Quasi periodic oscillations in XTE J0111.2–7317, highest frequency among the HMXB pulsars

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ABSTRACT

We report here discovery of Quasi Periodic Oscillations (QPOs) in the High Mass X-ray Binary (HMXB) Pulsar XTE J0111.20–7317 during a transient outburst in this source in December 1998. Using observations made with the proportional counter array of the Rossi X-ray Timing Explorer during the second peak and the declining phase of this outburst we have discovered a QPO feature at a frequency of 1.27 Hz. We have ruled out the possibility that the observed QPOs can instead be from the neighbouring bright X-ray pulsar SMC X-1. This is the highest frequency QPO feature ever detected in any HMXB pulsar. In the absence of a cyclotron absorption feature in the X-ray spectrum, the QPO feature, along with the pulse period and X-ray flux measurement measurement helps us to constrain the magnetic field strength of the neutron star.


1. Introduction

Quasi periodic oscillations (QPOs) in X-ray binary pulsars are thought to be related to the motion of inhomogeneous matter distribution in the inner accretion disk and give us useful information about the interaction between accretion disks and the central object. The frequencies of these oscillations in X-ray pulsars (excluding the millisecond accreting pulsars) range from \( \approx 1 \) mHz to \( \approx 40 \) Hz and they can be from \( \approx 100 \) times smaller to

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\[ \approx 100 \text{ times larger than the pulsar spin frequencies (Psaltis D. 2004). Owing to different behavior of the QPO features in different sources, especially its relation with the X-ray luminosity, it is not yet certain whether the QPOs in all the X-ray pulsars arise due to the same mechanism. Investigation of the QPOs and its variations with photon energy and luminosity state, therefore, gives us important clues about the extent and structure of the disk and QPO generation mechanism in accreting X-ray pulsars.} \]

The transient X-ray pulsar XTE J0111.2–7317 was discovered with the Proportional Counter Array (PCA) of the Rossi X-ray Timing Explorer (RXTE) in November 1998 (Chakrabarty et al. 1998a) and was simultaneously detected in hard X-rays with the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (CGRO) with a flux ranging from 18 to 37 mCrab (Wilson & Finger 1998). Public data of CGRO/BATSE and RXTE/ASM revealed that this source was seen in outburst in both hard and soft X-ray during 1998 November-1999 January. Follow-up observations were taken up by Advanced Satellite for Cosmology and Astrophysics (ASCA) to study the pulsations and the X-ray spectrum extending up to 10 keV and thus detected it with a flux of \(3.6 \times 10^{-10}\) erg s\(^{-1}\) cm\(^{-2}\) in the 0.7 - 10.0 keV band (Chakrabarty et al. 1998b; Yokogawa et al. 2000). The ASCA observations also revealed the presence of a pulsating soft excess, which subsequently led to detailed investigations of a similar feature in several accreting X-ray pulsars Her X-1, LMC X-4, SMC X-1 etc. (Endo, Nagase & Mihara 2000, Paul et al. 2002, Naik & Paul 2004a,b) and is now understood to be due to reprocessing of the hard X-rays from the inner accretion disk (Hickox, Narayan & Kallman 2004). ASCA observations during the outburst also gave the opportunity to find position of the source with an error circle of 15\(\text{''}\). BATSE observations found the pulsar to be spinning up with a short time-scale of \(\approx 20\) years (Yokogawa et al. 2000), which confirms that the compact object is a neutron star. This object is present in the direction of the Small Magellanic Cloud (SMC), and it is very likely that it belongs to SMC (Yokogawa et al. 2000). The SMC association was later on confirmed (Coe et al. 1998) by finding the average velocity shift of optical lines to be 166 \(\pm 15\) km s\(^{-1}\) which is comparable with \(\approx 166\) km s\(^{-1}\) for SMC (Feast et al. 1961). Optical counterpart of XTE J0111.2–7317 was first proposed to be a B star with strong H\(\alpha\) and H\(\beta\) emission (Israel et al. 1999) and later on confirmed to be a B0.5-B1Ve star (Covino et al. 2001).

In the subsequent sections we describe timing analysis of the archival X-ray data of XTE J0111.2–7317 from RXTE and we report the discovery of a QPO feature from this source. We investigated the possibility of the QPOs arising from the nearby bright X-ray pulsar SMC X-1 and discuss the implications of the QPOs in this source, especially regarding the strength of the neutron star magnetic field.
2. Observations and Analysis

XTE J0111.2–7317 went into an outburst in November 1998 and was discovered with RXTE-PCA during scans of the SMC X-1 region (Chakrabarty et al. 1998a). Subsequently, two short observations of the source were carried out on 18 December with RXTE-PCA and later the source was monitored frequently from 22 December 1998 to 19 February 1999 as a target of opportunity. There were twenty pointed observations during this time, each with an exposure of \( \sim 2-3 \) ks. For most of the pointings all the five proportional counter units (PCUs) were ON whereas on some occasions three to four PCUs were ON. The source was also regularly monitored by All Sky Monitor (ASM) on board RXTE. The nearby bright binary X-ray pulsar SMC X-1 is only 30' away from XTE J0111.2–7317 and it falls in the field of view (FOV) of RXTE-PCA during observations of XTE J0111.2–7317. Thus we have also used the RXTE-ASM data of SMC X-1 available for the outburst period of XTE J0111.2–7317 to know its flux contributions to the XTE J0111.2–7317 lightcurve and the power density spectrum. Long term lightcurves of XTE J0111.2–7317 and SMC X-1 measured with the RXTE-ASM are shown in Figure 1 for \( \sim 300 \) days, covering the outburst of XTE J0111.2–7317 and about five super-orbital intensity modulations of SMC X-1. Lightcurve of XTE J0111.2-7317 (contaminated by SMC X-1 in parts) taken with RXTE-PCA is also shown in the same Figure with a different marker and different normalization.

Lightcurves were extracted from observations of XTE J0111.2–7317 with the RXTE-PCA with a time resolution of 0.125 s using the Standard-1 data. The background count rates were simulated and subtracted from the Standard-1 lightcurves. The 31 s pulsations of XTE J0111.2–7317 were clearly seen in lightcurves, except during the last few days. The lightcurves were divided into small segments each of length 1024 s and a power density spectrum of each segment was generated. The power spectra were normalised such that their integral gives the squared rms fractional variability and the expected white noise level was subtracted. Figure 2 shows two power spectra averaged over the time ranges 'A' and 'B' marked in Figure 1 when at least one of the two sources XTE J0111.2–7317 and SMC X-1 was bright. The peak at \( \sim 0.032 \) Hz and its harmonics seen in the top spectrum of Figure 2 are due to the pulsations of XTE J0111.2–7317. A small hump seen in the same power spectrum at \( \sim 1.27 \) Hz is a Quasi periodic oscillations feature. The spectrum shown in the bottom of Figure 2 (representing the time range 'B' of Figure 1) shows the absence of 31 s pulsations while the 0.7 s pulsations of SMC X-1 and its harmonics are clearly detected. Figure 3 gives an expanded view of the power spectrum of XTE J0111.2–7317, in the frequency range of 0.5 to 4.0 Hz. The solid line is the best fitted model with one component for the continuum and a second Gaussian component for the QPO feature. From the individual power spectra we found that the QPO signature was prominent during the time of outburst from 51165 MJD to 51173 MJD and faded as the outburst decayed. Inclusion of the Gaussian QPO feature
in the model reduced the $\chi^2$ by 77 for 98 degrees of freedom. The QPO feature is detected with a signal to noise ratio of more than 9. The average QPO frequency was measured to be $1.266 \pm 0.018$ Hz with an rms fraction of $2.52 \pm 0.15\%$. The width of the QPO feature in the Gaussian model was measured to be $\sigma = 0.07 \pm 0.01$ Hz, making it one of the narrowest QPO features among accretion powered X-ray pulsars.

Since SMC X-1 lies within the FOV of RXTE-PCA during the XTE J0111.2–7317 observations, the QPO that is seen in the power spectrum of XTE J0111.2–7317 lightcurves could also be a contribution of SMC X-1. Figure 1 shows the RXTE-ASM lightcurves of SMC X-1 (filled circles) and XTE J0111.2–7317 (open circles) along with the scaled down PCA lightcurve of XTE J0111.2–7317 (crosses) during the 1999 outburst. The SMC X-1 ASM lightcurve clearly shows the semi-periodic intensity variations of about 60 days, which is supposedly its super-orbital period. As can be seen in Figure 1, during the outburst of XTE J0111.2–7317, the ASM count rate of SMC X-1 was considerably high. However as shown in Figure 2, the RXTE-PCA lightcurve of XTE J0111.2–7317 shows the 0.71 s pulsations due to SMC X-1 contamination during the later part of the observations when the flux of XTE J0111.2–7317 has decayed (segment 'B' if Figure 1). But during the peak of the outburst of XTE J0111.2–7317, from MJD 51165 to 51173 (segment 'A' in Figure 1), the lightcurve obtained by PCA does not show the 0.71 s pulsations due to SMC X-1. It is also during this time that the QPO feature is most prominent in the power spectra. We have investigat ed the binary phase of SMC X-1 during the observations of XTE J0111.2–7317 reported here and found out that the observations made in segment A are during the eclipse of SMC X-1. However the segment B observations were done when SMC X-1 was in eclipse egress. Figure 4 shows RXTE-PCA lightcurve of XTE J0111.2–7317 during segment A of Figure 1, along with the 10 year long RXTE-ASM light curve of SMC X-1, both folded with the orbital period of SMC X-1 (Paul, Raichur & Mukherje 2005) during the same time interval.

We have also used additional PCA data to estimate the possible level of contribution from SMC X-1 by its pulsed X-rays. SMC X-1 was observed extensively by RXTE from 24 November 1996 to 5 September 1998 over a range of intensity level of the source. We used the event mode data of RXTE-PCA to obtain the lightcurve of SMC X-1 during this time with a time resolution of 25 ms. We first measured the local spin periods of the pulsar from barycenter corrected lightcurves and then created the pulse profiles by folding the lightcurves at the respective spin period. The individual observations had short time spans of less than 3 ks and therefore the smearing of the pulse profile due to orbital motion of the pulsar was negligible. The difference between the maximum and minimum count rates in the pulse profile was taken as a measure of the pulsed X-ray intensity for each observation. The average X-ray intensity was measured by fitting a constant to the folded lightcurve. A plot of the pulsed X-ray intensity versus the average X-ray intensity of SMC X-1 measured
from the RXTE-PCA observations is shown in Figure 5. It can be clearly seen that pulsed X-ray intensity and the average X-ray intensity are very closely correlated, with a formal correlation coefficient of 0.97. Below an average source plus background count rate of 42 cnt s$^{-1}$ detector$^{-1}$, pulsations are not detected in SMC X-1. As we did not detect the SMC X-1 pulsations along with the 1.27 Hz QPOs (segment 'A' of Figure 1), we can separately conclude that contributions of SMC X-1 towards the total flux is negligible in segment 'A', and therefore, the QPOs must be a feature of XTE J0111.2-7317.

3. Discussion

We have discovered QPOs from observations of the High Mass X-ray Binary (HMXB) pulsar XTE J0111.2–7317 during the second peak and declining phase of its transient outburst in 1998-1999. The two peaks during the outburst can be clearly seen in the lightcurve taken by BATSE onboard CGRO during MJD 51120 to 51200 (Yokogawa et al. 2000). However RXTE-PCA observations for XTE J0111.2–7317 were made during the second peak of the outburst from MJD 51165 to 51228. The 700 ms pulsations of SMC X-1 are detected in part of the light curve near the end of the outburst (segment 'B' of Figure 1) and the corresponding power spectrum is shown in Figure 2. We have found out that the observations in segment 'B' were made when SMC X-1 was in eclipse egress. We have ruled out the possibility that the QPOs observed during the segment 'A' are from SMC X-1 which would have been equally interesting. QPOs have been detected in about one dozen accretion powered X-ray pulsars, including three pulsars with low mass companions, GRO 1744–28 (Zhang et al. 1996), 4U 1626–67 (Shinoda et al. 1990; Kommers et al. 1998) and Her X-1 (Boroson et al. 2000; Moon & Eikenberry 2001b; Makishima et al. 1999). Among the HMXB pulsars, QPOs seem to occur equally frequently in transient and persistent sources. Transient HMXB pulsars from which QPOs have been detected are EXO 2030+375 (Angelini et al. 1989), A 0535+262 (Finger et al. 1996), XTE J1858+034 (B. Paul et al. 1998, Mukherjee et al. 2006), V0332+53 (Takeshima et al. 1994, Qu et al. 2005) and 4U 0115+63 (Soong & Swank 1989) while the Persistent HMXB pulsars with intermittent QPO features have been detected are 4U 1907+09 (In’t Zand et al. 1998, Mukerjee et al. 2001), SMC X-1 (Angelini et al. 1991), Cen X-3 (Takeshima et al. 1991), LMC X-4 (Moon & Eikenberry 2001a, La Barbera et al. 2001) and X-Persei (Takeshima 1997). For most of the accretion powered pulsars the QPOs are a transient phenomenon. See Finger (1998) for a review of the QPOs in transient X-ray pulsars and evolution of the QPO feature along the X-ray outbursts. The QPO frequency in HMXB pulsars detected so far have frequency in the range of 1 mHz to 400 mHz. This is the highest frequency QPOs ever detected among the HMXB pulsars.
Several models have been proposed to explain the QPO generation mechanism in accretion powered X-ray pulsars among which Keplerian Frequency Model (KFM) and Beat Frequency Model (BFM) are used most frequently. Both KFM (QPOs arise from the modulation of the X-rays by inhomogeneities in the inner disk at the Keplerian frequency; van der Klis et al. 1987) and BFM (oscillations occur at the beat frequency between orbital frequency of matter in accretion disk at the Alfvén radius and the stellar spin frequency; Alpar & Shaham 1985, Shibazaki & Lamb 1987) are in good agreement with X-ray pulsars EXO 2030+375 and A 0535+262. In X-ray pulsars 4U 0115+63, V 0332+52, Cen X-3, 4U 1626-67 and SMC X-1, the pulsar frequency is higher than QPO frequency hence the KFM is not applicable in these sources because if the Keplerian frequency at the magnetospheric boundary is less than the spin frequency of the pulsar, propeller effect would inhibit accretion. KFM and BFM also expect a positive correlation between QPO centroid frequency and the X-ray luminosity of an X-ray pulsar, which is not seen in some of the X-ray pulsars like V 0332+52 and GRO J1744-28. Therefore, both KFM and BFM are not applicable in these sources. Recently, Shirakawa & Lai (2002) have shown that the low frequency QPOs in accreting X-ray pulsars can also be due to a magnetically driven precession of warped inner accretion disk.

In XTE J0111.2–7317, both the KFM and BFM models are applicable and as the spin frequency (0.032 Hz) is much smaller than the QPO frequency (1.27 Hz), both these models would give similar value of the radius at which the ~1.3 Hz QPOs are produced. Assuming a neutron star mass of 1.4M⊙ the radius of the QPO production region is calculated to be \( r_{QPO} = \left( \frac{GM_{NS}}{4\pi^2\nu_k} \right)^{1/3} = 1.4 \times 10^8 \text{ cm} \).

The ASCA observations of this source during the outburst measured a flux level of \( 3.6 \times 10^{-10} \text{ ergs cm}^{-2}\text{s}^{-1} \) in the energy range of 0.7-10.0 keV (Yokogawa et al. 2000) and BATSE/ASM on CGRO measured similar pulsed flux in energy band of 20-50 keV. Assuming a pulse fraction of about 50%, the total X-ray flux of XTE J0111.2–7317 can be estimated to be about 4 times of that found from the ASCA observations. As XTE J0111.2–7317 belongs to the Small Magellanic Cloud, the distance uncertainty is relatively less compared to the Galactic X-ray binaries and we assume a source distance of 65 kpc. Therefore, the total X-ray luminosity of the source \( L_X \) at 65 kpc is calculated to be about \( 7.3 \times 10^{38} \text{ erg s}^{-1} \). The radius of the inner accretion disk around a magnetised neutron star with mass of 1.4 M⊙ and a radius of 10 km, can be approximately expressed in terms of its magnetic moment and X-ray luminosity as \( r_M = 3 \times 10^8 L_{37}^{-2/7} \mu_{30}^{4/7} \) (Frank et al. 1992), where, \( L_{37} \) is the X-ray luminosity in the units of 10^{37} erg and \( \mu_{30} \) is the magnetic moment in units of 10^{30} cm^3 Gauss.

Assuming that the QPOs are produced at the inner accretion disk, i.e. equating \( r_{QPO} \)
with $r_M$, the magnetic moment of the neutron star is calculated to be $2.2 \times 10^{30}$ Gauss cm$^3$, which for a neutron star radius of 10 km, is equivalent to a magnetic field strength in the range of $2.2 \times 10^{12}$ to $4.4 \times 10^{12}$ Gauss depending on the magnetic latitude. The magnetic field strength in this pulsar is quite comparable to most other HMXB pulsars. In the absence of a cyclotron absorption feature (Coe et al. 1998) detected in the X-ray spectrum of this source, the QPO frequency and the X-ray luminosity provides us with the only way to estimate the magnetic field strength in this source. For neutron star magnetic field strength of $\sim 10^{12}$ Gauss, the energy of the cyclotron absorption feature on the stellar surface is $\sim 11.6$ keV, thus for this pulsar an absorption feature is expected in the energy range 25-50 keV. More sensitive spectroscopic observations in the hard X-ray band during future outbursts of this source will be useful to detect possible spectral feature due to a cyclotron absorption.

4. Conclusions

We have discovered X-ray Quasi-periodic oscillations at 1.27 Hz during an outburst of the transient high mass binary X-ray pulsar XTE J0111.2-7317. This is the highest frequency QPO feature in this class of objects. We have ruled out the possibility that the QPO feature is associated with the nearby bright X-ray pulsar SMC X-1. Using the X-ray luminosity and the measured QPO frequency and applying models in which the QPOs are produced because of motion of inhomogeneous matter in the inner accretion disk we have estimated the magnetic field strength of the neutron star, which is quite comparable to other pulsars of this class.

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Fig. 1.— RXTE-ASM Lightcurve of XTE J0111.2–7317 and SMC X-1 over a period of 300 days are shown here along with rescaled RXTE-PCA lightcurve from observations made towards XTE J0111.2–7317. Two time ranges MJD 51165.56 to 51177.32 and MJD 51228.00 to 51228.09 marked with 'A' and 'B' correspond to the time when the two sources XTE J0111.2–7317 and XMC X-1 were bright respectively. The two power density spectra for the segments 'A' and 'B' are shown in Figure 2.
Fig. 2.— Power density spectra generated from the lightcurves obtained from RXTE-PCA observations made towards XTE J0111.2–7317 are shown here. The top and bottom spectra are for the time ranges 'A' and 'B' respectively shown in Figure 1. The top figure has been multiplied by a factor of 500 for the sake of clarity.
Fig. 3.— Power density spectrum of XTE J0111.2−7317 generated from the lightcurve over the entire energy band of the PCA. The line represents the best fitted model for the continuum and a Gaussian centered at the QPO frequency.
Fig. 4.— RXTE-ASM light curve of SMC X-1 folded with its orbital period along with RXTE-PCA light curve of XTE J0111.2–7317 during segment A of Figure 1.
Fig. 5.— Relation between average count rate and pulsed count rate for SMC X-1 is shown here. The formal correlation coefficient is determined to be 0.97.