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Timing and Spectral study of Centaurus X-3 as seen by Suzaku

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Abstract

We present a detailed timing and spectral analysis of high mass X-ray binary pulsar Centaurus X-3(Cen X-3). The Cen X-3 was observed from December, 08-10, 2008 with the Japanese x-ray satellite Suzaku. We used this data for analysis and obtained pulse period of 4.8s. Using this pulse period, we created pulse profile in soft and hard energy band. In the soft energy range i.e. 10-20 keV and 20-30 keV, the profile is double peaked, broad and almost sinusoidal following pencil beam model for X-ray emission. However, the pulsation was absent above 50 keV. We have resolved three iron k -emission lines at 6.4 keV (Fe I), 6.65 keV (Fe XXV) and 6.9 (Fe XXVI). Absorption like feature is detected at E_{cyc}~28 keV. We also report a bump like feature in residual around 10 keV. We have tried to fit a Gaussian line around ~12 keV which improved the reduced chi-square marginally (1.18 for 1210 dof).

Key words- *X-ray binary, Pulsar, Cen X-3.*

Introduction

The Centaurus X-3 (Cen X-3) is one of the brightest observed accreting x-ray binary pulsar. (Schreier *et al.* 1972). It is a high mass x-ray binary pulsar with a spin period of ~ 4.8 s and orbital period of ~ 2.1 days (Nagase, 1989). The binary Cen X-3 consists of a neutron star with a mass of 1.21 ± 0.21 times the mass of the sun and its companion is an O6-8 III super giant star with a mass of 20.5 ± 0.7 M_S (Hutchings et al. 1979; Ash et al. 1999). According to Doppler shift's measurement the system is found at the distance of ~ 8 kpc (Krzeminski, 1974). The Cen X-3 is believed to be powered by an accretion disk fed by Roche lobe overflow. The presence of the disk is supported by the discovery of QPO at ~ 40 mHz from the source, which was successfully explained by the beat frequency model. The transient behavior is supported by the x-ray luminosity of the system that varies by a factor of 8 on a time scale of months from a high luminosity to low luminosity state.

Under temporal studies it is found that the pulse morphology also varies with energy and luminosity (Nagase *et al.,* 1992). At high energies (≥ 10 keV) the pulse profile is single peaked. At lower energies the pulse profile is more complex. In past 1 - 40 keV spectrum has been fitted with Fe- k line, and low energy absorption. In spectral study the iron emission line was detected at 6.4 keV. This emission line is not observed during eclipse so, it must be originated near the neutron star. It indicates that the dense matter exists near the neutron star. The X-ray spectrum analysis of this binary indicates that Cen X-3 consists of a flat power law with energy photon index around 1 and a high energy exponential roll-off with a cut-off energy ~15 keV. The detail spectrum analysis also shows photoelectric absorption at lower energies and the presence of iron like feature, which is combination of three different emission line at 6.4 keV , 6.67 keV (Fe XXV) and 6.97 keV (Fe XXVI) as reported by Ebisawa et al. (1996). With the high energy resolution of Chandra, Iaria *et al*. (2005), resolved the 6.6 keV line as three lines centered at 6.61 keV, 6.67 keV and 6.72 keV with an EW of 6 eV, 9 eV and 5 eV.

Observation and data analysis

Table 1: A summary of observation of Centaurus X-3

ID	403046010
RA	170.3158
Dec	- 60.6230
Observation Date; Start	2008-12-08; 06:55:36
Observation Date; End	2008-12-10 ;05:00:19
XIS	0, 1, 3
Observation mode	Pointing
XIS clock mode	Burst
PIN exposure	~80ks
XIS exposure	~48ks

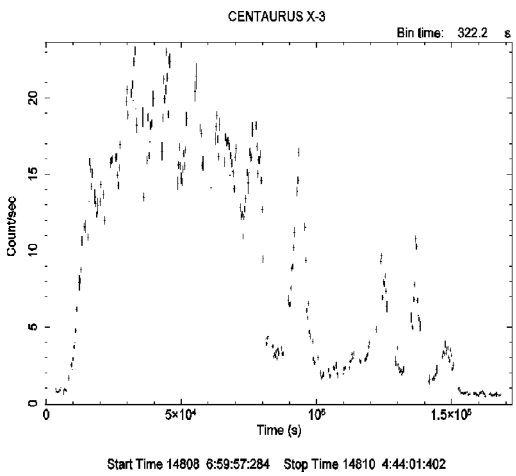
The HMXB Cen X-3 was observed from December, 08, 2008 to December, 10, 2008 with the Suzaku X-ray satellite. We used public archive data for the present work from NASA web site. The observation was pointed at (RA, DEC) = (170.3158, -60.6230) in the HXD nominal pointing mode. The XIS was operated with 1/ 4 window option which gives a time resolution of 2 s. Suzaku is the fifth Japanese X-ray astronomy satellite. It was launched on 2005 July 10. It covers the 0.2 – 600 keV energy range with two sets of instruments, X-ray CCDs (X-ray Imaging spectrometer: XIS) covering the soft X-rays in the energy range 0.2 -12 keV, and HXD (Hard X-ray detectors covering the energy range 10-70 keV with PIN diodes and 40-600 keV with GSO scintillators. XIS has four detectors XIS 0, 1, 2 and 3, out of which XIS 2 is no more operational. The used of data from HXD cleaned events and XIS events file which are taken from the public data archive. A barycentric correction was applied to the cleaned event data by using "aebarycen" task of XRONOS's V5.22 of FTOOLS. Using the Xselect software we extracted the images, source light curves and spectra from the event files. The light curves were extracted with bin size of 1s for XIS 0, XIS 1 and XIS 3 detectors respectively. To extract source spectrum, a circular region was selected with source at the center. Background spectrum was extracted from the same observation by selecting circular regions away from the source. Using this method we extracted light curves and spectra of the remaining XIS event data. Then we generated the response files and the effective area files for XIS detectors by using the "xisrmfgen" and "xissimarfgen" task of FTOOLS respectively. For spectral analysis, we filtered the PIN and GSO events using a good time interval (GTI). We have included PIN data in spectral analysis. As the HXD is a non imaging instrument, we cannot estimate background directly from the observation. So, we have used "tuned" non X-ray back ground (NXB) files V2.x for PIN background estimation. The pin light curves were obtained with time resolution of 0.5 s. The summery of observation is given in the table 1. Spectra were extracted for both observation and background file and background files were dead time corrected. The XIS and PIN data was suitably grouped using the task grppha. For HXD/PIN spectral analysis we have used the response matrix file of epoch 2008 Sep.1-2009 Sep. 30 (ae_hxd_pinXXXXXe5_20080716.rsp). So, used ds9 V6.1.2, astronomical imaging and data visualization application developed by SAO, Xselect V2.4a and XSPEC V 12.6.0 for data analysis.

Results and discussion

For timing analysis, a barycentric correction was applied to the arrivel times of the X-ray photon using "*aebarycen*" task of the ftools. Light curves for PIN (10 - 70 keV), GSO (50 -600 keV) and XIS 0, 1, 3 (0.2 -10 keV) were obtained, which are shown in the figure 5. 1, 5.2 and 5.3 respectively. The bin time was 322.2 sec for light curves HXD/PIN and HXD/GSO, and for XIS 0, 1 and 3 it was 322.2 sec. For HXD/PIN light curve, the maximum/minimum counting rate were almost 20/2 counts/sec. It was just half as compared to HXD/GSO and 1/5 of the XIS 0, 1 and 3. We found multipeaks in both light curves of detectors HXD/PIN & XIS 0, 1 and 3 and fine two broad peaks in light curve of detectors HXD/ GSO.

Table 2- Spectral parameters for Centaurus X-3

Model Component	Parameter	Value	Unit	Error
Edge	E	7.14	KeV	(-0.01017, +0.01189)
	τ_{max}	0.21		(-0.01763, +0.01289)
Wabs	N_H	1.478	1022	(-0.05642, +0.19973)
Highecut	E_{cutoff}	18.746	keV	(-0.70778, +0.36739)
	E_{fold}	9.045	keV	(-0.30256, +0.172321)
Cyclabs	D	0.52		(-0.04165, +0.04908)
	E_{cycl}	28.178	keV	(-0.64662, +0.41573)
	E	6.39	keV	(-0.00239, + 0.00374)
Gaussian	σ	0	keV	(0, 0.115834)
	N	1.34E-04		
	E	6.65	keV	(-0.00604, + 0.00935)
Gaussian	σ	0	keV	(0, 0.015512)
	N	4.81E-05		
	E	7.0121	keV	(-0.07085, + 0.04754)
Gaussian	σ	0.9527	keV	(-0.034357, +0.073209)
	N	5.70E-04		
Gaussian	E	12.3418	keV	(-0.075, + 0.16130)
	σ	2.87	keV	(-0.42927, +0.06383)
	N	2.81E-04		
Power law	Γ	1.03456		(-0.09922, +0.10297)
	N	1.07E-02		



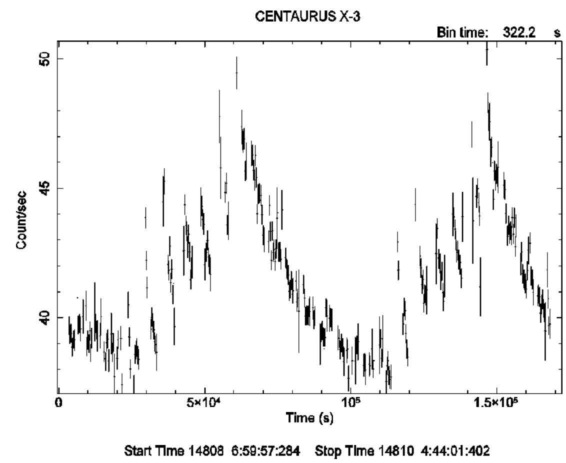


Fig. 1- The light curve for HXD/PIN (10 -70 keV) and HXD/GSO (50 - 600 keV)

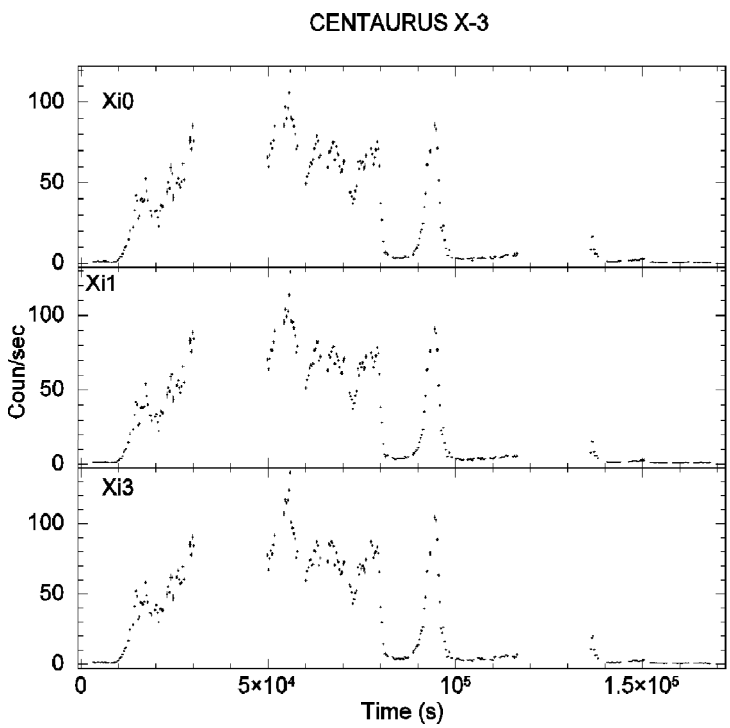


Fig. 2- The light curve for XIS 0, XIS 1 and XIS 3 (0.2 -10 keV)

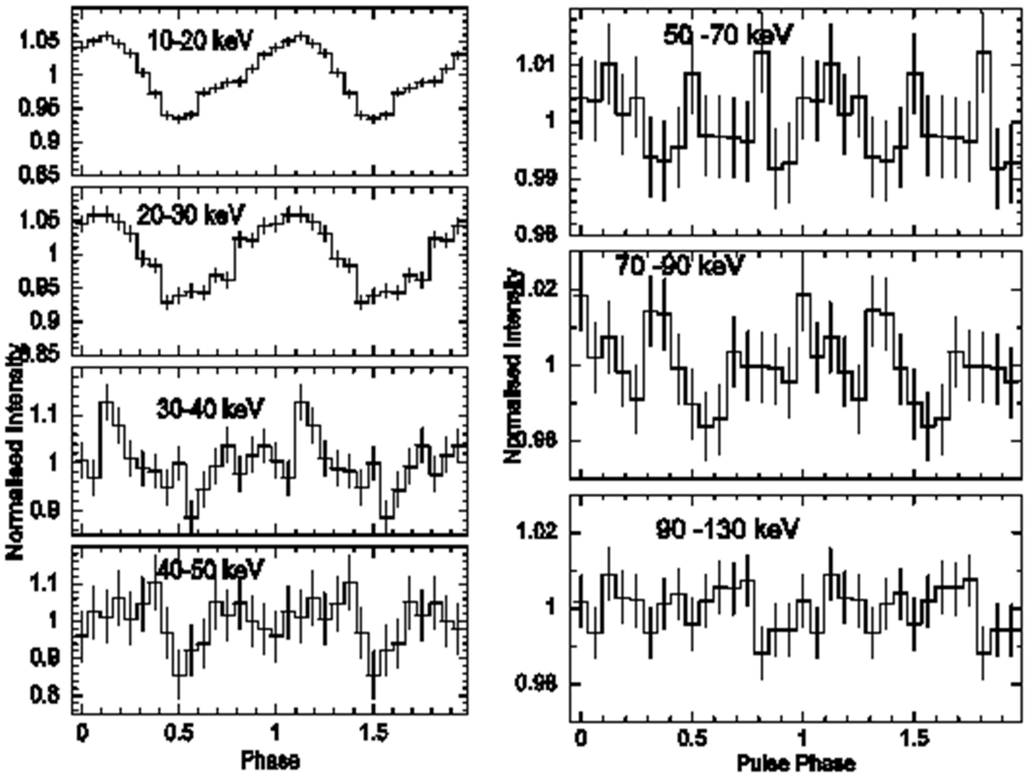
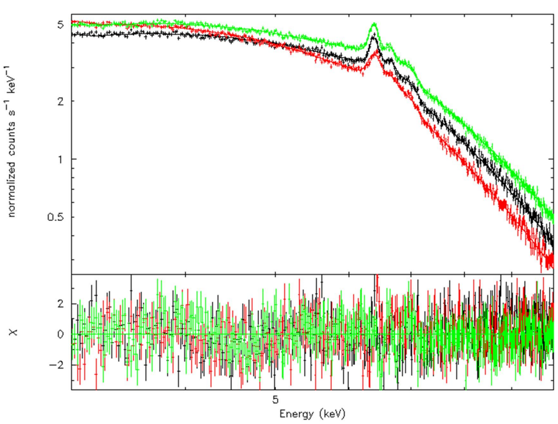


Fig. 3- The pulse profile of Cen X-3 in HXD/PIN (10-50keV) and HXD/GSO(50-130 keV)



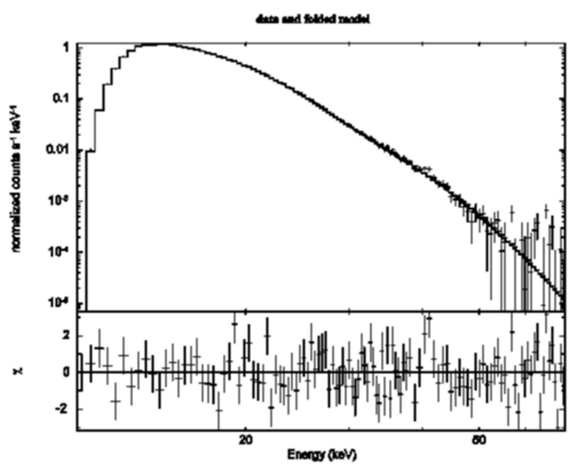


Figure 4

Figure 5

Fig. 4-The Energy spectrum of Cen X-3 obtained with the three XIS Detectors namely XIS 0 (Black), XIS 1 (Red) and XIS 3 (Green). The bottom panel shows contribution of the residuals to the χ^2 for each energy bin for the best fit model.

Fig. 5- The energy spectrum of Cen X-3 obtained with HXD/PIN data .The bottom panel shows contribution of the residual to χ^2 = 1.33 for 106 dof.

As a check we derived pulse period from the high statistical XIS data. We generated the light curve for XIS 0, 1 and 3. We combined these light curves using the ftool task "lcmath". Using the *efsearch*, we derive the pulse period using the combined XIS light curves by searching for the maximum in the χ^2 vs folding period. We obtained P_{pulse} = 4.8 s and folded at this period. This period is in good agreement with the earlier detected period for Cen X-3. Using the above pulse period, we created pulse profile for XIS (soft band). We also derived profiles for the PIN in the 10-50 keV energy range. The pulse profile was created by obtaining the light curves in 10-20 keV, 20-30 keV and 40-50 keV. The pulse profile are shown in the figure 3 and the panel shows significant differences in the pulse profile for the different X-ray energies.

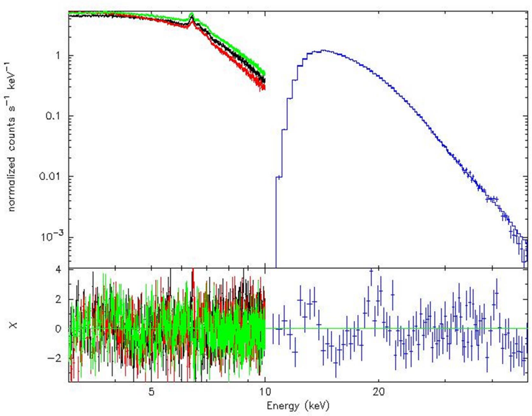


Fig. 6

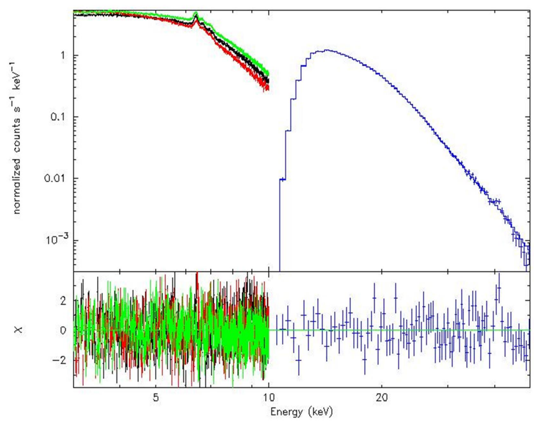


Fig. 7

Fig. 6-The Energy spectrum of Cen X-3 obtained with the three XIS and PIN Detectors without 13 keV emission line. The bottom panel shows contribution of the residuals to the χ^2 = 1.22 for 1129 dof for each energy bin for the best fit model (XIS 0 - Black, XIS 1- Red, XIS 3- Green and PIN- Blue).

Fig. 7-The Energy spectrum of Cen X-3 obtained with the three XIS and PIN detectors with 13 keV emission line. The bottom panel shows contribution of the residuals to the χ^2 = 1.18 for 1210 dof for each energy bin for the best fit model (XIS 0 - Black, XIS 1- Red, XIS 3-Green and Blue - PIN).

In 10-20 keV pulse profile is double peaked, broad and almost sinusoidal following pencil beam model for X-ray emission. Similar pattern is observable in the 20-30 keV range. In the energy range 30-40 keV, the double peak become clear and curve is not sinusoidal and in the 40-50 keV band the pulsation becomes weak but visibly appear to follow fan beam model for X-ray emission from pulsar. To check the pulsation in the higher energy range using GSO data we have created pulse profile in 50-70 keV, 70-90 keV and 90-130 keV. The pulse profile for the GSO data was also shown in the panel of figure 3. We can see that the pulsation is not present above 50 keV. So, we have detected X-ray pulsation in Cen X-3 up to 50 keV. It could happen only when accreting matter is guided by magnetic field of pulsar towards the pole for the case of pencil beam emission and thus pulse profile is sinusoidal. On the other hand if accreting matter push hard the magnetic field around the pulsar, then it could happen that emission takes place from over all surface of pulsar following fan model and pulse profile smears out. It is evident from panel of figure 3 which shows constant normalized intensity E > 50 keV. For spectral analysis, source and background spectra were extracted from the XIS event files as described in the previous section. The * .rmf and * .arf files for XIS detectors were generated by using the "xisrmfgen" and "xissimarfgen" respectively. For HXD/PIN the * .pha files was generated using the Xselect and "tuned" background file were used to extract the spectra. Initially the spectral fitting were done individually for XIS (XIS 0, 1 and

3) and HXD/PIN, and the best spectral parameters were obtained. The figures 4 and 5 show the energy spectral fitting for XIS and HXD/PIN with lower panel showing the contribution of the residual towards the reduced chi square is 1.22 for 1129 degree of freedom (dof) and 1.33 for 106 dof respectively. Iron k emission line 6.6 keV peak is clearly visible in each spectrum, but each peak differ in amplitude and position detected by the three XIS (figure 4). After that the simultaneous spectral fitting was done for XIS and HXD/PIN spectra, using the parameter obtained previously. The figure 6 shows the fitted spectrum from 3 – 50 keV with reduced chi square is 1.22 for 1129 dof. In the XIS data we excluded the energy range below 3 keV to avoid instrumental effects near the Au and Si edge (Miller et al. 2008). In the spectral fitting a wave like structure is present in the residual and a bump like feature is also present in 8-13 keV range. It suggests that some other peak is present around 12 keV. This feature has also been reported in past in many accreting X-ray pulsars Her X-1, Cen X-3, Vela X-1 etc (Coburn *et al*. 2002). So, we added another Gaussian line at ~ 12 keV, the X-ray spectrum plotted with the best fit model with their residual is shown in the figure 5.10. This has reduced the χ^2 value to 1.18 for 1210 dof and wave like residual also disappeared. The wave like residual has become a tool to identify undetected peaks in the observed spectrum. The spectral parameters obtained for this fit are shown in the table 2. The feature present in the range 8 -13 keV has been seen in many sources by several satellites and yet it is also not present in spectra of other sources like Crab nebula. It is safe to conclude that it is an inherent feature in the spectra of accreting pulsars.

Conclusion

We have resolved three iron k- emission lines at 6.4 keV (-0.00239, +0.0037) Fe I, 6.65 keV (-0.0060, +0.00935) Fe XXV and 6.9 (0.07085, +0.04754) Fe XXVI. Absorption like feature is detected at E_{cyc}~28 keV this feature is due to cyclotron resonance scattering. The second harmonic was given the value zero. As evident in the spectrum figure 6, we find a bump like feature in residual around 10 keV is present. This feature has been also detected in many accreting X-ray pulsars (Coburn et al. 2002). So, we tried to fit a Gaussian line around ~12 keV which improved the reduced chi-square marginally (1.18 for 1210 dof) and the wave like residual present in the figure 5.9 is completely disappeared (see figure 7). This structure around ~10 keV has also been reported previously in Cen X-3 (Santangelo et al. 1998) but we have tried to fit with Gaussian line and it improved the reduced chi- square and also wave residual disappeared. The hydrogen column density N_H is obtained ~ 1.47×10^{22} cm ^{2}, which is in agreement with previously obtained values. A broad feature at energies below the fundamental cyclotron line, mostly around ~ 10 keV, has been observed in several other cyclotron line sources *viz*. Her X-1, 4U 1626-67, 4U 1907+09 with RXTE. In Cen X-3 absorption feature was reported by Santangelo *et. al*. (1998). Such features in residual are generally described by an additional broad absorption line to improve fits. In our data we find the emission line at ~12.34 keV, by fitting this emission line by Gaussian absorption line improves the χ^2 value to 1.18 for 1210 dof as compared to 1.22 for 1129 dof. The CRSF parameters we obtained E_{cycle} = 28.17 are comparable to the previously obtained value. The value of $N_H = 1.47 \times 10^{22}$ cm^{-2} is also within the limit. The photon index of Γ =1.03 is slightly higher than the value obtained (Γ =0.92) by Suchy et al. (2008).

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