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QUASI-PERIODIC OSCILLATIONS IN XTE J0111.2−7317: HIGHEST FREQUENCY AMONG THE HMXB PULSARS

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ABSTRACT

We report the discovery of quasi-periodic oscillations (QPOs) in the high-mass X-ray binary (HMXB) pulsar XTE J0111.2−7317 during a transient outburst of the source in 1998 December. Using observations made with the Proportional Counter Array of the *Rossi X-Ray Timing Explorer* during the second peak and the declining phase of the outburst, we have discovered a QPO feature at a frequency of 1.27 Hz. We have ruled out the possibility that the observed feature could instead be from the neighboring bright X-ray pulsar SMC X-1. This is the highest frequency QPO ever detected in an HMXB pulsar. In the absence of a cyclotron absorption feature in the X-ray spectrum, the QPO, along with the pulse period and X-ray flux measurement, helps us to constrain the magnetic field strength of the neutron star.

Subject headings: binaries: general — pulsars: individual (XTE J0111.2−7317) — stars: neutron — X-rays: binaries — X-rays: individual (XTE J0111.2−7317) — X-rays: stars

1. INTRODUCTION

Quasi-periodic oscillations (QPOs) in X-ray binary pulsars are thought to be related to the motion of inhomogeneously distributed matter in the inner accretion disk, and they provide 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 $\simeq$1 mHz to $\simeq$40 Hz, and they can be from $\simeq$100 times smaller to $\simeq$100 times larger than the pulsar spin frequencies (Psaltis 2006). Owing to the different behavior of QPO features in different sources, especially their relation to the X-ray luminosity, it is not yet certain whether the QPOs in all X-ray pulsars arise from the same mechanism. Investigation of the QPOs and their variations with photon energy and luminosity state therefore can yield 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) on the *Rossi X-Ray Timing Explorer* (*RXTE*) in 1998 November (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 from BATSE and the *RXTE* All-Sky Monitor (ASM) revealed that this source was seen in outburst in both hard and soft X-rays from 1998 November to 1999 January. Follow-up observations were taken by the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) to study the pulsations and the X-ray spectrum up to 10 keV, detecting it with a flux of 3.6×10^{-10} ergs 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 similar features in several accreting X-ray pulsars: Her X-1, LMC X-4, SMC X-1, and others (Endo et al. 2000; Paul et al. 2002; Naik & Paul 2004a, 2004b). The excess is now understood to be due to reprocessing of the hard X-rays from the inner accretion disk (Hickox et al. 2004). *ASCA* observations during the outburst also provided the opportunity to locate the source within an error circle of 15″. BATSE observations found the pulsar to be spinning up with a short timescale of ~20 years (Yokogawa et al. 2000), thus confirming that the compact object is a neutron star. This object lies in the direction of the Small Magellanic Cloud (SMC), and it is very likely that it belongs to the SMC (Yokogawa et al. 2000), as confirmed (Coe et al. 1998) by the finding that the average velocity shift of the optical lines is 166 ± 15 km s^{-1}, which is comparable to the ~166 km s^{-1} for the SMC (Feast et al. 1961). The optical counterpart of XTE J0111.2−7317 was first proposed to be a B star with strong Hα and Hβ emission (Israel et al. 1999) and later confirmed as a B0.5–B1 Ve star (Covino et al. 2001).

In the following sections, we describe a timing analysis of archival X-ray data on XTE J0111.2−7317 from *RXTE*, and we report the discovery of a QPO feature in this source. We investigate the possibility that the QPOs arise 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's magnetic field.

2. OBSERVATIONS AND ANALYSIS

XTE J0111.2−7317 went into outburst in 1998 November and was discovered with the *RXTE* PCA during scans of the SMC X-1 region (Chakrabarty et al. 1998a). Subsequently, two short PCA observations of the source were carried out on December 18, and later the source was monitored frequently from 1998 December 22 to 1999 February 19 as a Target of Opportunity. There were 20 pointed observations during this time, each with an exposure of ~2–3 ks. For most of the pointings, all five Proportional Counter Units (PCUs) were on, although on some occasions, only three to four PCUs were on. The source was also regularly monitored by the *RXTE* ASM. The nearby bright binary X-ray pulsar SMC X-1 is only 30′ away from XTE J0111.2−7317, and it fell in the PCA field of view (FOV) during observations of XTE J0111.2−7317. Thus, we have also used the *RXTE* ASM data on SMC X-1 available for the outburst period of XTE J0111.2−7317 to ascertain its contributions to the light curve and the power density spectrum. Long-term light curves of XTE J0111.2−7317 and SMC X-1 measured with the *RXTE* ASM are shown in

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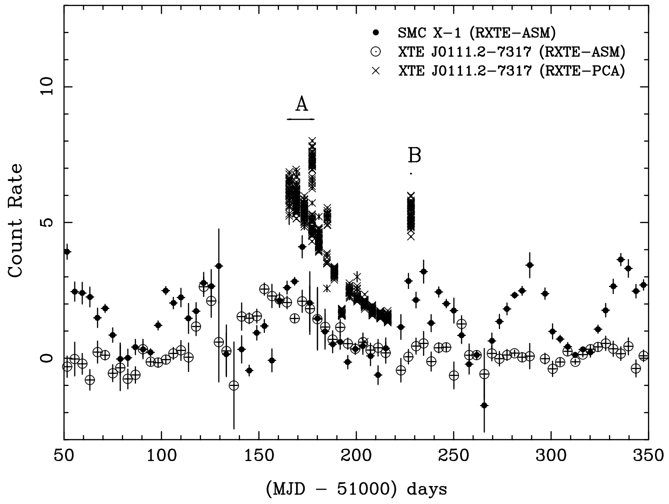

FIG. 1.—*RXTE* ASM light curves of XTE J0111.2−7317 and SMC X-1 over a period of 300 days, along with a rescaled *RXTE* PCA light curve from observations made toward XTE J0111.2−7317. The two time ranges marked "A" (MJD 51,165.56–51,177.32) and "B" (MJD 51,228.00–51228.09) correspond to the two power density spectra shown in Fig. 2.

Figure 1 for ∼300 days, covering the outburst of XTE J0111.2−7317 and about five superorbital intensity modulations of SMC X-1. The PCA light curve of XTE J0111.2−7317 (contaminated by SMC X-1 in places) is also shown, with a different normalization.

Light curves were extracted from the PCA observations with a time resolution of 0.125 s using the Standard-1 data. The background count rates were simulated and subtracted from these light curves. The 31 s pulsations of XTE J0111.2−7317 are clearly visible in the light curves, except during the last few days. The light curves were divided into small segments each of length 1024 s, and a power density spectrum of each segment was generated. The power spectra were normalized 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, during which at least one of the two sources was bright. The peak at ∼0.032 Hz and its harmonics seen in the top spectrum in Figure 2 are due to the pulsations of XTE J0111.2−7317. The small hump seen in the same power spectrum at ∼1.27 Hz is a QPO feature. The lower spectrum in Figure 2 (representing time range B of Fig. 1) shows an 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 XTE J0111.2−7317 power spectrum, in the frequency range 0.5–4.0 Hz. The solid curve is the best-fit model, with one component for the continuum and a second Gaussian component for the QPO. From the individual power spectra, we find that the QPO signature was prominent during the time of outburst, from MJD 51,165 to 51,173, and faded as the outburst decayed. Inclusion of the Gaussian QPO feature in the model reduced the χ^2 by 77 for 98 degrees of freedom. The QPO is detected with a signal-to-noise ratio of more than 9. The average QPO frequency was measured to be 1.266 ± 0.018 Hz with an rms fraction of 2.52% ± 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 such features among accretion-powered X-ray pulsars.

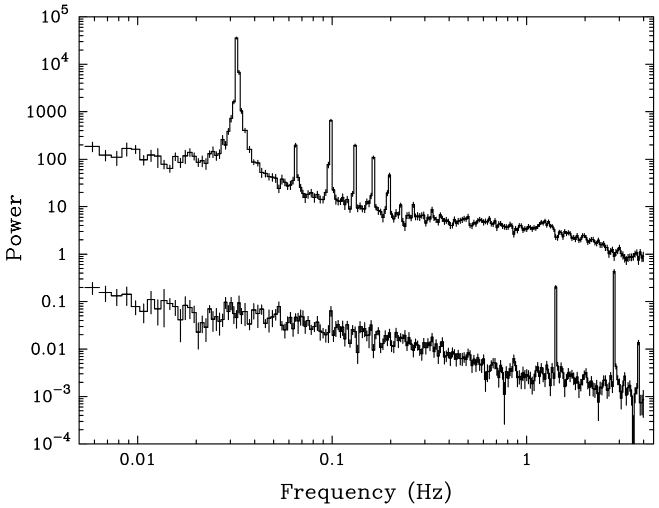

FIG. 2.—Power density spectra generated from the light curves obtained from the *RXTE* PCA observations made toward XTE J0111.2−7317. The upper and lower spectra are for the time ranges A and B, respectively, shown in Fig. 1. The upper spectrum has been multiplied by a factor of 500 for the sake of clarity.

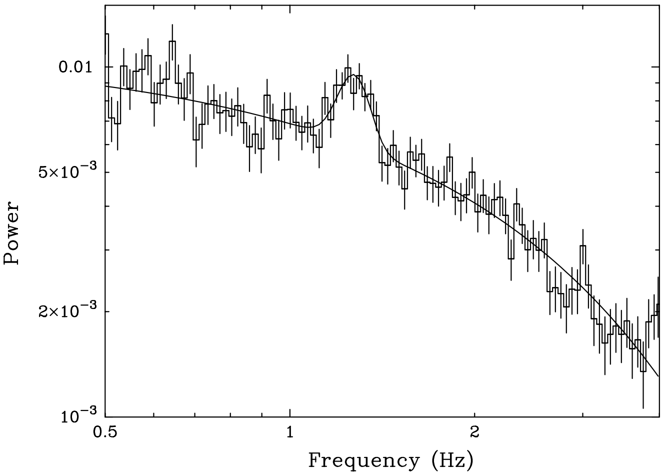

FIG. 3.—Power density spectrum of XTE J0111.2−7317 generated from the light curve over the entire energy band of the PCA. The solid curve represents the best-fit model, composed of the continuum and a Gaussian centered on the QPO frequency.

Since SMC X-1 lay within the FOV of the *RXTE* PCA during the XTE J0111.2−7317 observations, the QPO seen in the power spectrum could also be a contribution from SMC X-1. Figure 1 shows the ASM light curves for SMC X-1 (*filled circles*) and XTE J0111.2−7317 (*open circles*) along with the scaled-down PCA light curve of XTE J0111.2−7317 (*crosses*) during the 1999 outburst. The SMC X-1 light curve clearly shows semiperiodic intensity variations on a timescale of about 60 days, which is supposedly its superorbital 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 quite high. However, as shown in Figure 2, the PCA light curve of XTE J0111.2−7317 shows the 0.71 s pulsations due to SMC X-1's contamination during the later part of the observations, when the flux of XTE J0111.2−7317 had decayed (segment B of Fig. 1). But during the peak of the outburst of XTE J0111.2−7317, from MJD 51,165 to 51,173 (segment A of Fig. 1), the PCA light curve 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 investigated the binary phase of SMC X-1 during the observations of XTE J0111.2−7317 reported here and found that the observations made in segment A were during the eclipse of SMC X-1. However, the segment B observations were done when SMC X-1 was in eclipse egress.

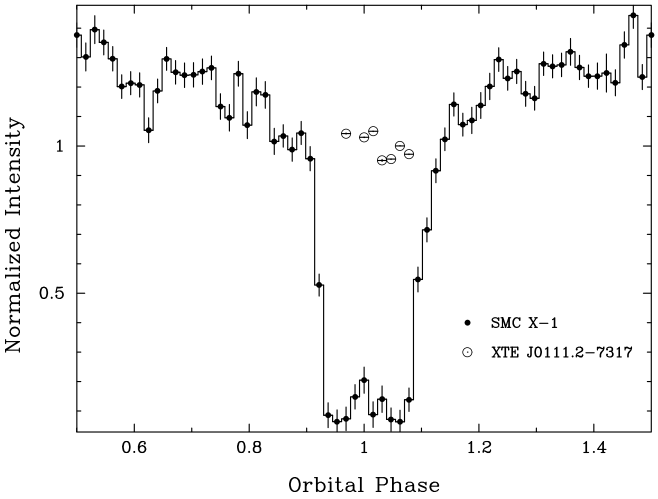

FIG. 4.—*RXTE* ASM light curve of SMC X-1 folded with its orbital period, along with *RXTE* PCA light curve of XTE J0111.2−7317 during segment A of Fig. 1.

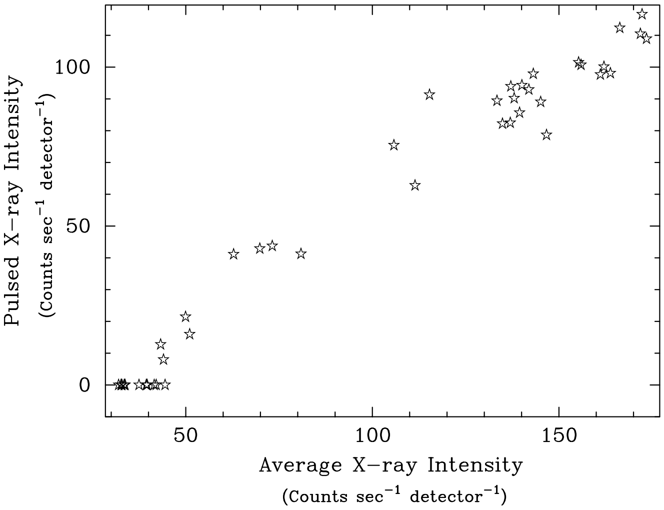

FIG. 5.—Relation between average and pulsed count rates for SMC X-1.

Figure 4 shows the *RXTE* PCA light curve of XTE J0111.2−7317 during segment A, along with the 10 yr *RXTE* ASM light curve of SMC X-1, both folded with the orbital period of SMC X-1 (Paul et al. 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 using its pulsed X-rays. SMC X-1 was observed extensively by *RXTE* from 1996 November 24 to 1998 September 5 over a range of intensity levels. We used the event-mode data from the *RXTE* PCA to obtain the light curve of SMC X-1 over this period with a time resolution of 25 ms. We first measured the local spin periods of the pulsar from barycenter-corrected light curves and then created pulse profiles by folding the light curves on the respective spin periods. The individual observations had short time spans of less than 3 ks, and therefore smearing of the pulse profile due to the 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 light curve. A plot of the pulsed X-ray intensity versus the average X-ray intensity of SMC X-1 measured from the PCA observations is shown in Figure 5. It can be clearly seen that the 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 counts s^{-1} per detector, pulsations are not detected in SMC X-1. As we did not detect the SMC X-1 pulsations along with the 1.27 Hz QPO (segment A of Fig. 1), we can separately conclude that the contribution of SMC X-1 to the total flux is negligible in segment A, and therefore the QPO must be a feature of XTE J0111.2−7317.

3. DISCUSSION

We have discovered QPOs from observations of the 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 light curve taken by BATSE during the period MJD 51,120–51,200 (Yokogawa et al. 2000). However, *RXTE* PCA observations of XTE J0111.2−7317 were made during the second peak of the outburst, from MJD 51,165 to 51,228. 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 Fig. 1), and the corresponding power spectrum is shown in Figure 2. We have found that the observations in segment B were made while SMC X-1 was in eclipse egress. We have ruled out the possibility that the QPOs observed during segment A are from SMC X-1, which would have been equally interesting. QPOs have been detected in about a dozen accretion-powered X-ray pulsars, including three 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), A0535+262 (Finger et al. 1996), XTE J1858+034 (Paul & Rao 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 that 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 Per (Takeshima 1997). For most accretion-powered pulsars, QPOs are a transient phenomenon (see Finger [1998] for a review of QPOs in transient X-ray pulsars and the evolution of the QPO feature during X-ray outbursts). The QPO frequencies in HMXB pulsars detected so far lie in the range of 1 mHz to 400 mHz. This is the highest frequency QPO ever detected from an HMXB pulsar.

Several models have been proposed to explain the QPO generation mechanism in accretion-powered X-ray pulsars, among which the Keplerian frequency model (KFM) and the beat-frequency model (BFM) are used most often. Both KFM (QPOs arise from 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 the orbital frequency of matter in the accretion disk at the Alfvén radius and the stellar spin frequency; Alpar & Shaham 1985; Shibazaki & Lamb 1987) are in good agreement with the X-ray pulsars EXO 2030+375 and A0535+262. In 4U 0115+63, V0332+52, Cen X-3, 4U 1626−67, and SMC X-1, the pulsar frequency is higher than the QPO frequency, and hence KFM is not applicable, because if the Keplerian frequency at the magnetospheric boundary is less than the spin frequency of the pulsar, the propeller effect would inhibit accretion. KFM and BFM also predict a positive correlation between QPO centroid frequency and the X-ray luminosity of an X-ray pulsar, which is not seen in some X-ray pulsars, such as V0332+52 and GRO J1744−28. Therefore, neither KFM nor BFM is applicable in these sources. Shirakawa & Lai (2002) have shown that the low-frequency QPOs in accreting X-ray pulsars can also be due to magnetically driven precession of a 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 would give similar values of the radius at which the ∼1.3 Hz QPOs are produced. Assuming a neutron star mass of 1.4 $M_\odot$, the radius of the QPO production region is calculated to be $r_{\rm QPO} = (GM_{\rm NS}/4\pi^2\nu_k^2)^{1/3} = 1.4 \times 10^8$ cm.

The *ASCA* observations of this source during the outburst measured a flux of 3.6×10^{-10} ergs cm^{-2} s^{-1} in the 0.7–10.0 keV energy range (Yokogawa et al. 2000), and BATSE/ASM on *CGRO* measured a similar pulsed flux in an 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 that found from the *ASCA* observations. As XTE J0111.2−7317 belongs to the SMC, the distance uncertainty is relatively small compared with Galactic X-ray binaries, and we assume a source distance of 65 kpc. Therefore, the total X-ray luminosity $L_{\rm X}$ of the source at 65 kpc is calculated to be about 7.3×10^{38} ergs s^{-1}. The radius of the inner accretion disk around a magnetized neutron star with mass of 1.4 $M_\odot$ and 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 units of 10^{37} ergs, and μ_{30} is the magnetic moment in units of 10^{30} cm^3 G.

Assuming that the QPOs are produced at the inner accretion disk, that is, equating $r_{\rm QPO}$ with r_M, the magnetic moment of the neutron star is calculated to be 2.2×10^{30} G cm^3, which for a radius of 10 km is equivalent to a magnetic field strength in the range $(2.2–4.4) \times 10^{12}$ G, 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 detected cyclotron absorption feature (Coe et al. 1998) in the X-ray spectrum of this source, the QPO frequency and the X-ray luminosity provide us the only way to estimate the magnetic field strength in this source. For a neutron star magnetic field of $\sim 10^{12}$ G, the energy of the cyclotron absorption feature on the stellar surface is ∼11.6 keV, so for this pulsar an absorption feature is expected to lie 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 a possible spectral feature due to cyclotron absorption.

4. CONCLUSIONS

We have discovered X-ray quasi-periodic oscillations during an outburst of the transient high-mass binary X-ray pulsar XTE J0111.2−7317. This is the highest frequency QPO feature seen so far in this class of objects. We have ruled out the possibility that the 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 the 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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