Long Term X-ray Intensity Variations of Cen X-3

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Abstract

We have carried out detailed investigations of the long term X-ray flux variations of the high mass X-ray binary pulsar Cen X-3 using archival X-ray data from the *Rossi X-ray timing Explorer (RXTE)*. In the lightcurves of several observations made with the Proportional Counter Array (PCA) and covering a wide range of X-ray intensity, we have detected Quasi Periodic Oscillation (QPO). We have observed a clustering of the QPO peak frequency at 40 and 90 mHz with no dependence of the QPO frequency and occurrence of QPOs on the X-ray intensity. If the observed X-ray intensity of Cen X-3 and its long term variations are related to the mass accretion rate, the lack of QPO frequency variation of Cen X-3 is in contrast with an inner disk origin of the QPOs. Using the same *RXTE*-PCA observations, we have also measured the pulsed flux of Cen X-3 in different flux states. We found that below a certain flux level, the X-ray lightcurve does not have any pulsations while above this level, the pulsed flux increases linearly with the peak flux. This is consistent with the X-ray emission of Cen X-3 having one unpulsed component and one varying component with a constant pulsed fraction. In the low state, the unpulsed component becomes dominant. The detected X-ray emission in the low state can be due to scattering of X-rays from the stellar wind of the companion star. We have also studied the orbital modulation of the Cen X-3 X-ray lightcurve using the long term X-ray lightcurve made with the All Sky Monitor on board the *RXTE*. We found an evolution of the orbital modulation of the X-ray lightcurve as a function of the flux state. In high state, the transitions are sharp indicating that most of the observed X-rays are produced in a small region. In the low state, the orbital modulation is smooth, indicating that most of the observed X-rays are produced in an extended region, probably by scattering of X-rays from a hidden central source. The QPO measurements, the pulsed flux measurements and the orbital modulation measurements indicate that the different flux states of Cen X-3 are produced by different degree of absorption. We propose that the absorption is caused by an aperiodically precessing accretion disk.

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

1. Introduction

Several persistent X-ray binary sources exhibit large flux variations in their X-ray lightcurves on timescales significantly longer than their orbital periods (Wen et al. 2006). The long term flux variations can be highly periodic (Her X-1, LMC X-4, 2S 0114+650, SS433, 4U 1820–303, XTE J1716–389, Cyg X-1 etc.), quasi-periodic or with unstable period (SMC X-1, GRS 1747–312, Cyg X-2, LMC X-3, X1730–333 etc.). The periodic long term intensity variations, as seen in Her X-1, are understood to be due to obscuration of the central X-ray source by a warped precessing accretion disc.

Cen X-3 is a high mass X-ray binary pulsar with a spin period of ~ 4.8 s, orbital period of ~ 2.08 d, and strong long term flux variations. The long term lightcurve of this source obtained with the All Sky Monitor (ASM) of the *Rossi X-ray Timing Explorer (RXTE)* showed aperiodic flux variations by a factor of more than 40, along with two different accretion modes (Paul, Raichur & Mukherjee 2005). As the long term intensity variation of Cen X-3 does not remotely appear to have any periodic or quasi-periodic nature, it is often assumed that the X-ray flux variation is due to changing mass accretion rate. However, *GINGA* observations revealed that there is no correlation between the observed X-ray flux and pulse period derivative of Cen X-3 (Tsunemi, Kitamoto & Tamura 1996) indicating that the observed X-ray flux of Cen X-3 may not represent its mass accretion rate.

We show here results from several investigations of Cen X-3 in different X-ray flux states, carried out

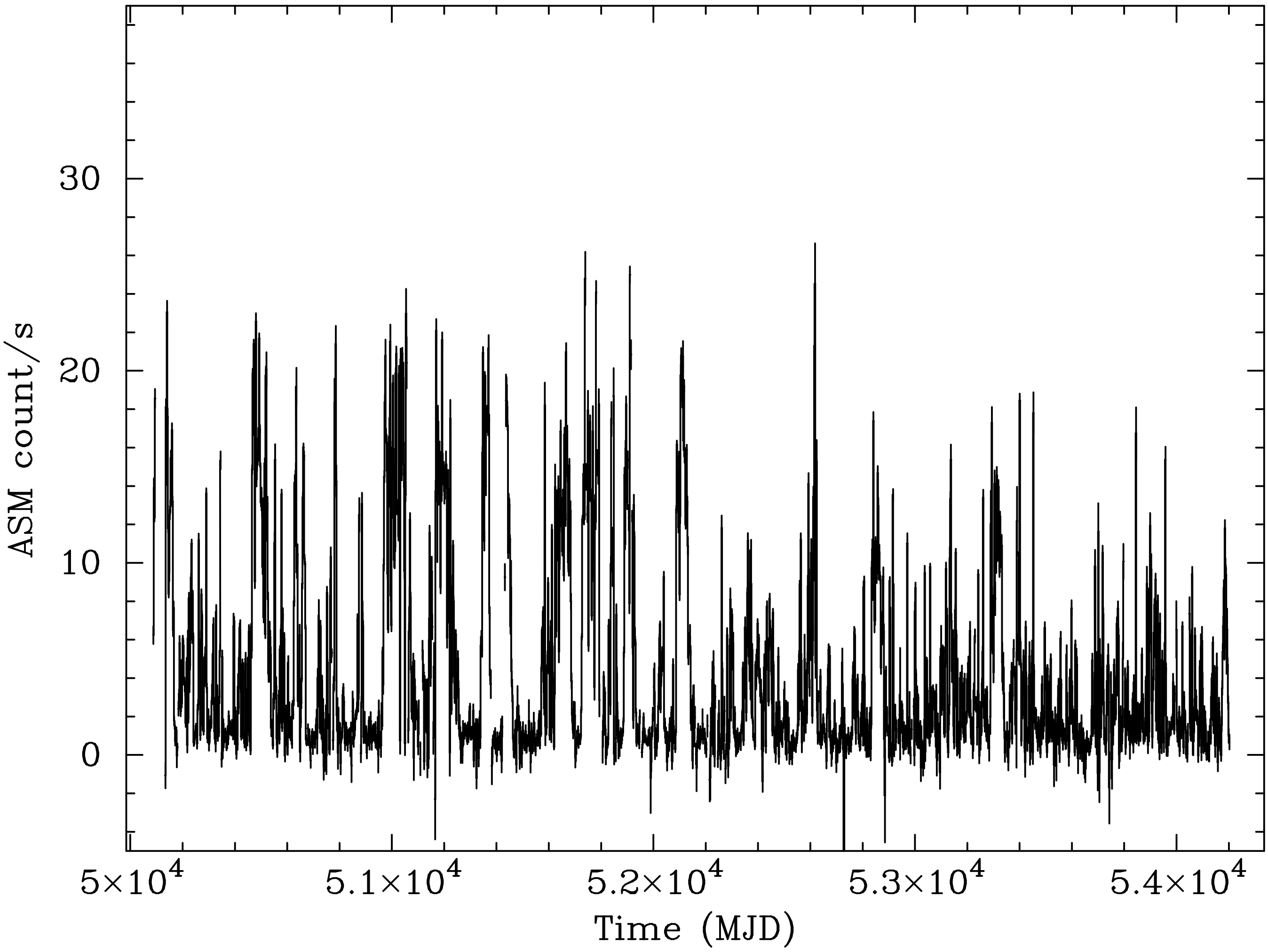

Fig. 1. The 1.5-12 keV *RXTE*-ASM lightcurve of Cen X-3 showing the aperiodic long term X-ray flux variations.

to understand the origin of its aperiodic long term flux variations. More details about these studies and comparison with Her X-1, LMC X-4 and SMC X-1 can be found in Raichur and Paul (2008a, 2008b).

2. Method

We have measured the Quasi Periodic Oscillation (QPO) feature in Cen X-3 in different flux levels using all the available *RXTE*-PCA data. In the accretion powered X-ray pulsars, the QPOs are produced due to inhomogenities in the inner accretion disk and the QPO frequency is expected to be related to the inner radius of the accretion disk. In several transient and persistent X-ray pulsars, the QPO frequency is found to be related to the X-ray flux or the inner radius (EXO 2030+375: Angelini, Stella & Parmar 1989, 3A 0535+262: Finger, Wilson & Harmon 1996, XTE J1858+034: Mukherjee et al. 2006, 4U 1626–67: Kaur et al. 2008). If the observed X-ray flux variation of Cen X-3 is due to changes in the mass accretion rate, a similar dependence of the QPO frequency and X-ray flux is expected.

We have measured the pulsed and peak X-ray emission of the source in its different flux states using the same *RXTE*-PCA observations. Evolution of the pulsed fraction with peak X-ray flux is useful to know the relative importance of scattered X-ray emission in different flux states.

We have also studied the orbital modulation of the Cen X-3 X-ray lightcurve as a function of its X-ray flux. The relative sizes of the observable X-ray source in different flux states can be known from the variations of the eclipse transition periods. The long term lightcurve obtained with the All Sky Monitor on board the *RXTE* has been used for this.

3. Results

We have analysed X-ray lightcurves from 81 observations of Cen X-3 made with the *RXTE*-PCA during 1996-

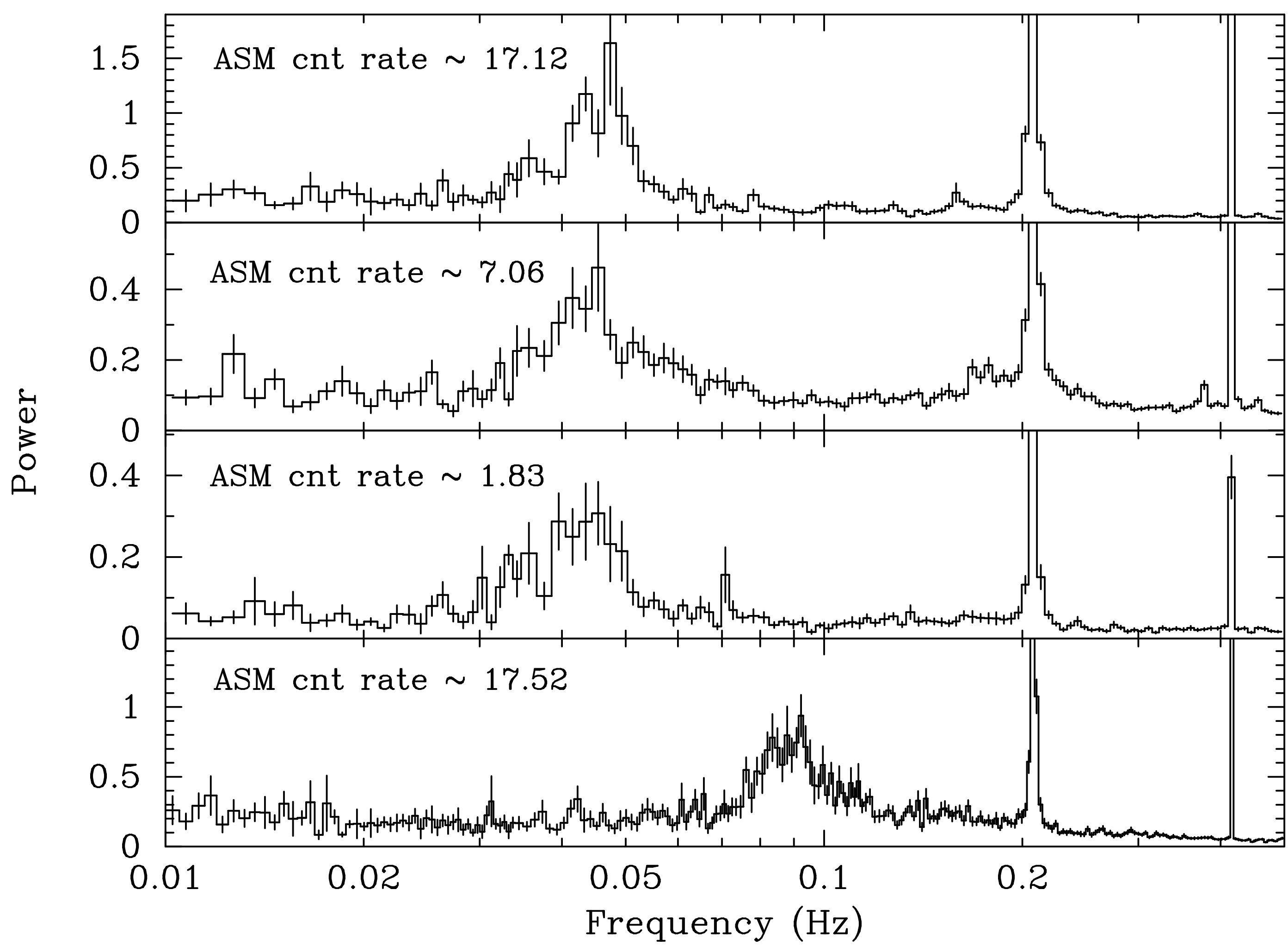

Fig. 2. The power spectra of Cen X-3 obtained from PCA lightcurves in different flux states are shown here. The top three panels show the 40 mHz QPO feature while the bottom panel shows the 90 mHz QPO feature detected only in 1996.

1998 and in 2000. The total useful exposure obtained from all these observations was 525 ks. Most of the observations were carried out outside the X-ray eclipse and data collected during the eclipses were excluded from our analysis. We have also used the 1.5-12 keV lightcurve of Cen X-3 obtained with the *RXTE*-ASM covering about 4100 days from January 1996 to study the orbital modulation in different flux states.

Power spectrum was created from each of the PCA lightcurves and we detected QPO features at 40 mHz in 9 observations and at 90 mHz in 2 observations. Four power spectra with QPO features detected in different flux states of Cen X-3 are shown in Figure 2. Inside each panel we have also shown the *RXTE*-ASM count rate of Cen X-3 during these observations indicating the flux level. We found that Cen X-3 shows intermittent QPOs in frequency ranges 40 mHz and 90 mHz. The QPO frequency and occurrence of the QPOs are not related to the flux state of the source.

Using a subset of the *RXTE*-PCA observations, we have also measured the pulsed flux of Cen X-3 as a function of the peak flux. We have selected 18 PCA observations representing a wide range of X-ray flux. The orbit averaged X-ray flux is measured simultaneously with the *RXTE*-ASM. No pulsations were detected when the orbit averaged ASM count rate of Cen X-3 was less than 0.8 count/sec which is equivalent to about 50 count/sec per proportional counter unit. In Figure 3 we have shown some of the pulse profiles obtained at different flux levels. In the top panel of Figure 3 we have shown a lightcurve folded in the low flux state when no pulses were detected. In Figure 3, apart from the changing pulsed fraction, the pulse shape is also different in different panel. We have independently verified that the pulse shape variation is not related to the X-ray flux.

In Figure 4 we have shown a plot of pulsed X-ray flux against the peak X-ray flux of Cen X-3. The pulse

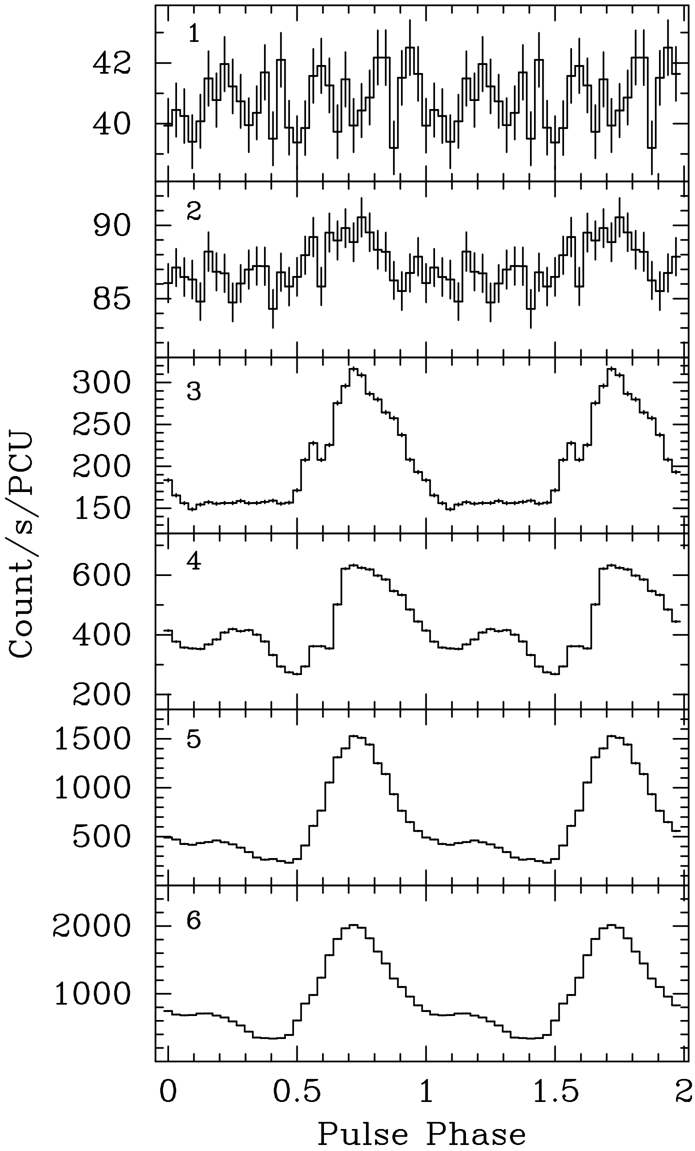

Fig. 3. Pulse profile of Cen X-3 is shown here in different flux states.

profiles shown in Figure 3 are shown in this plot with circles. We fitted the following two component function to the pulsed flux data.

$$F_{\rm max} - F_{\rm min} \simeq \begin{cases} 0, & F < F_0; \\ f(F_{\rm max} - F_0), & F \geq F_0; \end{cases} \qquad (1)$$

We determined the value of the pulsed fraction of the pulsating component to be to be 90%, while the maximum value of the unpulsed component is a count rate of 175.5 per PCU. The pulsed X-ray flux in different flux states is consistent with the X-ray emission having two components, one with a large and constant pulsed fraction and a second unpulsed component that dominates in the low state.

From the *RXTE*-ASM data, we have made 3 separate lightcurves, one each for the high, intermediate and low flux states. First we excluded the data acquired during the X-ray eclipse and the remaining data was segregated into three sets depending on the average count rate per binary orbit of Cen X-3. These 3 lightcurves were then folded with the orbital period and intensity dependent orbital modulaton curves were obtained. The orbital modulation curves, shown in Figure 5 have been normalised with respect to the average count rate calculated over an orbital phase of 0.2 near the peak flux. The orbital modulation curves for the high and intermediate flux state are shown in the top panel while same for the low flux state is shown in the bottom panel of Figure 5. The high state data points are marked with circles. From Figure 5 we note thatn from a sharp eclipse

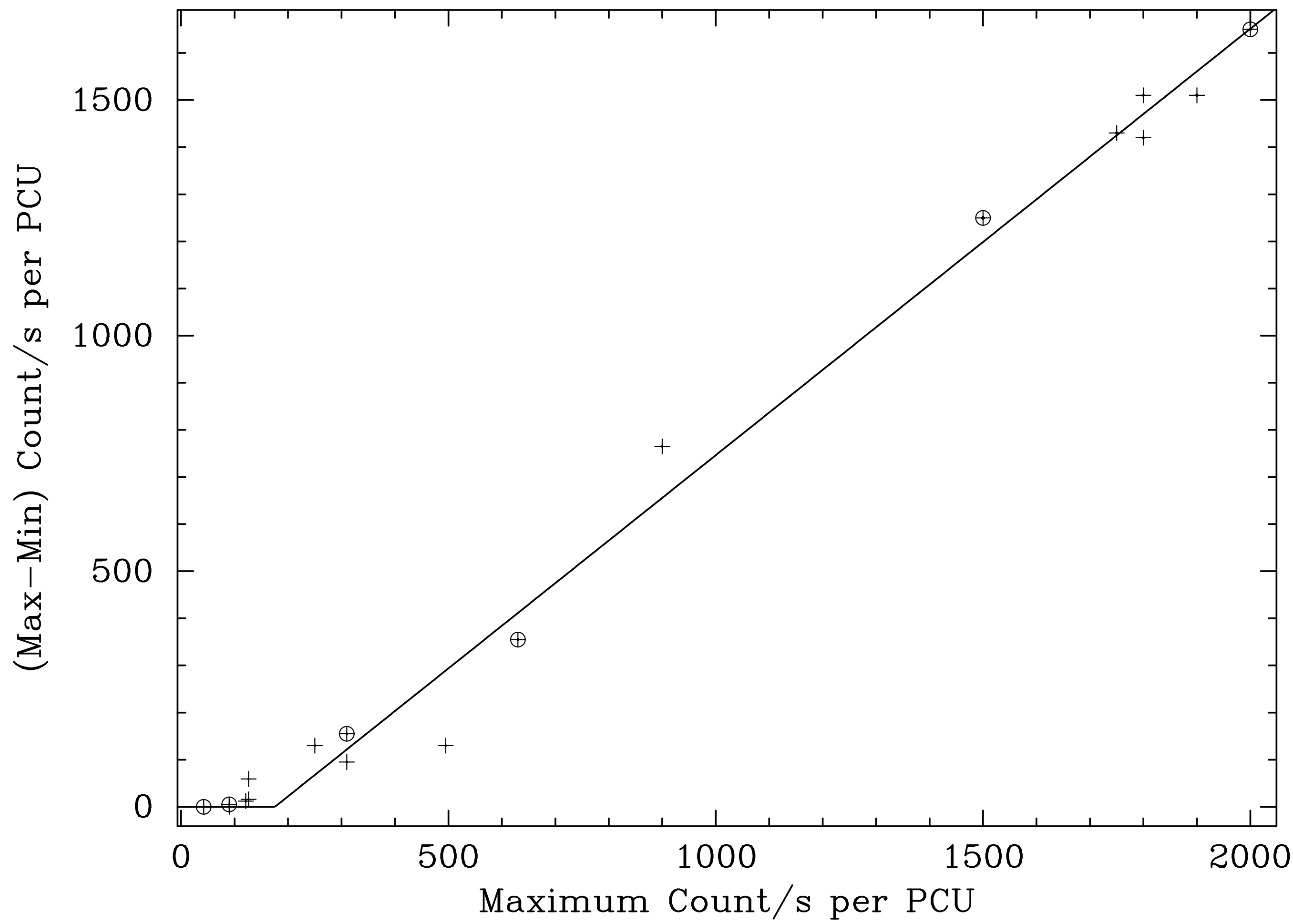

Fig. 4. Pulsed flux of Cen X-3 is plotted here against the peak flux. The points marked with circles correspond to the pulse profiles shown in Figure 3.

transition in the high flux state, the eclipse trnasitons become a gradual modulation in the low state. We have also measured that the the ratio of X-ray flux of Cen X-3 during eclipse and out-of-eclipse is larger in the low flux state by a factor of 7.0 ± 1.3 compared to the same in the high flux state. The flux state dependence of the orbital modulation pattern of Cen X-3 is very similar to that seen in the three accreting X-ray pulsars Her X-1, Cen X-3 and SMC X-1 (Naik & Paul 2003, Raichur & Paul 2008a, 2008b).

4. Discussions

The observed QPO properties of Cen X-3 is in agreement with a scenario in which the actual mass accretion rate and X-ray luminosity of the source does not change. The long term variation of the measured X-ray flux is due to change in obscuration by an aperiodically precessing warped accretion disk.

The measurement of pulsed X-ray flux as a function of the peak X-ray flux of Cen X-3 as shown in Figures 3 and 4, is consistent with a scenario in which the measured X-ray flux has two components. One component has a high pulsed fraction of 90% and is also highly variable, while the other componet is unpulsed. SMC X-1 also shows a similar characteristics over a wide range of its measured X-ray flux (Kaur, Paul, Raichur et al. 2007). The unpulsed component becomes dominant in the low state, leading to a non-detection of the pulses.

The flux dependent orbital modulations of Cen X-3 and its similarity with Her X-1, SMC X-1 and LMC X-4 indicate that in the low flux state, a large fraction of the observed X-rays are from an extended region which is comparable to the size of the companion star. A different visibility of the larger emission region in different orbital phases leads to the smooth orbital modulation in the low state.

Based on the three independent investigations briefly described above we have proposed (Raichur & Paul 2008a, 2008b) that the long term intensity variations in Cen X-3 are primarily due to obscuration of the compact

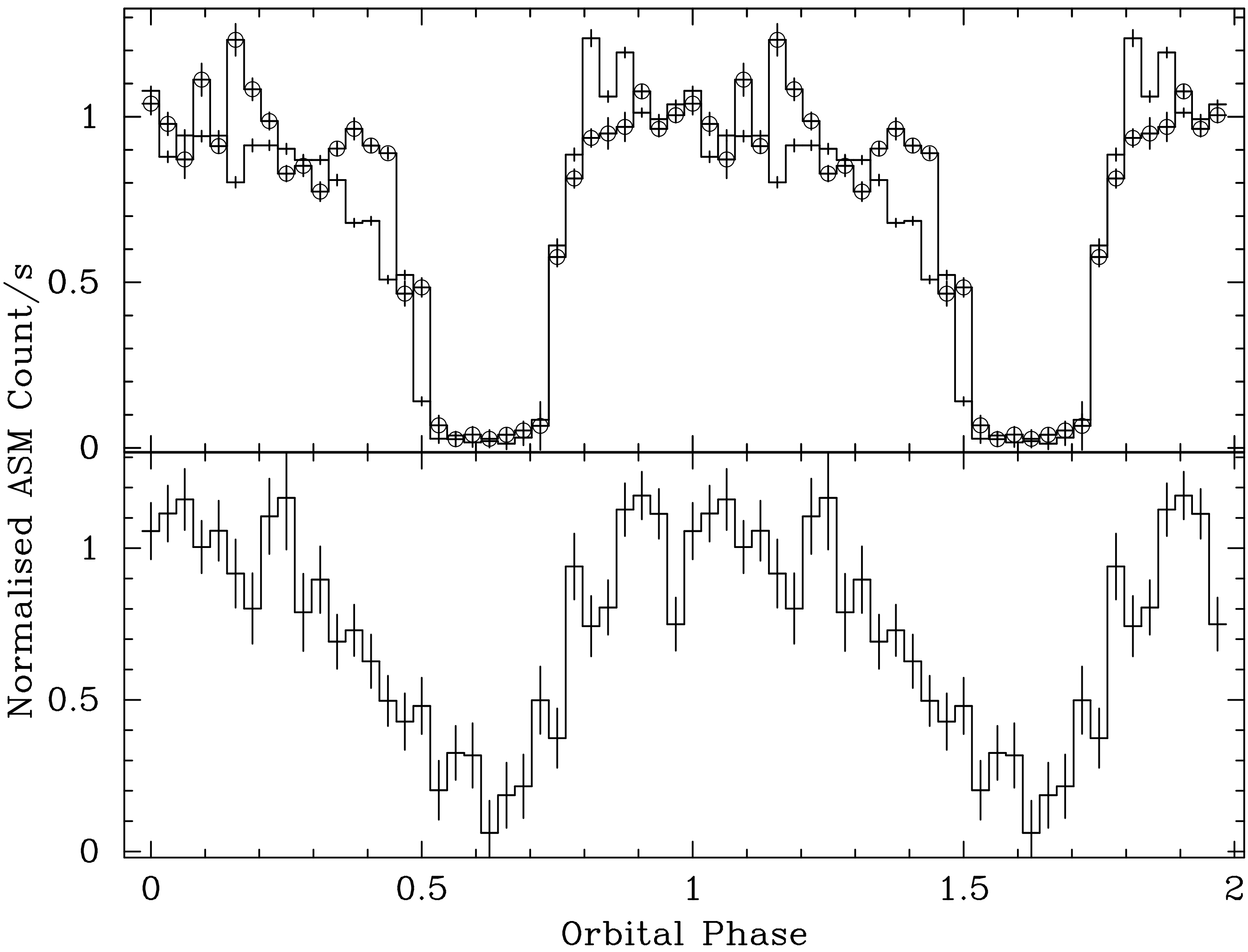

Fig. 5. Orbital X-ray modulation of Cen X-3 in high flux state (top panel, circles), medium flux state (top panel, crosses) and low flux state (bottom panel) are shown here.

X-ray source by the accretion disk. In the low flux state, the detected X-rays are unpulsed and originate from an extended region. The unpulsed X-ray emission from an extended region could be due to scattering of the X-rays from the central source by the stellar wind.

The MAXI mission will produce long term lightcurves of a large number X-ray sources with higher signal to noise ratio and over a larger energy band. The MAXI database will therefore be very useful for similar investigations in a large number X-ray binaries. For bright sources like Cen X-3, the MAXI datasets will be useful for more detailed investigations, including flux dependent spectral measurements.

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