed to the time-average value. This was because the errors obtained on this parameter, if left free for each component, was very large. The Chandra intensity resolved spectrum showed a residual, resembling an edge around 2.8±0.2 keV, which we have modeled using an edge model. This edge, possibly indicating the presence of S XVI, removes the residual and improves the fit (Δχ² 356.49 and Δdf of 3). The addition of this component in the time average spectrum only shows a small improvement in χ² (Δχ² of 5), making it a weak detection. We observe an increase in the column density of the ionized absorber and a decrease in the ionization state from the persistent to dipping spectra. A similar change in the ionized absorber parameters is observed for the intensity resolved Suzaku spectra as well. The column density of the ionized absorber increases from 0.36±0.15×10²²cm⁻² to 14.9±1.8×10²²cm⁻² and the ionization parameter shows a decrease from 2.6±0.2 to 1.45±0.1 as we go from the persistent to the dipping spectra. We fixed the 6.60 keV and 7.01 keV absorption line parameters, and the 0.72 keV broad emission line parameters to the time-averaged spectral parameter values. The best fit spectra for both the Chandra and Suzaku observations are shown in Figure 5 and Table 3 shows the best fit spectral parameters.

5 DISCUSSION

We have carried out spectro-temporal analysis of the dipping LMXB XTE J1710-281 using archival Chandra and Suzaku observations. We have observed evolution in the dip strength, duration and shape between successive orbital cycles, indicating evolution of the accretion disc structures in the timescale of hours. We have also detected highly ionized Fe species in the Suzaku spectra, which indicate signature of disk winds as observed in other dippers. The dip spectrum...
in Chandra and Suzaku observations is found to be best described by a power law component with a spectral index of Γ~2 with partial covering by a partially ionized absorber.

### 5.1 Evolution of the dips

High inclination LMXB sources exhibit intensity dips, which are usually characterized by increased spectral hardness (Díaz Trigo et al. 2009). These dips have been observed in some total eclipsing sources like EXO 0748-676, XTE J1710-281 and also in some partial eclipsing sources like 4U 2129+12 (Chou 2014). Recently Galloway et al. (2016) discovered, in the LMXB source Aql X-1, intermittent episodes of dipping, similar to those observed in high inclination binaries. Detailed characterization of dip parameters like the dip orbital phase, width and strength have been performed for many dippers, to extract information of orbital period and also dynamics of the accretion disc structures (Chou 2014; Chou & Grindlay 2001). Since dips are caused by absorption in the accretion disc structure, they are not exactly phase-locked, but they show phase jitters (e.g., ±0.05 cycle for 4U 1915-05, Chou & Grindlay 2001). In the case of XTE J1710-281 (Younes, Boirin & Sabra 2009 and the current work), on average, the dips are observed primarily at pre-eclipse orbital phases between the orbital phase range of 0.6-0.9. In the system EXO 0748-676, dips have also been seen at other orbital phases, even just after the eclipse (Raman & Paul 2017). A very interesting outcome of this current study of dips using Chandra observations is the evolving morphology from one orbital cycle to the next. The dip depth, width as well as shape (in terms of the number of narrow features present) are observed to vary. Irradiation-induced vertical structures (de Jong, van Paradijs & Augusteijn 1996; Pringle 1996), present usually at the outer accretion disc are azimuthally distributed in an asymmetric manner (Hakala et al. 2005). They are responsible for preferentially absorbing the primary X-ray photons at certain orbital epochs as was also observed in EXO 0748-676 (Parmar et al. 1986). The orbit-to-orbit dip profiles as seen in the Chandra light curves have different features, some are broad, some deep and some even have narrow features, similar to what was observed by Younes, Boirin & Sabra (2009) in the XMMS-Newton light curve. Nevertheless, the presence of varying dip intensities in successive orbital cycles in Chandra indicates not just any structure, but an evolving one. Warped discs also present a very physically compelling solution to explain different X-ray modulations in LMXBs (Ogilvie & Dubus 2001). These warps can develop at various disc-radii and can modulate the X-ray emission at certain orbital epochs. Another possible explanation for a hour-time-scale-varying dip morphology could be the variable mass accretion splashes at the stream-impact point on the outer accretion disc (White & Swank 1982). At these locations, the disc-extent increases vertically leading to temporary structures that block the primary X-ray photons from reaching the observer.

### 5.2 Detection of ionized species of Fe

The broad 0.72 keV emission line detected in the Suzaku spectrum, can be identified with an Fe L blend. It has an equivalent width of 93.03±66.98 eV. Owing to the fact that XTE J1710-281 is a relatively faint source, the Chandra spectrum does not have enough photons below 1 keV and was therefore not able to detect a line of similar strength. Line emission in the spectral energy range 0.7-2.0 keV, associated with the Fe L-shell ions, is understood to be a dominant spectral component arising in coronal plasmas (Liedahl, Osterheld & Goldstein 1995). Only ionized Fe ions (Fe XII and beyond) produce Fe L transitions that fall in the energy range 0.7-2 keV. In addition, two narrow, weak absorption lines are observed at 6.60 keV and 7.01 keV in the Suzaku spectrum (see Table 2). The absorption line at ~6.6 keV is most likely a blend of Fe XIX to Fe XXV lines (Díaz Trigo et al. 2006; Ponti, Muñoz-Darias & Fender 2014). Associating it to the nearest Fe XX-XXII transition at ~6.58 keV (Jiménez-Bailón et al. 2007), results in a blue-shifted velocity of 789 km/s (see for example as computed in King et al. 2014). Such blue-shifted velocities correspond to outflows such as disk wind as observed in several other disk accreting high inclination sources. The 7.01+/−0.03 keV is, however, only

| Parameter     | Model     | Chandra Obs-ID 12469 | Suzaku |
|---------------|-----------|----------------------|--------|
|               |           | Persistent | Dip       | Persistent | Dip       |
| nH\textsubscript{10}\textsuperscript{2}cm\textsuperscript{-2} | TBabs     | 0.72±0.02  | 0.23±0.01 | 0.17±0.06  |
| nH (10\textsuperscript{22}cm\textsuperscript{-2}) | zxipcf    | 12.9±0.1  | 65.6±0.15 | 14.9±0.1   |
| \text{log}(C) | zxipcf    | 3.43±0.57 | 1.85±0.15 | 2.6±0.15   |
| \text{Cov. f} | zxipcf    | 0.65±0.4  | 0.5±0.02  | 0.67±0.3   |
| Power law index | po      | 2.57±0.04  |         | 1.79±0.02  |
| E(keV)       | edge      | 2.8±0.2    |         |           |
| Max Tau      | edge      | 0.45±0.10  |         |           |
| red. \chi\textsuperscript{2} | for  | 0.92±0.3    | 1.13±0.3 | 581 d.o.f. |
|              |           |            |         | 375 d.o.f. |

Table 3. Best fit spectral parameters for intensity resolved Chandra (Obs-ID 12469) HETG spectra and Suzaku XIS0 spectra. The errors are quoted at 90% confidence interval. *Frozen to the time-averaged spectral parameter value.
marginally detected and we do not compute the velocities for this line. Such features at \( \sim 6.6 \text{ keV} \) have been observed in other NS LMXBs, for example 1B 1323-619, 1B 1916-053 (Diaz Trigo et al. 2006) [Boirin et al. 2005]. In their 2004 XMM-Newton observation of XTE J1710-281, Younes, Boirin & Sabra (2009) did not detect absorption lines due to ionized species like Fe XXIV, Fe XXV or Fe XXVI, that are commonly observed in other dippers (for example EXO 0748-676: Ponti, Muñoz-Darias & Fender 2014). However, they have derived upper limits on the equivalent width of the 6.6 keV absorption line corresponding to the Fe XXV 1s–2p transition, as 114, 50, and 73 eV in the persistent, shallow-dipping, and deep-dipping spectra, respectively.

We conservatively identify the edge feature at \( \sim 2.8 \text{ keV} \) in the Chandra spectra (within errors) as highly ionized Sulphur species, S XVI, which has been observed in Mr 2251-178 (Gelford et al. 2011), EXO 0748-676 Ponti, Muñoz-Darias & Fender 2014, GRS 1915+105 (Ueda, Yamaoka & Remillard 2009) and also in Cyg X-1 (Feng, Tennant & Zhang 2003). It is likely that, as seen in EXO 0748-676, the highly ionized absorber on the accretion disc, could be responsible for the S XVI absorption edge as well.

Such high ionization Fe lines are tracers for equatorial disc winds (Ponti, Muñoz-Darias & Fender 2014). The lines are suspected to be produced by absorption due to photo-ionized gas (Ponti et al. 2015). The Fe XXV Kα (E = 6.697 keV) and Fe XXVI Kα (E = 6.966 keV), as well as Fe XXV Kβ (E = 7.880 keV) absorption lines have been observed in three other eclipsing sources AX J1745.6-2901 (Hyodo et al. 2009), EXO 0748-676 (Ponti, Muñoz-Darias & Fender 2014) and IGR J17451-3022 (Bozzo et al. 2016), Hyodo et al. (2009) suggested a disc-corona origin for these lines in the source AX J1745.6-2901, since they were observed at all orbital phases. Other non-eclipsing, high inclination dippers like 4U 1254-690, 4U 1624-490 and MXB 1659-298 also show these features, suggesting an equatorial origin for these photo-ionized absorbing gas (Ponti, Muñoz-Darias & Fender 2014). In black hole binaries, these absorption features were found to have high outflow velocities and therefore were assumed to be equatorial winds (see Ponti et al. 2012 Ponti, Muñoz-Darias & Fender 2014).

In a recent review, Diaz Trigo & Boirin (2016) show that, from a total of 18 LMXBs exhibiting presence of photo-ionized plasma in the form of absorption lines of Fe XXV and Fe XXVI, 16 systems have highly ionized plasma (log(\( \xi \)) > 3). However, there are 4 systems that exhibit both high (log(\( \xi \)) > 3) and low (log(\( \xi \)) < 3) photo-ionization and two systems (MAXI J1305-704 and GX 339-4) that show only low photo-ionization. Results obtained from the Suzaku observation in this work, indicate that XTE J1710-281 could be one such system whose photo-ionized plasma has low ionization. Such photo-ionized plasma can be irradiation-induced, or even be the result of thermal or magnetic instabilities, etc.

### 5.3 Nature of the absorber

Various models have been proposed to explain the continuum emission in dippers. In order to particularly describe the comptonized component, a number of single and multi-component continuum powerlaw models have been previously explored. One set of models (Boirin et al. 2005 Diaz Trigo et al. 2006) incorporate a neutral or ionized absorber partially or completely covering the power law as well as the blackbody emission during dips. These models explain the dip spectra in sources like 4U 1323-62, EXO 0748-676 and 4U 1254-690. Another set of models (Parmar et al. 1985 Bonnet-Bidaud et al. 2001 Oosterbroek et al. 2001 Younes, Boirin & Sabra 2009) incorporate two-components. In these models, one fraction of the power law component is partially covered by an ionized or a neutral absorber and the remaining fraction is left uncovered. These models have been invoked to describe the dipping spectra in EXO 0748-676. Finally, the third set of models are the complex-continuum models (Church et al. 1998 Balucinska-Church et al. 1999). These models require two independent absorbing components, one for the extended comptonized power-law emission and another, for the point-like blackbody emission. Again, these complex models allow for neutral as well as ionized absorbers for the comptonized continuum component. Dippers like 4U 1323-62 were modeled in this manner (Boirin et al. 2005).

In the case of XTE J1710-281, the spectral properties of the dips are well described by an ionized absorber that partially obscures the non-thermal emission and does not require us to invoke other complicated models.

Considering that the ionized absorber is located at the outer accretion disc, we can compute the ratio of thickness \( d \), of a slab of the absorber, with respect to the distance \( r \), between the ionizing source and the absorber. For this, we consider the circularization radius to be the minimum possible value for the accretion disc radius, \( r \), and compute it using equation (4.21) (Frank, King & Raine 1992) for a system with mass ratio, \( q=0.3 \). We obtain \( R_{\text{circ}} \sim 0.32R_\odot \).

Since \( \xi = L/n_e r^2 \), and \( n_e \sim n_H e^{x_{\text{ion}}/f} / d \), we compute the ratio,

\[
\frac{d}{r} = \frac{r \times \xi \times n_H^{x_{\text{ion}}/f}}{L}
\]

where, \( \xi \) is the ionization parameter, \( L \) is the source luminosity, \( n_H \) is the electron number density and \( n_H^{x_{\text{ion}}/f} \) is the ionized absorber column density. Assuming a distance of 15 kpc to the source (Markwardt, Swank & Strohmayer 2001) and a considering a flux of \( 7.9 \times 10^{-12} \text{ ergs/s/cm}^{-2} \) (Table 2), we obtain a source luminosity of \( 2 \times 10^{38} \text{ ergs/s} \). This gives us a \( d/r \) ratio of 0.03 and 0.007 for the persistent and dipping intervals, respectively.

Also, there is strong reason to believe that the absorber responsible for the X-ray intensity dips, also causes the Fe line absorptions as well, mainly because these lines are observed...
Suzaku winds in the material. We have detected signatures of accretion disc using a power-law that is partially absorbed by ionized Chandra and time-scales as short as a few hours. The intensity resolved indicating accretion disc structures, which seem to evolve in an evolution of the dip morphology from orbit-to-orbit, we detect the presence of an absorption edge at 2.8 ± emission line complex at 0.72 keV. In the Chandra ∼ absorptions at 5 keV, corresponding to the highly ionized S XVI species. Fe strengths in these different intensity epochs (persistent and dipping), can allow us to probe the absorber characteristics. For example, lines detected during the dips, correspond to electronic transitions from less ionized species than during the weak line depths and statistical limitations of the dataset.

6 CONCLUSIONS

We have studied the eclipsing NS X-ray binary XTE J1710-281 using archival Chandra and Suzaku observations. Using Chandra folded orbital profiles, we detected an evolution of the dip morphology from orbit-to-orbit, indicating accretion disc structures, which seem to evolve in time-scales as short as a few hours. The intensity resolved Chandra and Suzaku continuum spectra are best described using a power-law that is partially absorbed by ionized material. We have detected signatures of accretion disc winds in the Suzaku spectra, in the form of highly ionized Fe absorption lines at ~6.60 keV and ~7.01 keV and a broad Fe emission line complex at 0.72 keV. In the Chandra spectra, we detect the presence of an absorption edge at 2.8±0.2 keV, corresponding to the highly ionized S XVI species. Fe lines are detected only in Suzaku spectrum, but we cannot rule out their presence in the Chandra observation (as we mention) and in the XMM-Newton (as Younes, Boirin & Sabra [2009] mention). There is no clear correlation between the flux, shape of the continuum and presence/absence of lines in these observations. The shape of the continuum is consistent between the different observations: the case of the XMM-Newton observation (Younes, Boirin & Sabra [2009]), and also for the case of Chandra and Suzaku observations (present work). Future observations of this object will help understand the distribution of ionized matter on the accretion disc and disc structure evolution scenarios better.

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