X-RAY SPECTROSCOPY OF THE HIGH-MASS X-RAY BINARY PULSAR CENTAURUS X-3 OVER ITS BINARY ORBIT

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ABSTRACT

We present a comprehensive spectral analysis of the high-mass X-ray binary (HMXB) pulsar Centaurus X-3 with the Suzaku observatory covering nearly one orbital period. The light curve shows the presence of extended dips which are rarely seen in HMXBs. These dips are seen up to as high as $\sim$40 keV. The pulsar spectra during the eclipse, out-of-eclipse, and dips are found to be well described by a partial covering power-law model with high-energy cutoff and three Gaussian functions for 6.4 keV, 6.7 keV, and 6.97 keV iron emission lines. The dips in the light curve can be explained by the presence of an additional absorption component with high column density and covering fraction, the values of which are not significant during the rest of the orbital phases. The iron line parameters during the dips and eclipse are significantly different compared to those during the rest of the observation. During the dips, the iron line intensities are found to be lesser by a factor of 2–3 with a significant increase in the line equivalent widths. However, the continuum flux at the corresponding orbital phase is estimated to be lesser by more than an order of magnitude. Similarities in the changes in the iron line flux and equivalent widths during the dips and eclipse segments suggest that the dipping activity in Cen X-3 is caused by an obscuration of the neutron star by dense matter, probably structures in the outer region of the accretion disk, as in the case of dipping low-mass X-ray binaries.

Key words: pulsars: individual (Cen X-3) – stars: neutron – X-rays: stars

1. INTRODUCTION

Orbital-phase-dependent dipping activity in X-ray binaries is believed to be caused by the obscuration of X-rays from the compact object by structures located in the outer regions of the disk particularly believed to be impact region of the accretion flow from the binary companion (White & Swank 1999; Narita et al. 2003; Bałma 2009, and references therein). This approach explains the spectral changes during the dipping intervals by the partial and progressive covering by an opaque neutral absorber. It is found that the dipping activities in the X-ray intensity are very common in LMXBs (Parmar et al. 1997). This approach explains the spectral changes during the dipping intervals by the partial and progressive covering by an opaque neutral absorber. It is found that the dipping activities in the X-ray intensity are very common in LMXBs (Parmar et al. 1997). The dips in 4U 1907+09 during which the X-ray intensity faded below the detection threshold of the RXTE/Proportional Counter Array. These dips in 4U 1907+09 are interpreted as being due to the cessations of the mass accretion by the neutron star (in’t Zand et al. 1997). The dips in Vela X-1 are described as the onset of the propeller effect, which inhibits further mass accretion from the binary companion (Kreykenbohm et al. 2008). These are the only known HMXB pulsars showing the presence of intensity dip in the X-ray light curve. Here in this paper, we discuss the presence of several intensity dips in the X-ray light curve of another HMXB pulsar Cen X-3 during its orbit using data from Suzaku observatory.

Cen X-3 was the first binary pulsar to be discovered in X-rays (Giacconi et al. 1971). It is an eclipsing HMXB pulsar with a pulse period of $\sim$4.8 s and an orbital period of $\sim$2.1 days (Schreier et al. 1972). The binary system consists of a neutron star with a mass of $1.21 \pm 0.21 M_\odot$ accompanied by an O 6–8 III supergiant star (V779 Cen) with a mass and radius of $20.5 \pm 0.7 M_\odot$ and 12 $R_\odot$, respectively (Hutchings et al. 1979; Rappaport & Joss 1983; Ash et al. 1999). The distance to the binary system was earlier estimated to be $\sim$8 kpc (Krzeminski 1974). However, using the energy-resolved dust-scattered X-ray halo, Thompson & Rothschild (2009) estimated the distance to Cen X-3 to be $5.7 \pm 1.5$ kpc. The high luminosity of the X-ray source ($\sim5.0 \times 10^{37}$ erg s$^{-1}$; Suchy et al. 2008) suggests that the predominant mode of accretion is via a disk, fed by incipient Roche lobe overflow, although a strong stellar wind
does emanate from the supergiant (Nagase et al. 1992; Day & Stevens 1993). The optical light curve (Tjemkes et al. 1986) supports the presence of an accretion disk, fed by Roche lobe overflow. Furthermore, quasi-periodic oscillations observed at \( \sim 40 \) mHz (Takeshima et al. 1991; Raichur & Paul 2008a) strengthen the case for the presence of an accretion disk.

The broadband (0.12–100 keV) out-of-eclipse pulse-phase-averaged spectrum of Cen X-3 is generally described by an absorbed power law plus a broad iron emission line at \( \sim 6.7 \) keV along with a high-energy cutoff at \( \sim 14 \) keV (Santangelo et al. 1998). A soft excess found in the spectrum below 1 keV has been interpreted as a blackbody with \( kT \sim 0.1 \) keV (Burderi et al. 2000) that is now known to be present in many binary X-ray pulsars (Paul et al. 2002; Naik & Paul 2004a, 2004b, and references therein). A cyclotron resonance feature at \( \sim 28 \) keV has also been detected and the corresponding magnetic field is \( \sim (2.4-3.0) \times 10^{12} \) G (Santangelo et al. 1998). A number of emission lines are expected in the X-ray spectrum of this source due to its high luminosity (\( \sim 10^{35} \)–\( 10^{37} \) erg s\(^{-1}\)) and the presence of a strong stellar wind from the companion star (Ebisawa et al. 1996; Wojdowski et al. 2003; Iaria et al. 2005). Investigation of emission lines, in particular iron lines in the 6.4–7.1 keV energy range, at different orbital phases provides significant information on the physical condition of the system. It is understood that the 6.4 keV iron emission line is due to fluorescence of cold material close to the neutron stars (Nagase 1989), whereas the 6.7 keV and 6.9 keV lines are considered to be originated in the highly photoionized accretion disk corona (Kallman & White 1989). ASCA observation of Cen X-3 clearly resolved three iron emission lines at 6.4 keV, 6.7 keV, and 6.9 keV during the eclipse and out-of-eclipse data. The line parameters during the eclipse and out-of-eclipse data confirmed that the 6.4 keV fluorescent line is emitted from the region close to the neutron star, whereas the highly photoionized plasma that emits 6.7 and 6.9 keV lines is more extended than the size of the companion star (Ebisawa et al. 1996).

In the present work, we have carried out an extensive spectral analysis of the Suzaku observation of the HMXB pulsar Cen X-3 covering the eclipse, out-of-eclipse and the rarely observed dipping activity. For this purpose, we describe the observations, data analysis, and results in the following section. Then in the next section, we discuss the results.

2. OBSERVATION, ANALYSIS, AND RESULTS

Cen X-3 was observed with the Suzaku satellite from 2008 December 8 06:55:36 to 2008 December 10 05:00:19 using the X-ray Imaging Spectrometers (XISs), Hard X-ray Detectors (HXD)/PIN, and HXD/GSO detectors. The observation has a total integration time of 97.587 ks. The Suzaku, the fifth Japanese X-ray astronomy satellite (Mitsuda et al. 2007), covers the 0.2–600 keV energy range with the two sets of instruments, XISs covering the 0.2–12 keV energy range and the HXD which covers 10–70 keV with PIN diodes and 30–600 keV with GSO scintillators. Among the four sets of XISs, XIS-1 is back illuminated (BI), whereas XIS-0, XIS-2, and XIS-3 are front illuminated (FI). The field of view of the XIS is \( 18^\circ \times 18^\circ \) in a full window mode with an effective area of 340 cm\(^2\) (FI) and 390 cm\(^2\) (BI) at 1.5 keV. The HXD is a non-imaging instrument that is designed to detect high-energy X-rays. The effective areas of PIN and GSO detectors are \( \sim 145 \) cm\(^2\) at 15 keV and 315 cm\(^2\) at 100 keV, respectively. For a detailed description of the XIS and HXD detectors, refer to Koyama et al. (2007) and Takahashi et al. (2007). Cen X-3 was observed in the HXD nominal mode. As XIS-2 is no longer operational, data from the other three XISs are used in the present analysis.

We used public data (ver-2.2.11.22) from a Suzaku observation of the pulsar in the present work. We used heasoft6.5.1 for our analysis. FTOOLS packages such as PIN-hxdtimexdspxdphaxgredxis-xispihxsiscleanhxdgrade were applied to the unfiltered event files with standard screening criteria to create cleaned XIS and PIN event files. The effective exposures, after applying the dead time corrections to the XIS and HXD/PIN data, are found to be 48.452 ks and 79.656 ks, respectively. Barycentric correction was then applied to the reprocessed XIS and PIN event files using the aebarycen task of FTOOLS. A quick tuned (bgd) non-X-ray background was used for HXD/PIN. A good time interval file was generated for the processed PIN data using the above background file. For XISs, the source region was selected using rectangular box regions in such a way so that it covered the entire source. The background region for XISs is generated by selecting a region far away from the source. The response file, released in 2008 July 16, was used for HXD/PIN. The ancillary response file and redistribution matrix file for XISs were generated using xissimarfgen and xisrmfits of FTOOLS, respectively.

Light curves were extracted from the processed event files for PIN and XISs using the standard procedures with 4 s and 100 s resolutions. Figure 1 shows the XIS-0 and HXD/PIN light curves with 100 s time resolution. From the figure, it is found that the light curves contain distinctive features of eclipsing, out-of-eclipse phase and dips. This compelled us to carry out the time-resolved spectroscopy of the source in these regions. Source and background spectra were extracted from the processed event data for three XISs and PIN. A dead time correction (the ftool task hxdtcor) was applied to the PIN source spectrum. To determine the start and end of the eclipse, we folded the light curves obtained from the RXTE/ASM dwell data and the Suzaku HXD/PIN event data using the orbital period of 2.08706 days (Raichur & Paul 2008b). It is found that the eclipse covers a ~0.2 orbital phase range (~0.42 days; Raichur & Paul 2008b) of the binary system. We figured out that the eclipse in the Suzaku observation was at the beginning and end of the observation (marked by horizontal lines in both panels of Figure 1). Apart from these two eclipsing parts in the light curve, there are several other low X-ray flux regions which are dips. Light curves at different energy bands were extracted and after appropriate background subtraction are plotted together in Figure 2. From the figure, it can be seen that the dipping feature in the light curve is present up to ~40 keV beyond which the light curve seems to be featureless.

To understand and compare the properties of the X-ray source during the dips, eclipse, and the rest of the regions, the entire light curve was divided into different segments, viz., eclipse, eclipse-ingress, eclipse-egress, high count rate region, dip-ingress, dip-egress, etc. The light curve showing the various segments is plotted in Figure 3. Each letter in the figure represents a certain duration for which the spectral analysis was carried out. We extracted XISs and HXD/PIN source spectra for all segments by applying suitable time filters (as shown in Figure 3) in xselect. These spectra contain two eclipses, three dips, four egresses, five ingresses, six high count regions, and two bumps with different exposure time and count rates. Dead time corrections were applied to all of the 22 HXD/PIN spectra. After appropriate background subtraction, simultaneous spectral fitting was performed using the XIS and PIN spectra.
Figure 1. Light curves (with 100 s binning time) obtained from the Suzaku observation of the high-mass X-ray binary pulsar Cen X-3. Data from XIS-0 and HXD/PIN detectors are plotted here. The observation was carried out covering nearly the entire orbit of the pulsar. The horizontal lines in the beginning and end of the XIS and PIN light curves in both the panels show the duration of eclipse covered during the Suzaku observation.

Figure 2. Light curve (with 200 s binning time) obtained from the Suzaku observation of the high-mass X-ray binary pulsar Cen X-3. Data from XIS-0 and HXD/PIN detectors are plotted here. The observation was carried out covering nearly the entire orbit of the pulsar.

with XSPEC V12. All of the spectral parameters other than the relative normalization were tied together for all of the detectors. Because an artificial structure is known to exist in the XIS spectra at around the Si edge, we ignored energy bins between 1.75 and 1.85 keV in the spectral analysis. Apart from the Si edge, large fit residuals due to calibration uncertainties are often observed near the edge structures of the XIS/X-ray telescope instrumental responses. Therefore, additional model components for possible fluorescence lines at energies below ~3.5 keV are not considered during the spectral fitting. The
relative instrument normalizations of the three XISs and PIN detectors were kept free and the values are found to be in agreement with that at the time of detector calibration.

In order to evaluate the spectra during the eclipses and dips in the light curve in a model-independent manner, we normalized them to that of the high count rate segment (out-of-eclipse and non-dip region). The resulting ratios in XIS and HXD/PIN energy bands are presented in Figure 4. For simplicity, we only used XIS-0 data to obtain the spectral ratio and plotted it in the figure. The ratios in XIS energy band indicate the enhancement in the equivalent width of three iron emission lines during the eclipses and dips in the light curve compared to the high count rate segment. Apart from the iron emission lines, the ratios also indicate some changes in the shape of the continuum. The ratios in the HXD/PIN energy band (right panels of Figure 4) show that the photons up to $\sim40$ keV are affected by the absorption/obscuration during the dips (bottom two panels) in the light curve. During the eclipse segments, however, the photons in the entire energy band are affected in the same manner as the ratios (top two panels) and are more or less constant.

To quantify the inference from Figure 4, we carried out a simultaneous spectral fitting of the XIS and PIN data during the high X-ray count rate region to find a suitable model explaining the spectral features in the source. The broadband energy spectra (in the 0.8–70 keV energy range) were fitted with a model consisting of a power-law continuum component modified with edge and high-energy cutoff along with the interstellar absorption, and a Gaussian function for the iron fluorescence line at 6.4 keV. The presence of line-like features in the residuals at 6.7 keV and 6.9 keV allowed us to add two more Gaussian functions with the spectral model. Initially, we ignored data below 4 keV. A cyclotron resonance feature at $\sim30$ keV was also found in the spectral fitting. However, as the cyclotron features in this pulsar will be presented elsewhere, no further discussion is made here.
we concentrated on the variation of other spectral parameters at different X-ray intensity phases over the binary orbit. Although the above model, with the cyclotron resonance feature, fitted well to the high count rate spectra, there was inconsistency in the value of other spectral parameters during several other segments where the values of high-energy cutoff and folding energy are found to be $<4$ keV, i.e., beyond the fitted energy band with the power-law photon index significantly different to that during the high count rate segments. Therefore, the above model was not suitable for the spectral fitting to the spectra of all the segments.

We then tried to explore other continuum models to get a better fit to the broadband spectrum of Cen X-3. In the process, we found that a partially covering high-energy cutoff power-law continuum model (as in other cases; Naik et al. 2011, and references therein), along with three Gaussian functions, Galactic absorption, and the cyclotron resonance feature, fits the pulsar spectrum with acceptable parameters for the spectra of all segments. The partial covering model consists of two power-law continua with a common photon index, but with different absorbing hydrogen column densities. Once we found the suitable continuum model, we extended the fitting to low energies ($\sim 0.8$ keV) and estimated the spectral parameters for all segments. The time-resolved count rate spectra, along with the best-fit model components, of the pulsar Cen X-3 are shown in Figure 5 for eclipse (A and V), eclipse-egress (B), high count rate segments (D and F), dip (K, P, and T), and dip-ingress (O) segments (as shown in Figure 3). In the figure, the iron emission lines are found to be most prominent during the dips and eclipse segments.

The best-fit parameters obtained from the simultaneous spectral fitting to the XIS and PIN data for all segments (as given in Figure 3) of the Suzaku observation of Cen X-3 are given in Table 1. The values of the additional absorption column density ($N_{\text{H2}}$) are found to vary in a wide range starting from $\sim 10^{22}$ atoms cm$^{-2}$ to $132 \times 10^{22}$ atoms cm$^{-2}$. The significantly high values of $N_{\text{H2}}$, along with the corresponding covering fractions during dips and the eclipse segments in the light curve, are understood to be because of the obscuration/absorption of the X-ray photons from the pulsar by dense matter along the line of sight. Apart from the significantly high value of $N_{\text{H2}}$ and covering fractions at the dips and eclipse segments, the iron emission line parameters are also observed to be very different from those during the high count rate segments. The change in values of

![Figure 5](https://example.com/figure5.png)
### Table 1

| Spec. | $N_{\text{H}1}$ | $N_{\text{H}2}$ | Cov. | Photon | 6.4 KeV Line | 6.7 KeV Line | 6.97 KeV Line |
|-------|-----------------|-----------------|------|--------|-------------|-------------|--------------|
|       | Fraction | Index | Flux$^a$ | Eqwb$^b$ | Flux$^a$ | Eqwb$^b$ | Flux$^a$ | Eqwb$^b$ |
| A     | 1.06 ± 0.03    | 88.1 ± 3.0     | 0.94 ± 0.01 | 2.03 ± 0.02 | 0.30 ± 0.03 | 0.43 ± 0.05 | 0.20 ± 0.02 | 0.26 ± 0.03 |
| B     | 0.50 ± 0.04    | 32.4 ± 0.6     | 0.96 ± 0.43 | 0.89 ± 0.05 | 0.50 ± 0.11 | 0.08 ± 0.02 | 0.24 ± 0.11 | 0.03 ± 0.02 |
| C     | 2.63 ± 0.03    | 3.9 ± 0.2      | 0.54 ± 0.01 | 0.96 ± 0.01 | 1.80 ± 0.16 | 0.08 ± 0.01 | 0.43 ± 0.17 | 0.02 ± 0.01 |
| D     | 1.43 ± 0.01    | 2.3 ± 0.1      | 0.64 ± 0.01 | 0.90 ± 0.01 | 2.55 ± 0.01 | 0.08 ± 0.01 | 1.29 ± 0.09 | 0.04 ± 0.01 |
| E     | 1.01 ± 0.01    | 0.9 ± 0.1      | 0.57 ± 0.01 | 0.10 ± 0.01 | 3.55 ± 0.10 | 0.07 ± 0.01 | 2.69 ± 0.10 | 0.06 ± 0.01 |
| F     | 1.13 ± 0.01    | 1.1 ± 0.1      | 0.34 ± 0.01 | 0.10 ± 0.01 | 3.78 ± 0.18 | 0.08 ± 0.01 | 1.92 ± 0.13 | 0.04 ± 0.01 |
| G     | 1.13 ± 0.01    | 0.9 ± 0.1      | 0.29 ± 0.01 | 0.10 ± 0.01 | 3.32 ± 0.12 | 0.09 ± 0.01 | 1.85 ± 0.13 | 0.05 ± 0.01 |
| H     | 1.09 ± 0.01    | 1.2 ± 0.2      | 0.39 ± 0.01 | 0.98 ± 0.01 | 3.74 ± 0.14 | 0.10 ± 0.01 | 1.68 ± 0.19 | 0.04 ± 0.01 |
| I     | 1.30 ± 0.01    | 3.8 ± 0.3      | 0.34 ± 0.01 | 0.83 ± 0.01 | 4.12 ± 0.30 | 0.10 ± 0.01 | 0.87 ± 0.29 | 0.02 ± 0.01 |
| J     | 1.11 ± 0.02    | 3.6 ± 0.4      | 0.32 ± 0.01 | 0.88 ± 0.01 | 2.11 ± 0.18 | 0.16 ± 0.01 | 0.42 ± 0.13 | 0.03 ± 0.01 |
| K     | 0.95 ± 0.02    | 59.8 ± 1.0     | 0.86 ± 0.01 | 1.20 ± 0.01 | 1.23 ± 0.05 | 0.28 ± 0.01 | 0.43 ± 0.06 | 0.09 ± 0.01 |
| L     | 1.17 ± 0.03    | 9.7 ± 0.3      | 0.75 ± 0.01 | 0.74 ± 0.01 | 3.63 ± 0.20 | 0.22 ± 0.01 | 1.60 ± 0.19 | 0.09 ± 0.01 |
| M     | 1.04 ± 0.01    | 1.9 ± 0.2      | 0.28 ± 0.01 | 0.84 ± 0.01 | 5.19 ± 0.30 | 0.17 ± 0.01 | 2.62 ± 0.29 | 0.08 ± 0.01 |
| N     | 1.18 ± 0.01    | 2.2 ± 0.2      | 0.35 ± 0.01 | 1.10 ± 0.01 | 2.89 ± 0.26 | 0.08 ± 0.01 | 1.28 ± 0.33 | 0.04 ± 0.01 |
| O     | 1.29 ± 0.02    | 92.9 ± 5.4     | 0.47 ± 0.01 | 1.01 ± 0.01 | 1.30 ± 0.15 | 0.11 ± 0.01 | 0.21 ± 0.11 | 0.02 ± 0.01 |
| P     | 0.92 ± 0.01    | 79.2 ± 1.9     | 0.84 ± 0.01 | 1.32 ± 0.01 | 0.94 ± 0.04 | 0.38 ± 0.02 | 0.32 ± 0.03 | 0.12 ± 0.01 |
| Q     | 0.80 ± 0.02    | 56.3 ± 0.7     | 0.91 ± 0.01 | 0.92 ± 0.01 | 1.23 ± 0.05 | 0.21 ± 0.01 | 0.57 ± 0.04 | 0.09 ± 0.01 |
| S     | 0.85 ± 0.04    | 33.9 ± 0.8     | 0.88 ± 0.01 | 0.58 ± 0.01 | 1.61 ± 0.12 | 0.18 ± 0.01 | 1.10 ± 0.20 | 0.12 ± 0.02 |
| T     | 0.65 ± 0.02    | 85.0 ± 1.1     | 0.96 ± 0.26 | 1.31 ± 0.01 | 0.51 ± 0.03 | 0.24 ± 0.02 | 0.24 ± 0.04 | 0.10 ± 0.02 |
| U     | 0.66 ± 0.04    | 84.9 ± 1.9     | 0.96 ± 0.45 | 0.83 ± 0.02 | 0.62 ± 0.04 | 0.34 ± 0.02 | 0.28 ± 0.06 | 0.13 ± 0.03 |
| V     | 1.34 ± 0.04    | 132.2 ± 4.5    | 0.97 ± 0.64 | 2.89 ± 0.03 | 0.10 ± 0.02 | 0.39 ± 0.06 | 0.10 ± 0.02 | 0.35 ± 0.06 |

| V$^c$ | 1.05 ± 0.05 | ... | ... | 2.38 ± 0.07 | 0.14 ± 0.01 | 0.46 ± 0.02 | 0.14 ± 0.01 | 0.32 ± 0.01 |

Notes. $N_{\text{H}1}$: equivalent hydrogen column density (in $10^{22}$ units). $N_{\text{H}2}$: additional hydrogen column density (in $10^{22}$ units).

* In $10^{-11}$ erg cm$^{-2}$ s$^{-1}$ unit.

$^b$ Equivalent width (in keV).

$^c$ Best-fit parameters obtained by fitting the eclipse spectrum (segment “V”) by using a high-energy cutoff power-law model with interstellar absorption and three Gaussian functions for the three iron emission lines.

$N_{\text{H}2}$, covering fraction and the power-law photon index over the orbital phase of the pulsar during the Suzaku observation are shown in Figure 6. In the figure, the mid-eclipse time (derived from the orbital parameters given in Table 1 of Paul et al. 2005) is considered as phase zero. From Table 1 and Figure 6, it can be seen that the values of $N_{\text{H}2}$ and the covering fraction for the spectral segment “O” are different from that of during the dips/ eclipse segments or high count rate segments. The value of $N_{\text{H}2}$ is high and found to be comparable to that in the next segment, which is a dip. But the covering fraction is only about ~0.5. This is consistent with the scenario of progressive covering.

The dependence of the three iron $K_{\alpha}$ emission line intensities and equivalent widths on the X-ray intensity at different segments of the orbit is shown in Figure 7. It is found that the line intensities are minimum during the eclipse segments. During the dips, the lines are comparatively more intense than during the eclipse segments, the line flux is significantly low compared to the high count rate segments. The equivalent width of the 6.4 keV line during the dips is found to be comparable to that during the eclipse segments which is ~400 eV. However, the equivalent width of the 6.7 and 6.97 keV lines during dips was significantly low compared to that during the eclipse segments. These results suggest that the iron emission line parameters during the dip evolve due to a progressive covering. Compared to the 6.4 keV line, the 6.7 and 6.97 keV lines evolve slightly differently as they originate further away from the neutron star. This indicates that the dipping activity during the Suzaku observation of Cen X-3 is possibly because of the presence of structures in the outer region of the accretion disk, as seen in LMXB systems.

![Figure 6](image_url)
Table 1 and Figure 6 show that the source spectrum during the eclipse segments (“A” and “V” in Figure 3) is steep compared to the rest of the binary phases; the power-law photon index is as high as 3, whereas during the other segments it is $\sim$1. We attempted to fit the eclipse spectrum using a high-energy cutoff power-law model with interstellar absorption and three Gaussian functions for the iron emission lines. The best-fit parameters for the simultaneous spectral fitting to the eclipse data using this model are given in the last line of Table 1. The high value of power-law index during the eclipse compared to the rest of the orbital phases is seen in earlier observations of Cen X-3 (Thompson & Rothschild 2009, and references therein). Similar changes in the spectral slope during the eclipse and the rest of the binary phases are also seen in 4U 1538-52 (Robba et al. 2001). The observed spectral steepness during the eclipse of these objects is attributed to the interstellar dust scattering. Numerous studies of the eclipse and out-of-eclipse spectra of these types of objects found that the dust-scattered component has a spectrum that is steeper by a factor proportional to $E^{-2}$ that affects the eclipse spectrum most (Nagase et al. 2001; Robba et al. 2001; Clark 2004; Thompson & Rothschild 2009).

3. DISCUSSION

The HMXB pulsar Cen X-3, though, has been observed at many different epochs with various observatories. Suzaku observation of the pulsar in 2008 December 8–10 is one of the longest imaging spectroscopic observation. This observation covers almost the entire orbital period of the binary system. Significant flux variation over the orbit has been seen in the X-ray light curve of the pulsar. The presence of dips in the light curve which is common in the LMXBs and rare in HMXBs is the key feature of the observation. A detailed orbital-phase-resolved spectroscopy of the pulsar in wide X-ray band is, therefore, very important to understand the properties of the binary system.

Selection of an appropriate continuum model is important to investigate the presence of several features such as the soft excess represented by a blackbody component, emission lines, cyclotron absorption features, etc., in the X-ray binary pulsar spectrum. The phenomenological model which has been commonly used to describe the continuum spectra of X-ray binary pulsars is a combination of a power law of photon index $\sim$1, a blackbody component with a temperature of a few hundred eV, and a high-energy cutoff above 10 keV. Over and above, there are emission lines from ions and broad absorption lines due to cyclotron resonances (Orlandini 2006). In the case of a few other X-ray binary pulsars, it has been reported that the absorption has two different components (Endo et al. 2000; Mukherjee & Paul 2004; Naik et al. 2011, and references therein). In this model, one absorption component absorbs the entire spectrum, whereas the other component absorbs the spectrum partially. This model is known as the partial covering absorption model. Although the power law with a high-energy cutoff model explains the pulse-phase-averaged pulsar spectra well, it runs into problems while fitting the spectra during the dip phases of pulsars showing dips or dip-like features in the pulse profiles. However, the partial absorption model fits very well to all pulse-phase-resolved spectra of these pulsars (Her...
power laws, respectively. It is seen from Table 1 that the Norm
$301$ accounts for the rest of the material along with the Galactic absorption. The covering fraction is defined as $Norm2/(Norm1 + Norm2)$, where $Norm1$ and $Norm2$ are normalizations of the two power laws, respectively. It is seen from Table 1 that the $Norm1$ and covering fraction remain substantially high ($>50 \times 10^{22}$ units and $>80\%$, respectively) during the dips and the eclipse regions in the light curve. This means that there is dense and clumpy material present at certain orbital phases of the Cen X-3 binary system causing dips in the light curve. A study of iron emission line parameters during eclipse-ingress, eclipse, and eclipse-egress with the ASCA fluorescent 6.4 keV line is emitted from a region close to the neutron star, whereas the 6.7 keV and 6.97 keV line emission region is much larger and more extended than the size of the companion star (Ebisawa et al. 1996). This information can be used to compare the iron line parameters during the dips and eclipse segments of the Suzaku observation of the pulsar. It is found that the equivalent widths of the three iron emission lines are significantly larger during the dips and eclipse segments in the light curve (Figure 7). The flux of these lines is also considerably low during these orbital phases compared to that of the high count rate phases in the light curve. The high equivalent width and low flux of iron emission lines at dips and eclipse segments also suggest the presence of significant absorption and reprocessing during corresponding orbital phases of the binary system. This feature is similar to that seen in Her X-1 and LMC X-4 (Naik & Paul 2003), two other sources that show strong superorbital X-ray intensity variations understood to be due to a varying degree of obscuration by the precessing accretion disk.

During the ASCA observation of Cen X-3, unlike the present work, the equivalent width of the 6.4 keV line hardly varied during the eclipse-ingress, eclipse, and eclipse-egress (Ebisawa et al. 1996). In fact, this is in contrast with the similar HMXBs Vela X-1 and GX 301−2. During the eclipse, in Vela X-1, the 6.4 keV iron line equivalent width increases significantly in comparison to that during the out-of-eclipse (Nagase et al. 1994, and references therein). Although GX 301−2 does not show binary eclipse, a significant increase in the 6.4 keV iron emission line equivalent width was observed during an intensity dip that is thought to be due to the occultation of the neutron star by dense matter (Leahy et al. 1988). During the intensity dips in Cen X-3 (present work), it is found that the iron emission line intensity dropped by a factor of 2−3 with a significant increase in the line equivalent widths. However, the drop in continuum flux is found to be by an order of magnitude or more during the dips (Figure 7). The decrease in the continuum flux during the dips suggests that the direct power-law component in the partial covering model is almost vanished or completely absorbed, whereas the second power-law component contributes to the X-ray flux observed during the dips. Therefore, the presence of dips in the X-ray light curve of Cen X-3 can be explained by the eclipse/obscuration of the neutron star by dense matter which is smaller in size compared to the scattering region surrounding the neutron star, as seen in GX 301−2.

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REFERENCES

Ash, T. D. C., Reynolds, A. P., Roche, P., Norton, A. J., Still, M. D., & Morales-Rueda, L. 1999, MNRAS, 307, 357
Balman, S. 2009, ApJ, 113, 50
Burderi, L., et al. 2000, ApJ, 530, 429
Church, M. J., Dotani, T., Balucinska-Church, M., Mitsuda, K., Takahashi, T., Inoue, H., & Yoshida, K. 1997, ApJ, 491, 388
Clark, G. W. 2004, ApJ, 610, 956
Day, C. S. R., & Stevens, I. R. 1993, ApJ, 403, 322
Devasia, J., James, M., Paul, B., & Indulekha, K. 2011a, MNRAS, 414, 1023
Devasia, J., James, M., Paul, B., & Indulekha, K. 2011b, MNRAS, in press
Ebisawa, K., et al. 1996, PASJ, 48, 425
Endo, T., Nagase, F., & Mihara, T. 2000, PASJ, 52, 223
Giacconi, R., et al. 1971, ApJ, 167, L67
Hutchings, J. B., et al. 1979, ApJ, 220, 1079
Iaria, R., et al. 2005, ApJ, 634, L161
in ’t Zand, J. J. M., Strohmayer, T. E., & Baykali, A. 1997, ApJ, 479, L47
Kallman, T. R., & White, N. E. 1989, ApJ, 341, 955
Koyama, K., et al. 2007, PASJ, 59, 23
Kreykenbohm, I., et al. 2008, A&A, 492, 511
Krzeminski, W. 1974, ApJ, 192, L135
Leahy, D. A., Nakajo, M., Matsuoka, M., Kawai, N., Koyama, K., & Makino, F. 1988, PASJ, 40, 197
Maitra, C., Paul, B., & Naik, S. 2011, MNRAS, submitted
Mitsuda, K., et al. 2007, PASJ, 59, 1
Mukherjee, U., & Paul, B. 2004, A&A, 427, 567
Nagase, F. 1989, PASJ, 41, 1
Nagase, F., Zylstra, G., Sonobe, T., Kotani, T., Inoue, H., & Woo, J. 1994, ApJ, 436, L16
Nagase, F., et al. 1992, ApJ, 396, 147
Nagase, F., et al. 2001, in AIP Conf. Proc. 599, X-ray Astronomy: Stellar Endpoints, AGN, and the Diffuse X-ray Background, ed. N. E. White, G. Malaguti, & G. G. C. Palumbo (Melville, NY: AIP), 794
Naik, S., Mukherjee, U., Paul, B., & Choi, C. S. 2009, Adv. Space Res., 43, 900
Naik, S., & Paul, B. 2003, A&A, 401, 265
Naik, S., & Paul, B. 2004a, ApJ, 600, 351
Naik, S., & Paul, B. 2004b, A&A, 418, 655
Naik, S., Paul, B., & Callanan, P. J. 2005, ApJ, 618, 866
Naik, S., Paul, B., Kachchara, C., & Vadawale, S. V. 2011, MNRAS, 413, 241
Narita, T., Gridley, J. E., Bloser, P. F., & Chou, Y. 2003, ApJ, 593, 1007
Orlandini, M. 2006, Adv. Space Res., 38, 2742
Parnar, A. N., et al. 1999, A&A, 351, 225
Paul, B., Nagase, F., Endo, T., Dotani, T., Yokogawa, J., & Nishiuchi, M. 2002, ApJ, 579, 411
Paul, B., Raichur, H., & Mukherjee, U. 2005, A&A, 442, L15
Raichur, H., & Paul, B. 2008a, ApJ, 685, 1109
Raichur, H., & Paul, B. 2008b, MNRAS, 387, 439
Rappaport, S. A., & Joss, P. C. 1983, in Accretion Driven Stellar X-ray Sources, ed. W. H. G. Lewin & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 1
Robba, N. R., Burderi, L., Di Salvo, T., Iaria, R., & Casusmano, G. 2001, ApJ, 562, 950
Santangelo, A., et al. 1998, A&A, 340, L55
Schreier, E., Levinson, R., Gursey, H., Kellogg, E., Tananbaum, H., & Giacconi, R. 1972, ApJ, 172, L79
Sych, S., et al. 2008, ApJ, 675, 1487
Takahashi, T., et al. 2007, PASJ, 59, 35
Takeshima, T., Dotani, T., Mitsuda, K., & Nagase, F. 1991, PASJ, 43, L43
Thompson, T. W. J., & Rothschild, R. E. 2009, ApJ, 691, 1744
Tjemkes, S. A., van Paradijs, J., & Zuiderwijk, E. J. 1986, A&A, 154, 77
White, N. E., & Swank, J. H. 1982, ApJ, 253, L61
Wojdowski, P. S., et al. 2003, ApJ, 582, 959