Long term flux variations in Cen X-3: clues from flux dependent orbital modulation and pulsed fraction

Harsha Raichur\textsuperscript{1,2}, Biswajit Paul\textsuperscript{1}

\textsuperscript{1} Raman Research Institute, Sadashivanagar, C. V. Raman Avenue, Bangalore 560 080, India
\textsuperscript{2} Joint Astronomy Programme, Indian Institute of Science, Bangalore 560 080, India
(E-mail: sharsha@rri.res.in, bpaul@rri.res.in)

ABSTRACT

We have investigated the long term flux variation in Cen X-3 using orbital modulation and pulsed fraction in different flux states using observations made with the All Sky Monitor and the Proportional Counter Array on board the Rossi X-ray Timing Explorer. In the high state, the eclipse ingress and egress are found to be sharp whereas in the intermediate state the transitions are more gradual. In the low state, instead of eclipse ingress and egress, the lightcurve shows a smooth flux variation with orbital phase. The orbital modulation of the X-ray lightcurve in the low state shows that the X-ray emission observed in this state is from an extended object. The flux dependent orbital modulations indicate that the different flux states of Cen X-3 are primarily due to varying degree of obscuration. Measurement of the pulsed fraction in different flux states is consistent with the X-ray emission of Cen X-3 having one highly varying component with a constant pulsed fraction and an unpulsed component and in the low state, the unpulsed component becomes dominant. The observed X-ray emission in the low state is likely to be due to scattering of X-rays from the stellar wind of the companion star. Though we can not ascertain the origin and nature of the obscuring material that causes the aperiodic long term flux variation, we point out that a precessing accretion disk driven by radiative forces is a distinct possibility.

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

\section{INTRODUCTION}

Several persistent X-ray binaries show large flux variations in their X-ray lightcurves on timescales significantly longer than their orbital periods (Wen et al. 2006). Highly periodic flux variations at time scales larger than their respective orbital periods are seen in Her X-1 (35 d: Tananbaum et al. 1972, Still & Boyd 2004), LMC X-4 (30.28 d: Paul & Kitamoto 2002), 2S 0114+650 (30.75 d: Farrell, Sood & O’Neill 2006), SS 433 (164 d: Eikenberry et al. 2001; Fabrika 2004), Cyg X-2 shows quasi periodic long term variability with period in the range of 40-90 d (Paul & Lochner 1992, Paul, Kitamoto & Makino 2000) and LMC X-3 also shows long term flux variations with periodicity in the range of 100-500 d (Wen et al. 2006) that is unstable over a longer period (Paul, Kitamoto & Makino 2000, Wen et al. 2006). Long term quasi periodic variations with a period of about 217 d are also seen from the Rapid Burster (X1730–333) which is in the form of recurrent outburst rather than a gradual change in X-ray flux (Masetti 2002).

Cen X-3 is a high mass X-ray binary pulsar with a spin period of $\sim 4.8$ s and an orbital period of $\sim 2.08$ d, discovered with \textit{UHURU} (Giacconi et al. 1971). This X-ray binary is known to have strong long term flux variations with transient quasi-periodicity (Priedhorsky & Terrell 1983). The long term lightcurve of this source obtained with the All Sky Monitor (ASM) of the \textit{Rossi X-ray Timing Explorer (RXTE)} showed very strong aperiodic flux variations along with two different accretion modes...
In the present work we investigate the orbital modulation of the 1.5-12 keV X-ray flux of Cen X-3 when the source is in high, intermediate and low states to understand if the aperiodic variations are occurring due to a variable mass accretion rate or due to the variable obscuration of the central X-ray source by an accretion disk precessing under tidal force. The tidal precession can be in the form of forced precession of accretion disks in the gravitational field of the companion star (Katz 1973) or slaved precession of accretion disc due to the rotation axis of the star being inclined (Roberts 1974). Tilted and twisted disks due to coronal winds (Schandl & Meyer 1994; Schandl 1996) and radiation pressure induced warped precessing disks (Iping & Petterson 1990; Wijers & Pringle 1999; Maloney, Begelman & Pringle 1996) can have variable or chaotic precession periods. Iping and Petterson (1990) simulated the temporal evolution of radiatively warped accretion disk and found that it can give rise to aperiodic variability in the X-ray lightcurves. They suggested that the long term variability of Cen X-3 could be caused by such a radiatively warped accretion disk. Other more detailed disk warping models have also been developed where warping instabilities are incorporated into the models which give rise to unstable and chaotic disk precession with no stable long term period (Wijers & Pringle 1999; Ogilvie & Dubus 2001). Accretion torque induced precession of magnetic axis can also be a possible explanation for the observed flux variations (Truemper et al. 1986) in some X-ray binaries. Third body mechanism is also known to cause periodic X-ray flux variation by modulating the mass accretion rate (Zdziarski, Wen & Gierliński 2007b).

2 OBSERVATIONS AND ANALYSIS

The ASM on board RXTE has three detectors which scan the sky in a series of 90 s dwells in 3 energy bands, namely 1.5-3, 3-5 and 5-12 keV (Levine et al. 1996). We have used the 1.5-12 keV lightcurves of four sources Cen X-3, Her X-1, SMC X-1 and LMC X-4, covering about 4100 days from January 1996 to study and compare the orbital modulation of these sources in three different flux states. The lightcurves of the 4 sources binned with their respective orbital periods after excluding the eclipse data are shown in Figure 1, for 500 days. The distinctly aperiodic flux variation of Cen X-3 is in sharp contrast with the periodic modulation in Her X-1 (with one main-on and one short-on state), LMC X-4 (with smaller signal to noise ratio) and the quasi-periodic modulation in SMC X-1 (with some scatter within each high state).

For each of the three sources Cen X-3, Her X-1 and SMC X-1, we have made 3 separate lightcurves, one each for the high, intermediate and low flux states. To do this, we first calculated the average count rate per orbit after excluding the eclipse data (see Paul et. al. 2005 for more details). Depending on the average count rate in a binary orbit, the data points available during that orbit were collected in one of the three high, intermediate or low state lightcurves (see Table 1 for the interval of count rates defining different flux states the three sources). These 3 lightcurves of each source were then folded with the respective orbital period of the source to get the orbital modulation lightcurves.

We have adopted a slightly different analysis for LMC X-4 since its signal to noise ratio is small. We first folded the ASM lightcurve with the superorbital period and determined the ephemeris for superorbital modulation as follows.

\[
T_{\text{min}}[\text{MJD}] = 50092.8 + (30.31 \pm 0.01)N,
\]

where \(N\) is an integer. The high, intermediate and low states were determined based on the suesorbital phase being 0.35 to 0.55, 0.20 to 0.35, and 0.20 to 0.20, respectively. Data points from the full ASM lightcurve belonging to the three different states were then used to make three different lightcurves and folded with the orbital period of LMC X-4 to get the orbital modulation lightcurves.

In Figure 2 we have shown the orbital modulation of the four sources in different flux states. For each source, the orbital modulation lightcurves of the high and intermediate flux states are shown in the top panel, high state points are indicated by circles. The low state modulations are shown in the bottom panels. All the orbital modulation curves are normalised by dividing the original lightcurves by the average count rate calculated over an orbital phase of 0.2 near the peak flux of the respective orbital modulation curve. The low state ASM lightcurve for LMC X-4 does not show any orbital modulation. In Table 1 we have also given the orbital periods and eclipse durations of these 4 sources determined from the RXTE-ASM lightcurves. In Figure 3, we have shown the flux dependent orbital modulation lightcurves of Cen X-3 separately for the hard spectral state, that started in December 2000 and ended in April 2004 (Paul et al. 2005). We have also investigated the pulsation characteristics of Cen X-3 at different flux levels in the 2-60 keV band. Cen X-3 was observed by RXTE-PCA many times dur-
ing the years 1996, 1997 and 1998. All these observations have been obtained when Cen X-3 was in the soft spectral state. We have chosen 18 PCA observations depending on the orbit averaged ASM count rates at that time such that a wide range of X-ray flux is covered. The 2-60 keV band lightcurves were obtained from the Standard-1 mode data of the PCA. Background lightcurves were generated using the background models provided for RXTE-PCA by HEASARC and were subtracted from Standard-1 lightcurves to get the source lightcurves. The source lightcurves were first barycenter corrected and then searched for the spin period of the neutron star. We did not detect any pulsations when the orbit averaged ASM count rate of Cen X-3 was less than 0.8 count/sec (equivalent to about 50 count/sec per proportional counter unit) with a 90% per cent upper limit of 0.8% on the pulsed fraction. The pulse profiles were then generated by folding the barycenter corrected lightcurves by the respective spin period found in that lightcurve. To avoid smearing of the pulse profiles due to the orbital motion of the pulsar, the pulse profiles were generated from short data segments of duration of a hundred pulses. In Figure 4 we have shown six pulse profiles obtained at different source flux levels including a lightcurve folded in the low flux state with a period of 4.81 s when no pulses were detected. Figure 5 is a plot of the maximum-minimum count rate per Proportional Counter Unit (PCU) against the maximum count rate per PCU for the 18 pulse profiles. The points marked with the circles are for the pulse profiles shown in Figure 4. Epochs of the six PCA observations, pulse profiles from which are shown in Figure 4, are marked in the top panel of Figure 1. A two component function was fitted to the points in Figure 5.

\[
F_{\text{max}} - F_{\text{min}} \approx \begin{cases} 
0, & F < F_0; \\
F(F_{\text{max}} - F_0), & F \geq F_0; 
\end{cases}
\]

The pulse fraction \( f \) of the pulsating component was determined to be 90%, while the unpulsed component grows up to a count rate of \( F_0 = 175.5 \) per PCU.

As seen in Figure 4, apart from the changing ratio of the unpulsed component of the flux to the total flux, the pulse shape is also varying from one observation to another. To see whether the pulse shape changes are related to the flux, we selected three different observations with very similar eclipse subtracted orbit average ASM count rates of 17.12 ± 1.35, 17.52 ± 1.21 and 17.73 ± 1.47. Within these three observations, the pulse shape changed from a double peak profile to a broad single peak profile but the pulsed fraction remained the same. We therefore conclude that while the pulsed flux of Cen X-3 is related to the total flux, the pulse shape is independent of the X-ray flux.

### 3 INTERPRETATION AND DISCUSSION

We have found that in the four sources Cen X-3, Her X-1, SMC X-1 and LMC X-4, the binary orbital modulation of the X-ray flux shows remarkable dependence on the X-ray flux state (Figure 2). X-ray eclipses are found to be sharp in the high flux state which becomes more gradual in the intermediate state. In the low state, instead of sharp eclipse ingress and egress, there is a smooth flux variation with orbital phase. Though the orbital modulation of LMC X-4 is not detectable in the low state of LMC X-4 with ASM data, we note that a weak and smooth orbital modulation in the low state of LMC X-4 was clearly detected earlier with BeppoSAX observations (Naik & Paul, 2003). The Her X-1 orbital lightcurves show some pre-eclipse dips (Figure 2). In the intermediate state of Cen X-3 the eclipse egress starts earlier in phase by 0.03 compared to the high state as is shown with a vertical dashed line.

Using a subset of the RXTE-ASM lightcurve for Her X-1, Scott & Leahy (1999) also found that the orbital modulation is shallower in the short-on state compared to the same in the main-on state. In the BeppoSAX observations of LMC X-4, the absence of clear eclipse transitions in low state was interpreted as due to obscuration of the central X-ray source by the precessing accretion disk. The weak orbital modulation of the lightcurve in the low state is due to an extended X-ray scattering region, emission from which dominates the detectable X-rays in the low state.

The flux dependent orbital modulations of these four sources indicate that at lower flux, an increasing fraction of the observed X-rays are from a larger region, comparable to the size of the companion star. The larger emission region may have different visibility at different orbital phases, leading to the smooth orbital modulation in the low state. Reprocessing of X-rays emitted from the compact star by scattering from stellar wind of the companion star is one likely scenario. However, for Her X-1, which has a low mass companion star, the scattering medium is more likely to be part of the accretion disk and disk outflows than the stellar wind. Zdziarski et al (2007a) have performed a similar analysis of RXTE-PCA lightcurve of the X-ray binary 4U 1820–303 and found a significant dependence of the profile of the orbital modulation on the average count rate. However, in 4U 1820–303, the superorbital modulation is associated with an accretion rate modulation, probably due to third body interaction. Poutanen, Zdziarski & Ibragimov (2008) discovered a superorbital phase dependence of the soft X-ray orbital modulation in Cyg X-1 in its hard spectral state, which is related to the size of a bulge in the outer accretion disk.

The ratio of the X-ray flux when the source is in eclipse and when it is out-of-eclipse is a measure of the relative scattering efficiency. Only for Cen X-3 there is good enough statistics to compare the ratios. We find that the out-of-eclipse count rates differ by large factor (22.02 ± 0.07, 7.56 ± 0.02 and 1.23 ± 0.02 for high, intermediate and low states respectively) while the in-eclipse count rates of the three states are comparable (0.69 ± 0.07 for high, 0.48 ± 0.03 for intermediate and 0.27±0.03 for low state). The eclipse count rate varies by a factor of only about ∼2.5 while the out of eclipse count rate varies by a factor of ∼18. The ratio of X-ray flux of Cen X-3 during eclipse and out-of-eclipse is larger in the low state by a factor of 7.0±1.3 compared to the same in the high state. This behaviour is similar to SMC X-1, in which the eclipse count rate was found to be comparable in high and low states whereas the out-of-eclipse count rate varied by more than a factor of 20 (Wojdowski et al. 1998).

The measurement of pulsed X-ray flux as a function of the peak X-ray flux of Cen X-3 as presented in the Figures 4 and 5, is also consistent with a scenario in which the measured X-ray flux has two components. One component is highly variable with a pulsed fraction of about 90% and a second component that is unpulsed. Similar result was
obtained for SMC X-1 over a wide range of its measured X-ray flux (Kaur et al. 2007). In the low state, the unpulsed component becomes dominant leading to non-detection of pulses. We also note that in all the four sources mentioned here, the X-ray pulsations (pulse period of ∼4.8 s in Cen X-3, 1.24 s in Her X-1, 0.7 s in SMC X-1 and 13.5 s in LMC X-4) have never been detected during the low state of the superorbital period, indicating that most of the radiation observed in low state is probably reprocessed emission from a large region (Wojdowski et al. 1998) [Naik & Paul 2003]. The non-detection of pulsations is not due to faintness of the sources. Even in the low state, Cen X-3, Her X-1 and SMC X-1 are bright enough for detection of a few percent pulse modulation with the RXTE-PCA.

We point out the possibility that the intrinsic X-ray luminosity of the central X-ray source may remain unchanged for a long time. It can be seen in Figure 1 that except during the anomalous low state events of Her X-1, the peak luminosity of superorbital modulation of Her X-1, SMC X-1 and LMC X-4 does not change very much and the peak of the 5-12 keV X-ray luminosity of Cen X-3 also has a ceiling (see Figure 1 of Paul et al. 2005). Though the results presented here indicate that the different flux states of Cen X-3 are largely due to varying degree of obscuration, as is the case with Her X-1, SMC X-1 and LMC X-4, we cannot completely rule out some contribution to the variability from a varying mass accretion rate, especially the variations associated with spectral change. But as shown in Figure 3, even during the hard spectral state of Cen X-3 from December 2000 to April 2004, the orbital modulation lightcurve indicate an extended X-ray source at low flux level. Detailed observations over a wide spectral range with future missions like ASTROSAT can throw more light on these aperiodic variations and spectral mode changes seen in Cen X-3 lightcurves.

4 CONCLUSIONS

(i) The binary orbital modulation of X-ray from Cen X-3 is similar to that seen in the other three accreting X-ray pulsars. From sharp eclipse in high state, it turns to a gradual modulation in the low state. Cen X-3 eclipse egress starts earlier in the intermediate state compared to the high state. These observations indicate a larger emission region in the low state of Cen X-3. The ratio of X-ray flux of Cen X-3 during eclipse and out-of-eclipse is larger in the low state by a factor of 7.0 ± 1.3 compared to the same in the high state.

(ii) A measurement of the pulsed X-ray flux in different flux states of Cen X-3 is consistent with the X-ray flux having two components, one with a large pulsed fraction and a second unpulsed component that dominates in the low state.

(iii) We propose that the long term intensity variations in Cen X-3 are mostly due to aperiodic obscuration of the compact source by the accretion disk. The unpulsed X-ray emission from an extended region appears to be due to scattering of the X-rays from the central source by the stellar wind.

5 ACKNOWLEDGEMENTS

We thank the referee A. Zdziarski for very useful suggestions that helped us very much to improve this paper. This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA’s Goddard Space Flight Centre.

REFERENCES

Clarkson, W. I., Chales, P. A., Coe, M. J., Laylock, S., Tout, M. D., Wilson, C. A., 2003, MNRAS, 339, 447
Cornellisse, R., Charles, P. A., Robertson, C., 2006, MNRAS, 366, 918
Elkenberry, S. S., Cameron, P. B., Fierce, B. W., Kull, D. M., Dror, D. H., Houck, J. R., Margon, B., 2001, ApJ, 561, 1027
Fabrika, S., 2004, ASPRv, 12, 1
Farrell, S. A., Sood, R. K., O’Neill, P. M., 2006, MNRAS, 367, 1457
Finger, M. H., Wilson, R. B., Fishman, G. J., 1994, Second Compton Symposium, p 304
Giacconi, R., Gursky, H., Kellogg, E., Schreier, E., Tananbaum, H., 1971, ApJ, 167, 67
Gruber, D. E., Rothschild, R. E., 1984, ApJ, 283, 546
In’t Zand, J. J. M., Hullemann, F., Markwardt, C. B., Mendez, M., Kuulkers, E., Cornettes, R., Heise, J., Strohmayer, T. E., Verbunt, F., 2003, A&A, 406, 233
Iping, R. C., Pettersson, J. A., 1990, A&A, 239, 221
Katz, J. L., 1973, Nature Physical Sciences, 246, 87
Kaur, R., Paul, B., Raichur, H., Sagar, R., 2007, ApJ, 660, 1049
Kitamoto, S., Egoshi, W., Miyamoto, S., Tsuemi, H., Jing, J. C., Wheaton, W. A., Paul, B., 2000, 531, 546
Lachowicz, P., Zdziarski, A. A., Schwarzenberg-Czerny, A., Pooley, G. G., Kitamoto, S., 2006, MNRAS, 368, 1025
Levine, A. M., Bradt, H., Cui, W., Jernigan, J. G., Morgan, E. H., Remillard, R., Shirey, R. E., Smith, D. A., 1996, ApJ, 469, 33
Maloney, P. R., Begelman, M. C., Pringle, J. E., 1996, ApJ, 472, 582
Masetti, N., 2002, A&A, 381, L45
Naik, S., Paul, B., 2003, A&A, 401, 265
Ogilvie, G. I., Dubus, G., 2001, MNRAS, 320, 485
Paul, B., Kitamoto, S., 2002, IAA, 23, 33
Paul, B., Kitamoto, S., Makino, F., 2000, ApJ, 528, 410
Paul, B., Raichur, H., Mukherjee, U., 2005, A&A, 442, L15
Poutanen, J., Zdziarski, A. A., Ibragimov, A. 2008, arXiv0802.1391, Submitted to MNRAS
Priedhorsky, W. C.; Terrell, J., 1983, ApJ, 273, 709
Roberts, W. J., 1974, ApJ, 187, 575
Schandl, S., 1996, A&A, 307, 95
Schandl, S., Meyer, F., 1994, A&A, 289, 149
Scott, D. M., Leahy, D. A., 1999, ApJ, 502, 253
Smale, A. P., Lochner, J. C., 2002, ApJ, 539, 582
Still, M., Boyd, P., 2004, ApJ, 606, L135
Tananbaum, H., Gursky, H., Kellogg, E. M., Levinson, R., Schreier, E., Giacconi, R., 1972, ApJ, 174, L143
Truemper, J., Hakahbka, P., Ogelman, H., Pietch, W., Voges, W., 1986, ApJ, 300, 63
Tsunemi, H., Kitamoto, S., Tamura, K., 1996, ApJ, 456, 316
Wen, L., Levine, A. M., Corbet, R. H. D., Bradt, H. V., 2006, ApJS, 163, 372
Wijers, R. A. M. J., Pringle, J. E., 1999, MNRAS, 308, 207
Wojdowski, J., Clark, G. W., Levine, A. M., Woo, J. W., Zhang, S. N., 1998, ApJ, 502, 253
Zdziarski, A. A., Gierliński, M., Wen, L., Kostrzewa, Z., 2007a, MNRAS, 377, 1017
Zdziarski, A. A., Wen, L., Gierliński, M., 2007b, MNRAS, 377, 1006
Table 1. The source parameters

| Source     | Orbital Period$^1$ (days) | Eclipse Duration (days) | Orbit averaged Count rate for |
|------------|---------------------------|-------------------------|-------------------------------|
|            |                           | High                    | Inter- | low    |
| Cen X-3    | 2.08706 ± 0.00009         | 0.52                    | 18.0   | 18.0 – 2.0 | ≤ 2.0 |
| Her X-1    | 1.70015 ± 0.00009         | 0.22                    | 2.5    | 2.5 – 1.0   | ≤ 1.0 |
| SMC X-1    | 3.8921 ± 0.00004          | 0.62                    | 1.3    | 1.3 – 0.7   | ≤ 0.7 |
| LMC X-4$^2$| 1.40840 ± 0.00006         | 0.23                    | -      | -        | -     |

$^1$Orbital periods are measured from RXTE-ASM lightcurves.
$^2$The high, intermediate, and low states of LMC X-4 were determined using the phases of its stable superorbital period. See §2 for details.
Figure 1. The ASM lightcurve of Cen X-3, Her X-1, SMC X-1 and LMC X-4 are shown here for 500 days binned with the orbital period of the respective sources. The Cen X-3 lightcurve clearly shows aperiodic superorbital variations, Her X-1 and LMC X-4 lightcurves show periodic flux variations whereas SMC X-1 lightcurve shows quasi periodic flux variations. The numbered arrows in the Cen X-3 lightcurve represent the times during which the respective pulse profiles of Figure 4 are taken.
Figure 2. The orbital modulation in high, intermediate and low states are shown here for four X-ray sources Cen X-3, Her X-1, SMC X-1 and LMC X-4. The high and intermediate state plots are shown in the upper panel, with the circles denoting the high state points. The plot in the lower panel shows the low state orbital modulation. All the plots are normalised by dividing the original curve with the respective maximum count rate of the curve.
Figure 3. Flux dependent orbital modulation of Cen X-3 in hard spectral state during December 2000 to April 2004. Upper pannel plots show high and intermediate state orbital modulation, with high state points being marked with circles. Lower pannel plot shows low state orbital modulation.
Figure 4. Pulse profile of Cen X-3 is shown here in different flux states of the source. The count rate is per PCU. Hundred consecutive pulses are folded with arbitrary pulse phase and the local spin period to get each of the above pulse profiles.
Figure 5. Pulsed emission of Cen X-3 is plotted here against the maximum count rate per detector over a range of X-ray flux of the source. The points marked with circles correspond to the pulse profiles shown in Figure 4. The solid line in the figure is a fit to the function given in the text.