

QUASI-PERIODIC OSCILLATIONS IN CEN X-3 AND THE LONG-TERM INTENSITY VARIATIONS

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ABSTRACT

We have investigated the properties of the quasi-periodic oscillation (QPO) features in the accretion-powered X-ray pulsar Cen X-3 over a period of about 4 years using observations carried out with the Proportional Counter Array (PCA) of the *Rossi X-ray Timing Explorer (RXTE)*. The observations cover a wide range of X-ray intensity of the source in excess of the binary intensity modulation. In 11 of 81 pointings with the PCA, we have detected QPOs with rms intensity fluctuation up to 10%. The QPO peak frequency shows clustering around 40 and 90 mHz, with the QPO frequency having no dependence on X-ray intensity. This indicates that either (1) the observed X-ray luminosity of the source is not related to the mass accretion rate or inner radius of the accretion disk, or (2) the QPO generation mechanism in Cen X-3 is different from the beat frequency model or Keplerian frequency model that is believed to operate in most other transient and persistent X-ray pulsars. We have also found that the rms variation in the 40 mHz QPO feature is not dependent on the X-ray energy, indicating that the origin of the QPO is unlikely to be related to disk absorption.

Subject headings: binaries: general — pulsars: individual (Cen X-3) — stars: neutron — X-rays: binaries — X-rays: individual (Cen X-3) — X-rays: stars

1. INTRODUCTION

The light curves of X-ray binary pulsars show periodic intensity variations with the spin of the neutron star and its orbital motion. But a few persistent X-ray binary pulsars also show a long-term periodic intensity variation with timescales more than an order of magnitude greater than the orbital period of the binary. Periodic superorbital intensity variations are seen in Her X-1 (35 days; Still & Boyd 2004), LMC X-4 (30.5 days; Paul & Kitamoto 2002), and 2S 0114+650 (30.7 days; Farrell et al. 2006). SMC X-1 shows quasi-periodic superorbital intensity variations with a 50–60 day cycle (Clarkson et al. 2003). The intensity variations in these systems are understood to be due to obscuration of the central X-ray source by a warped precessing accretion disk. Spectral studies of Her X-1 and LMC X-4 show the iron line intensity and equivalent width evolving during the superorbital periods. The absorption column density along the line of sight is also found to be higher during the low-intensity states, indicating an excess of absorbing matter in the line of sight during these times (Naik & Paul 2003).

Cen X-3 is a high-mass X-ray binary pulsar with very strong but aperiodic long-term intensity variations (Fig. 1). This was the first X-ray pulsar discovered (Giacconi et al. 1971), and is also the brightest persistent pulsar. It has a spin period of ~ 4.8 s and an overall spin-up trend with alternate spin-up and spin-down intervals that last from about 10 to 100 days (Finger et al. 1994). It has an orbital period of 2.1 days and a companion star of about $20 M_{\odot}$ (Avni & Bahcall 1974). Although Cen X-3 is a persistent pulsar, its binary-period-averaged X-ray intensity varies by a factor of more than 40 (Paul et al. 2005). Since the long-term intensity variation of Cen X-3 does not appear to have any periodic or quasi-periodic nature (Paul et al. 2005), it is natural to assume that the X-ray flux variation is due to a changing mass accretion rate. However, using the strong dependence of the orbital modulation and the pulsed fraction of Cen X-3 on its X-ray

intensity state, we have shown that the long-term X-ray intensity variation in this source could be due to a change in obscuration by an aperiodically precessing warped accretion disk (Raichur & Paul 2008). In this scenario, as the X-ray intensity decreases, reprocessed and unpulsed X-rays from a relatively large scattering medium progressively dominate the observed X-ray intensity. We further investigate this hypothesis using the quasi-periodic oscillations (QPO) in Cen X-3 with respect to its intensity state. In accretion-powered X-ray pulsars, QPOs are understood to be due to inhomogeneities in the inner accretion disk, and therefore the frequency is expected to be related to the inner radius of the accretion disk. A correlation between the QPO frequency and X-ray luminosity (and hence mass accretion rate and inner disk radius) has been observed in several transient and persistent X-ray sources, which show a large range of X-ray intensity (EXO 2030+375, Angelini et al. 1989; 3A 0535+262, Finger et al. 1996; XTE J1858+034, Mukherjee et al. 2006; 4U 1626–67, Kaur et al. 2008).

QPOs are known to be present in all types of accreting X-ray pulsars. In most sources it is a transient phenomenon, and QPOs have been detected in about a dozen out of about 100 known accreting X-ray pulsars. With a few exceptions (e.g., 4U 1748–288, Zhang et al. 1996; XTE J 0111.2–7317, Kaur et al. 2007), the QPO frequency is usually in the range of 40–200 mHz, consistent with it being related to the inner radius of the accretion disk around a highly magnetized neutron star in its bright X-ray state. Previous studies of Cen X-3’s power spectrum have shown QPOs at ~ 40 mHz (Takeshima et al. 1991).

In the present work, we mainly study the QPOs of Cen X-3 in relation to the source intensity, if any. For this purpose, we have analyzed all the available archival data from the *Rossi X-ray Timing Explorer (RXTE)* proportional counter array (PCA) from 1996 to 2000.

2. OBSERVATIONS AND DATA ANALYSIS

Cen X-3 was observed extensively by *RXTE* PCA during 1996–1998 and again for some time in 2000. We have analyzed X-ray light curves from all the data available during this period.

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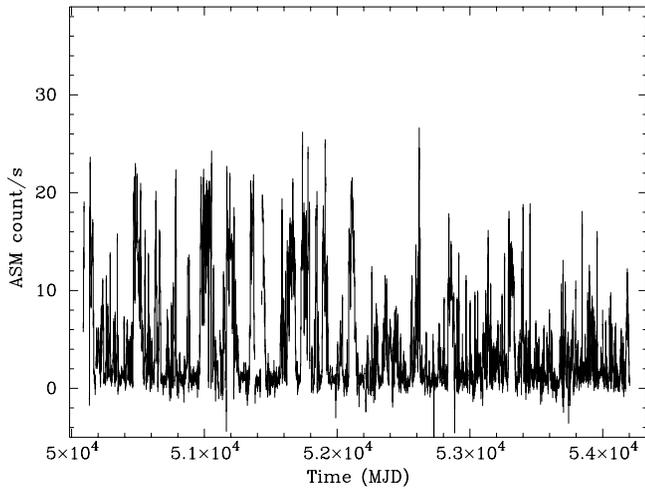


Fig. 1.— The 1.5–12.0 keV band *RXTE* ASM light curve of Cen X-3, shown here with a bin size that is the same as the orbital period.

A total of 525 ks of data was obtained from 81 pointings carried out in this period. Very few of the observations were carried out during the eclipse or ingress/egress of eclipse, and data collected during these periods were excluded from further analysis. Table 1 gives details of the observations.

Light curves were extracted from all the observations using Standard-I data, which has a time resolution of 0.125 s. A power spectrum was obtained for each of these observations using the Standard-I light curve from data stretches of duration 1024 s. Power spectra from all such stretches within one observation pointing were averaged and normalized such that their integral gives the squared rms fractional variability, and the expected white noise level was subtracted. We have detected QPO features at different frequencies, as described below. However, QPO features were not present in all the data sets. Table 2 lists midtimes of the 11 segments in which QPOs were detected, along with the QPO frequencies. We have detected the earlier reported QPOs around 40 mHz in all of the years, although not in every observation. The QPO at 90 mHz was seen only in the observations made in 1996 and never again. The two QPOs at 40 mHz and 90 mHz are not seen together. In all the power spectra in which the QPOs were detected, the peak associated with pulsar spin period was seen very clearly at ~ 0.2 Hz, along with several harmonics. As reported earlier, pulsations were not detected below a background-subtracted count rate of 50 per proportional counter unit, with an upper limit of 0.8% on the pulsed fraction (Raichur & Paul 2008). Some representative power spectra in different intensity states, with and without the QPO features, are shown in Figures 2 and 3.

Another feature seen in most of the power spectra is a broadening of the fundamental spin frequency peak. To investigate the reason for this broadening, we chose the observation with the highest rms of the spin frequency broadening feature (ObsID P20104, TJD of observation 10,508.012–10,508.713). The total length of this observation is about 60,608 s, giving 51 intervals of 1024 s each. A final power spectrum using 1024 s of data stretches averaged over all the intervals was made and then fitted with the model power spectrum given by Lazzati & Stella (1997). The model power spectrum considers the fact that any aperiodic variability in the emission from accretion column(s) of a magnetic neutron star should be modulated at the X-ray pulsar period, hence giving rise to a coupling between the periodic and aperiodic variability (Burderi et al. 1997; Menna et al. 2003).

TABLE 1
LIST OF OBSERVATIONS

| Year | ObsID | No. of Pointings | Total Duration (ks) |
|-----------|--------|------------------|---------------------|
| 1996..... | P10063 | 3 | 40 |
| | P10132 | 5 | 18 |
| | P10133 | 4 | 92 |
| | P10134 | 7 | 143 |
| | P10144 | 5 | 32 |
| 1997..... | P20104 | 12 | 32 |
| | P20105 | 3 | 26 |
| | P20106 | 7 | 14 |
| 1998..... | P30083 | 10 | 13.6 |
| | P30084 | 23 | 65 |
| 2000..... | P40072 | 2 | 50 |

The coupling parameter R , as defined in the model, is a measure of the degree of coupling between the periodic and the aperiodic variabilities. The effects due to a finite length of the light curve are built into the model. Fitting this model (eq. [5] of Lazzati & Stella 1997) to our power spectrum gives $R \approx 0.64$, similar to the results derived by Lazzati & Stella (1997) using *EXOSAT* data for Cen X-3. A value of $R \approx 1.0$ or greater indicates a strong coupling between the aperiodic and periodic variabilities.

In the top panel of Figure 4, a plot of the QPO frequency is shown against the 2–30 keV X-ray flux measured with the PCA. To determine the X-ray fluxes, we have fitted the X-ray spectra with a simple model consisting of a high-energy cutoff power law along with line-of-sight absorption and iron emission lines. Some of the X-ray light curves that showed pre-eclipse X-ray dips were excluded from the X-ray flux determination. The PCA X-ray light curves from which the power spectra have been generated represent the instantaneous measurement of X-ray flux over a small period of a few ks. However, even outside the X-ray eclipse, within one orbital period, the X-ray intensity of Cen X-3 varies smoothly by more than a factor of 2, and rapidly by a factor of up to 4 during the pre-eclipse dips. In a circular orbit, the orbital intensity variation is due to different visibility of the X-ray source and its reprocessing region, rather than changing mass accretion rate. Therefore, we have also looked at the QPO frequency against the orbital-phase-averaged X-ray intensity using data from the All Sky Monitor (ASM) on board *RXTE*. ASM has three detectors which scan the sky in a series of 90 s dwells in three energy bands, namely 1.5–3, 3–5, and 5–12 keV (Levine et al. 1996). The combined ASM light curve, with about 10–20 exposures during each binary orbit of Cen X-3, gives a better estimate of the overall X-ray intensity state of the source. We used the corresponding binary period averaged count rates from the ASM light curve to look for any dependence of the QPO frequency on the X-ray intensity. The ASM count rates given in Table 2 are obtained from orbital-period-averaged light curves after removal of data taken during the eclipse. A plot of the QPO frequency with the ASM count rate is shown in the bottom panel of Figure 4. It is very clear from the figure that there is no dependence of QPO frequency with the instantaneous or orbital-phase-averaged X-ray intensity. The QPO features are clustered around two frequencies, 40 and 90 mHz. Even within each cluster, there is no dependence of QPO frequency with the X-ray intensity. In the top panel of Figure 4 we also show a plot of the expected QPO frequency as a function of the X-ray flux in the beat frequency model. To calculate the X-ray flux expected by the beat frequency model, we have taken a source distance of

TABLE 2
 DETAILS OF QPOS DETECTED IN Cen X-3

| Mid Time of Observation (MJD) | ASM Count Rate | QPO Frequency (Hz) | QPO Width | rms |
|-------------------------------------|-------------------|-----------------------|---------------------|------------------|
| 50146.7283..... | 17.52 ± 1.21 | 0.0903 ± 0.0013 | 0.0091 ± 0.0012 | 10.95 ± 1.93 |
| 50147.3781..... | 17.52 ± 1.21 | 0.0931 ± 0.0015 | 0.0094 ± 0.0016 | 6.21 ± 1.52 |
| 50345.6888..... | 17.12 ± 1.35 | 0.0452 ± 0.0010 | 0.0068 ± 0.0010 | 10.88 ± 2.23 |
| 50509.5281..... | 13.60 ± 0.92 | 0.0384 ± 0.0008 | 0.0113 ± 0.0009 | 5.11 ± 0.46 |
| 50991.4068..... | 10.09 ± 1.80 | 0.0454 ± 0.0019 | 0.0125 ± 0.0027 | 5.71 ± 1.19 |
| 50998.7648..... | 17.73 ± 1.47 | 0.0403 ± 0.0016 | 0.1281 ± 0.0026 | 6.19 ± 1.03 |
| 50999.7818..... | 17.73 ± 1.47 | 0.0419 ± 0.0019 | 0.0048 ± 0.0036 | 3.43 ± 1.18 |
| 51094.9594..... | 1.83 ± 1.21 | 0.0431 ± 0.0009 | 0.0069 ± 0.0010 | 5.93 ± 1.16 |
| 51095.9637..... | 1.83 ± 1.21 | 0.0445 ± 0.0015 | 0.0064 ± 0.0015 | 4.93 ± 1.57 |
| 51578.9780..... | 8.97 ± 1.19 | 0.0402 ± 0.0016 | 0.0051 ± 0.0013 | 3.75 ± 1.01 |
| 51579.9307..... | 7.06 ± 1.06 | 0.0502 ± 0.0022 | 0.0101 ± 0.0018 | 6.49 ± 1.29 |

8 kpc (Krzeminski 1974), and a magnetic field strength of 3.4×10^{12} G (Coburn et al. 2002).

We have also carried out an energy-resolved QPO analysis from one of the observations (ID P10132) in which strong QPOs were detected at ~ 40 mHz using energy-resolved binned mode and event mode data. We extracted light curves with a time resolution of 0.125 s in energy bands of 2–4.1, 4.1–6.6, 6.6–9.5, 9.5–13.1, 13.1–16.7, 16.7–20.4, 20.4–25.7, and 25.7–34.8 keV. The energy-resolved analysis of the 40 mHz QPO, as shown in Figure 5, did not reveal any measurable dependence of the rms fractional variability on energy. Energy-resolved analysis for the 90 mHz QPO could not be done, as the data from the corresponding observation did not have the required energy and timing resolution in any of the data storage modes.

3. RESULTS AND DISCUSSIONS

We can summarize the principal results of our analysis as follows:

1. Cen X-3 shows intermittent QPOs in different frequency ranges, namely 40 and 90 mHz.
2. Neither the presence nor the frequency of the QPOs are related to the luminosity state of the source. The rms fluctuations associated with the QPOs are also not correlated with the luminosity of the source.
3. The rms fluctuation of the 40 mHz QPO is energy independent.
4. A weak coupling is measured between the low-frequency aperiodic variabilities and the spin frequency.

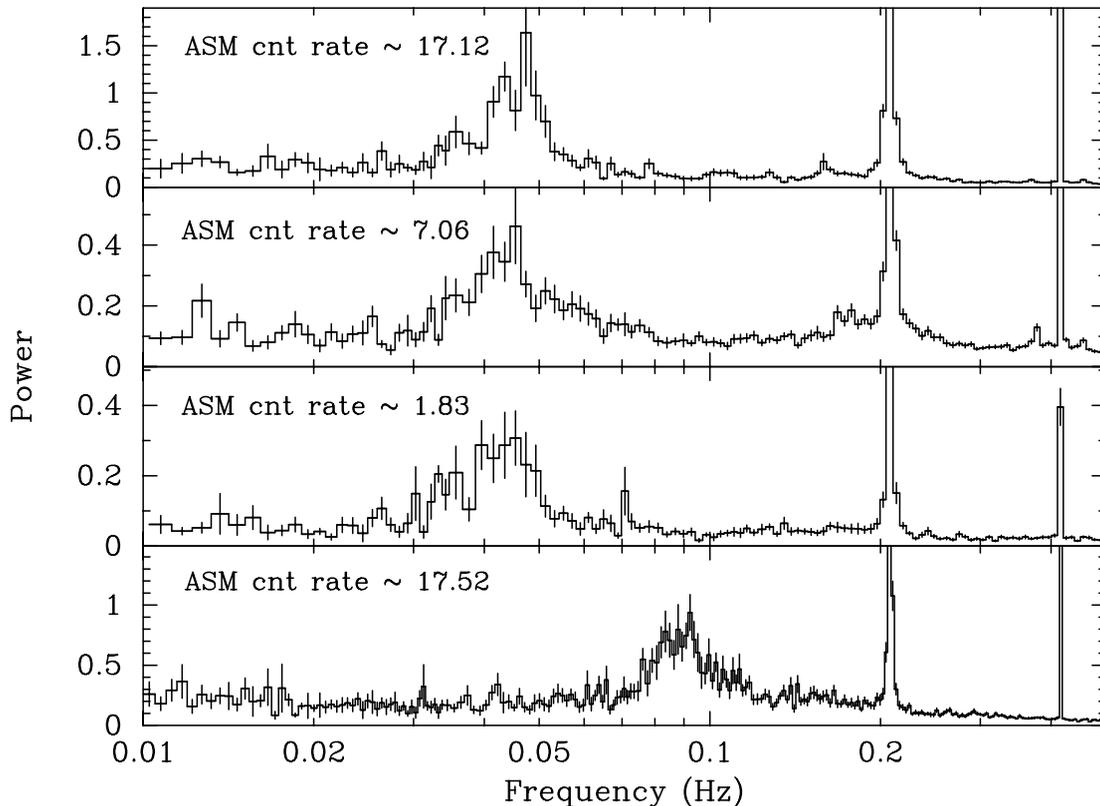


FIG. 2.—Representative power spectra of X-3 with QPOs. Top three panels show the 40 mHz QPO at different intensity states of Cen X-3. Bottom panel shows the 90 mHz QPO seen only during the high-intensity state of Cen X-3 in 1996.

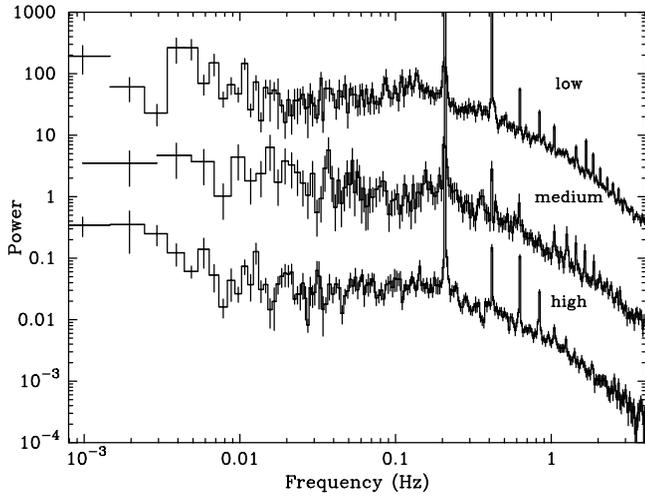


FIG. 3.— Representative power spectra of Cen X-3 at different intensity states without QPOs. The first and second plots are offset for clarity.

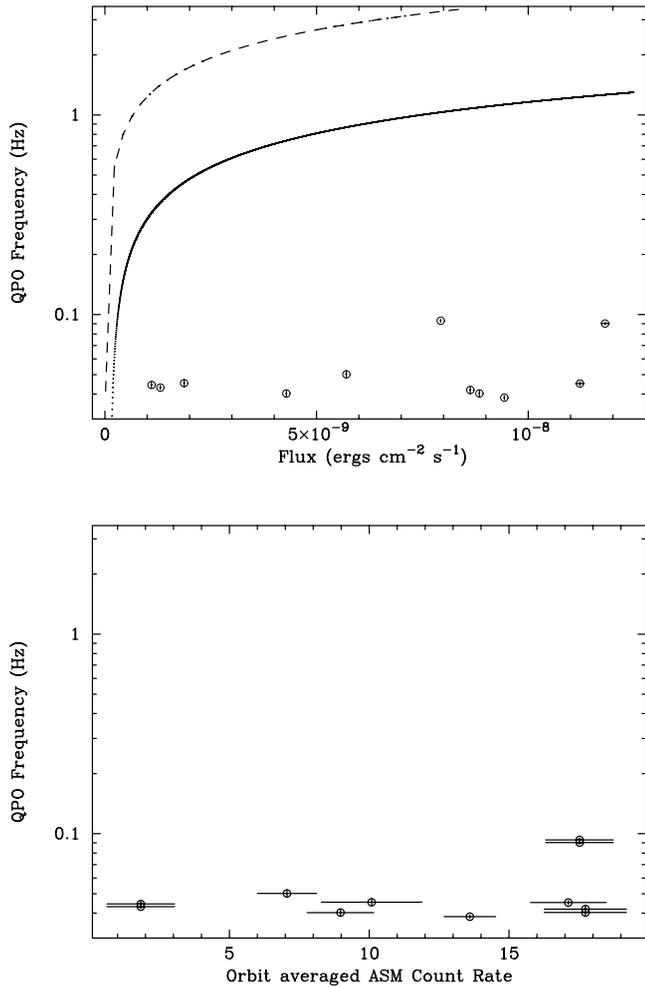


FIG. 4.— Upper panel plots the observed QPO frequency vs. the instantaneous flux as measured using the PCA spectrum (circled points). The dashed line shows the relation of the QPO frequency and the flux of the source as expected from the BFM when r_M is calculated using a scaling factor of 0.5. The solid line shows the same relation when r_M is calculated without using the scaling factor. The lower panel plots the QPO frequency against the orbit-averaged ASM count rate of Cen X-3 at the time of observation.

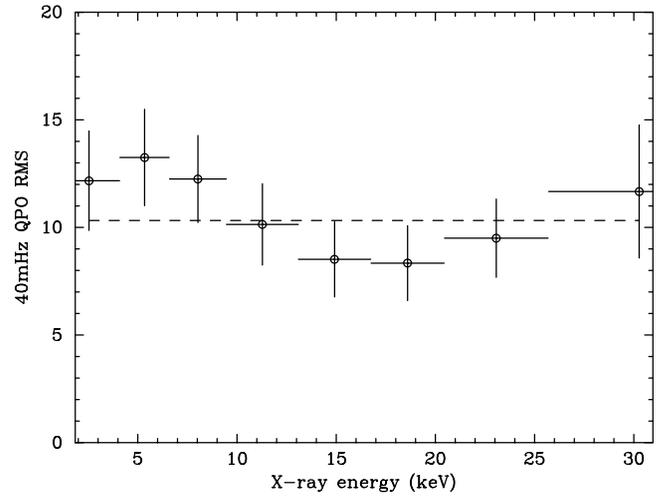


FIG. 5.— Plot of the rms fluctuation in the 40 mHz QPO feature, shown here as a function of energy for observation ID P10132. The average rms value is shown by the dashed line.

In the discussion that follows we argue that the observed QPO properties of Cen X-3 is in agreement with a scenario in which the long-term X-ray intensity variation is due to change in obscuration by an aperiodically precessing warped accretion disk (Raichur & Paul 2008).

The radius of the inner accretion disk around a magnetized neutron star with a mass of $1.4 M_{\odot}$ and a radius of 10 km can also be approximately expressed in terms of its magnetic moment and X-ray luminosity as (Frank et al. 1992)

$$r_M = 3 \times 10^8 L_{37}^{-2/7} \mu_{30}^{4/7}, \quad (1)$$

where L_{37} is the X-ray luminosity in the units of 10^{37} erg, and μ_{30} is the magnetic moment in units of 10^{30} G cm³. For disk accretion, often a scaling factor of 0.5 is used with the above expression of r_M . Then the radius of the inner accretion disk would be $R_M = 0.5r_M$. Coburn et al. (2002) have estimated the magnetic field of Cen X-3 neutron star to be $B \simeq 3.4 \times 10^{12}$ G (i.e., $\mu_{30} = 3.4$) using the cyclotron absorption line in the X-ray spectrum of the source.

The lowest and highest 3–30 keV X-ray fluxes at which the 40 mHz QPO feature is seen are 1.1×10^{-9} and 1.18×10^{-8} erg cm⁻² s⁻¹, respectively. Assuming a distance of 8 kpc (Krzeminski 1974), these correspond to X-ray luminosity of $L_{\text{low}} = 2.64 \times 10^{37}$ erg s⁻¹ and $L_{\text{high}} = 2.83 \times 10^{38}$ erg s⁻¹. If the observed X-ray luminosity represents the true X-ray luminosity and a proportional mass accretion rate of Cen X-3, the inner accretion disk radius (R_M) will approximately vary between 3×10^8 cm and 1.5×10^8 cm. We note that the corotation radius of Cen X-3 ($P_{\text{spin}} \sim 4.8$ s) is 4.7×10^8 cm, larger than the inner disk radius for the lowest X-ray luminosity, and the QPO detections are outside a possible propeller regime.

The two most common QPO models are the beat frequency model (BFM) and the Keplerian frequency model (KFM). The BFM explains the QPO as the beat between the spin frequency ν_{spin} and the Keplerian frequency ν_K of the inner accretion disk $\nu_{\text{QPO}} = \nu_K - \nu_{\text{spin}}$. Thus the radius of the inner accretion disk according the BFM is given by

$$r_{M,\text{BFM}} = \left[\frac{GM_{\text{NS}}}{4\pi^2(\nu_{\text{spin}} + \nu_{\text{QPO}})^2} \right]^{1/3}. \quad (2)$$

In KFM, the QPO occurs at the Keplerian frequency of the inner accretion disk, $\nu_{\text{QPO}} = \nu_{\text{K}}$. Then the radius of the inner accretion disk due to KFM will be

$$r_{M,\text{KFM}} = \left(\frac{GM_{\text{NS}}}{4\pi^2\nu_{\text{QPO}}^2} \right)^{1/3}. \quad (3)$$

However, in the case of Cen X-3, since the ν_{spin} is larger than the observed QPO frequencies, KFM is not applicable. This is because if the inner accretion disk rotates slower than the neutron star, a propeller effect is expected to inhibit accretion of material from the accretion disk. Thus, assuming an inner accretion disk origin of the QPOs and using equations (1) and (2), one can express a relation between the QPO frequency and the X-ray luminosity. In the top panel of Figure 4, we have shown the expected QPO frequency against the measured X-ray for a source distance of 8 kpc. It is obvious from the figure that the QPO frequency of Cen X-3 does not have the flux dependence expected in the beat frequency model.

From a study of the X-ray intensity dependence of the orbital modulation and pulsed fraction in Cen X-3, recently we proposed that the different flux states of Cen X-3 are primarily due to a varying degree of obscuration by an aperiodically precessing warped accretion disk (Raichur & Paul 2008). The nearly constant QPO frequency (ignoring the rare 90 mHz feature) reported here is indeed consistent with this hypothesis. We propose that the mass accretion rate and thus the inner accretion disk radius of Cen X-3 is not highly variable; thus, the source produces a nearly constant QPO frequency. We note here that the frequencies predicted by the BFM are significantly larger than the measured ones. However, the expression used here for magnetospheric radius is only approximate, and a different prescription for the magneto-

spheric radius (for example, if it is considerably larger than r_M given in eq. [1]) could explain the observed QPO frequencies at the highest observed X-ray flux state, and also be consistent with the proposal that the QPO frequency is insensitive to the measured X-ray flux, since the X-ray flux variation is primarily due to disk obscuration.

We also note another possibility, that the QPOs in Cen X-3 may not be due to any material inhomogeneity in the inner accretion disk, as is the case for a few other X-ray binary pulsars, such as A0535+262 (Finger et al. 1996), EXO 2030+375 (Angelini et al. 1989), XTE J1858+034 (Mukherjee et al. 2006), and 4U 1626–67 (Kaur et al. 2008). In these transient binary X-ray pulsars, the QPO frequency is well or somewhat correlated with the X-ray luminosity of the source, and hence the QPO frequency variations are understood to be due to changes in the mass accretion rate and associated changes in the radius of the inner accretion disk.

One approach which could give us more insight would be to study the emission lines from neutral, H-like, and He-like iron atoms in the photoionized circumstellar material. Such spectral observations done during the eclipse ingress and egress of the source would give us information about the distance at which the lines are produced. Measurements carried out at different intensity states of the source would tell us if the observed X-ray intensity is a true measure of the X-ray luminosity and the ionization parameter.

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