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Quasi-periodic oscillations discovered in the new X-ray pulsar XTE J1858+034

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Abstract. We report the discovery of low frequency quasi-periodic oscillations centered at 0.11 Hz in the newly discovered 221 s X-ray pulsar XTE J1858+034. Among about 30 known transient X-ray pulsars this is the sixth source in which QPOs have been observed. If the QPOs are produced because of inhomogeneities in the accretion disk at the magnetospheric boundary, the low frequency of the QPOs indicate a large magnetosphere for this pulsar. Both the Keplerian frequency model and the beat frequency model are applicable for production of QPOs in this source. The QPOs and regular pulsations are found to be stronger at higher energy which favours the beat frequency model. The magnetic field of the pulsar is calculated as a function of its distance. The energy spectrum is found to be very hard, consisting of two components, a cut-off power law and an iron fluorescence line.

Key words: X-rays: stars – pulsars: individual: XTE J1858+034

1. Introduction

Quasi periodic oscillations (QPOs) observed in X-ray binaries are generally thought to be related to the rotation of the inner accretion disk. When the accretion disk can reach very close to the compact object, like in the case of black hole candidates and low magnetic field neutron star sources, the rotation of the inhomogeneities or hot blobs of material in the inner disk are reflected in the light curve as QPOs. In X-ray pulsars, however, the disk is interrupted at a large distance by the strong magnetic field of the neutron star, and the inner transition zone of the disk, which is at a large distance from the neutron star, does not emit in X-rays. Hence strong QPOs are believed to be rare in X-ray pulsars.

The hard X-ray transient XTE J1858+034 was discovered with the RXTE All Sky Monitor (ASM) in 1998 February (Remillard & Levine 1998). The spectrum was found to be hard, similar to the spectra of X-ray pulsars. Observations were made immediately after this with the Proportional Counter Array (PCA) of the RXTE and regular pulsations with a period of 221.0 ± 0.5 s were discovered (Takeshima et al. 1998). The pulse profile is found to be nearly sinusoidal with a pulse fraction of $\sim 25\%$. From the transient nature of this source and pulsations they suggested that this is a Be-X-ray binary. The position of the X-ray source was refined by scanning the sky around the source with the PCA (Marshall et al. 1998).

From the XTE target of opportunity (TOO) public archival data of the observations of XTE J1858+034, made in 1998 February 20 and 24, we have discovered the presence of low frequency QPOs. We also have obtained the pulse profile of this source in two energy bands and the energy spectrum in one of the observations. In the following sections we describe the archival data that has been used, the analysis and results and discuss some implications of the detection of QPOs in this source.

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Table 1. The observation log

Obs.	Observation duration (UT)	Useful exposure time (s)	Count rate (s^{-1})
A	1998 Feb. 20 21:52 to 22:08	934	138
B	1998 Feb. 24 10:53 to 11:24	1918	167
C	1998 Feb. 24 15:31 to 16:10	2318	144
D	1998 Feb. 24 17:07 to 17:46	1702	148

2. Data

We have analysed four RXTE/PCA observations of XTE J1858+034 made in the high state of the source. The raw data was obtained from the XTE Science Operations Facility (SOF) public data archive. We generated light curves from the raw data in two energy bands $1.3-7$ keV and > 7 keV with 1 s time resolution. Details of the data used for this analysis, with start and end time of the data stretches, average PCA background subtracted count rates etc. are given in Table 1. The light curves obtained from these observations are shown in Fig. 1 with 5 s time bin. Information about the PCA detectors and the RXTE can be found in Jahoda et al. (1996).

3. Results

3.1. Periodic pulsations

Pulsations with 221 s period as reported by Takeshima et al. (1998) are clearly seen in the light curves (Fig. 1). We have used all four observation stretches and obtained the pulsation period by χ^2 maximising method. The period obtained thus is 220.7 ± 0.1 s. The pulsation period could not be determined very accurately because of only about 7000 s of useful data and a large pulse period. Barycentric corrections were not applied which is about one order of magnitude smaller than the error in period estimation. All the light curves were folded with this period and the resultant pulse profiles in two energy bands are shown in the top two panels of Fig. 2 for two cycles. The pulse profile is single peaked and nearly sinusoidal as reported earlier by Takeshima et al. (1998). The pulse fraction (defined as the ratio of pulsed flux to total flux) in the higher energy band ($>$ 7 keV) is 20%, significantly larger than that of 10% in the lower energy band (1.3$-$7 keV). There is indication of significant change in the spectrum with the pulse phase, as the hardness ratio, shown in the bottom panel of Fig. 2, varies by about 15% during the pulsation. A detailed analysis of pulse phased spectrum is in progress.

3.2. Power density spectrum

We generated power density spectrum (PDS) from the 1 s time resolution data. The light curves were broken into segments of length 512 s and the PDS obtained from each of these segments were averaged to produce the final PDS as shown in Fig. 3. A broad QPO feature around 0.1 Hz is very prominent in the PDS. The PDS in the frequency range of 0.006 to 0.6 Hz fits well with a model consisting of a power-law type spectrum and a Gaussian (χ_r^2 of 1.4 for 68 degrees of freedom). The value of χ_r^2 is 2.3 when only a power law is used indicating that the presence of the feature at 0.11 Hz is very significant. The power-law index for the best fit model is found to be -0.95 and the Gaussian, representing the QPO feature is centered at 0.11 ± 0.01 Hz with a width of 0.02 Hz. While fitting the PDS to this model, the region below 0.006 Hz were excluded to avoid the power due to the regular pulsations at 0.0045 Hz. The rms variability in the QPO feature is 6.5%. PDS were also generated in the two energy bands of 1.3$-$7 keV and $>$ 7 keV. The PDS in the two energy bands are found to be identical in shape, comprising of one power law component of index -0.95 and a QPO feature. The rms variation in the high energy band is generally higher and rms in the QPOs is much more in the higher energy band (7.8%) compared to the same in the lower energy band (3.7%). There was no detectable difference in the QPO frequency in the four data sets.

3.3. Energy spectrum

We have generated the count spectrum in 129 binned channels of the PCA detectors from the observation A (see Table 1). The background was generated using the "pcabackest" model provided by the XTE guest observer facility (GOF). Data from all the 5 detectors were added together to produce the spectrum. One low energy channel and channels corresponding to energy greater than 50 keV were ignored because of low signal to noise ratio. The new pulsar XTE J1858+034 is in the Galactic ridge (l $\sim$ 36°.8 and b $\sim$ 0°.138). The background subtraction model that we have used takes care of the diffuse cosmic X-ray emission and the internal background, but not the emission from extended source like the Galactic ridge. From a detailed obser-

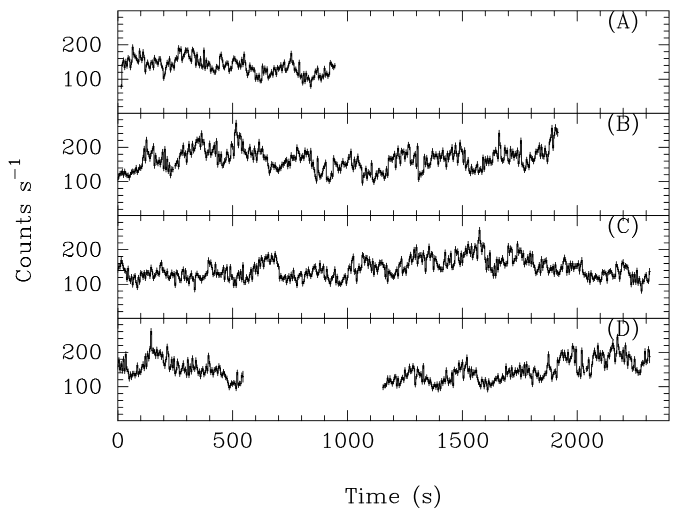

Fig. 1. The background subtracted X-ray light curves of XTE J1858+034 obtained from PCA detectors in the energy range of 1.3$-$100 keV are shown for the four observations (described in the text). The time bin is 5 s. Modulations at the 221 s pulse period are clearly seen.

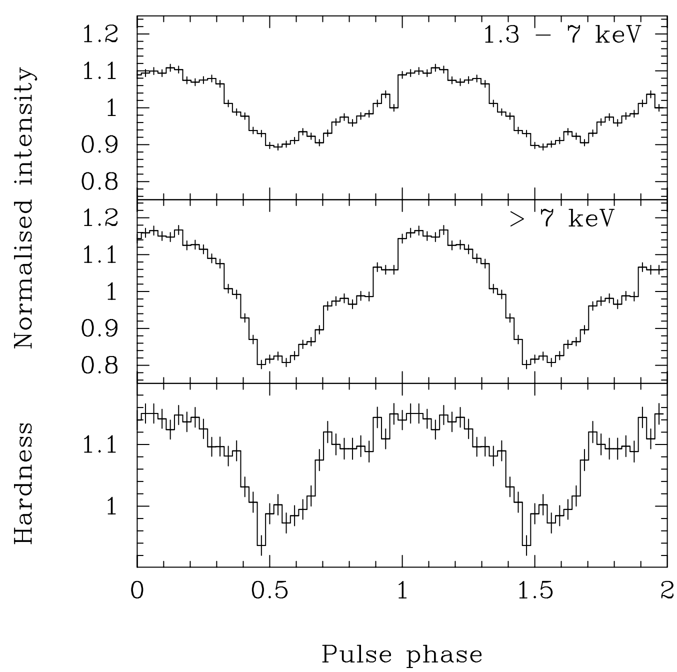

Fig. 2. The pulse profiles of XTE J1858+034 folded at a period of 220.7 s are shown in two energy bands along with the hardness ratio. The profiles are repeated for 2 cycles for clarity.

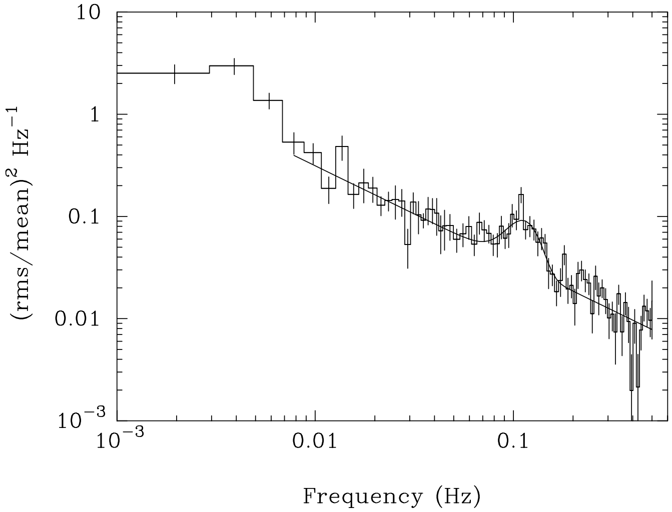

Fig. 3. The power density spectrum of XTE J1858+034 generated from the light curve over the entire energy band of the PCA. The line represents the best fitted model in the frequency range of 0.006−0.6 Hz comprising a power-law type spectrum and a Gaussian centered at the QPO frequency.

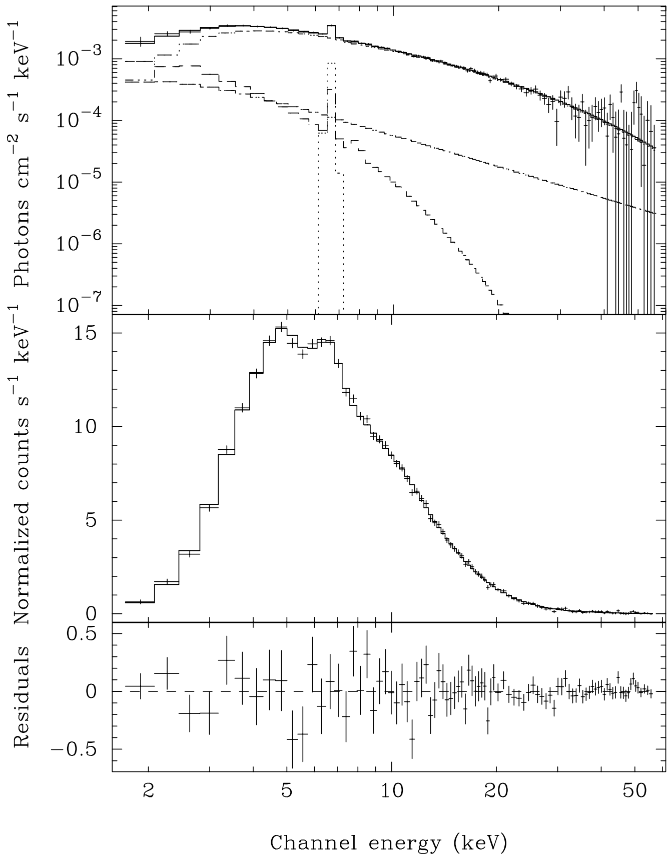

Fig. 4. The X-ray spectrum of XTE J1858+034 is fitted with a cut-off power-law of index 1 and Gaussian line at 6.6 keV of equivalent width 165 eV. The Galactic ridge emission is modeled as a Raymond-Smith plasma of temperature 2.6 keV and a power-law of index 1.7.

vation of the Galactic ridge obtained using the PCAs (Valinia & Marshall, 1998) we estimate that about 10% of the observed flux can be accounted for by the Galactic ridge emission. We have attempted a spectral fitting for the pulse averaged spectrum of XTE J1858+034 by explicitly taking the Galactic ridge emission as a sum of a Raymond-Smith plasma and a power-law, with parameters constrained to be within the range obtained for the ridge emission in Valinia & Marshall (1998). The residual spectrum in 1.7−50 keV range is found to be very hard which can be described as a cut-off power law with a power-law photon index close to 1, cut-off energy of 21 keV, along with a neutral absorption with an equivalent Hydrogen column density of 6 $\times$ 10^{22} cm^{-2}. A narrow emission line, which can be ascribed to atomic Iron inner shell emission, was also found at 6.6 keV, with an equivalent width of 165 eV. Though an acceptable value of χ^2 was obtained (82 for 83 degrees of freedom), parameters values could not be constrained due to the large number of free parameters involved. The total incident flux in the 1.3 − 100 keV band is 6.5 $\times$ 10^{-10} erg cm^{-2} s^{-1} for the pulsar and 0.5 $\times$ 10^{-10} erg cm^{-2} s^{-1} for the Galactic ridge emission. The best fit spectrum with the parameters mentioned above is shown in the top panel of Fig. 4 along with the observed spectrum deconvolved through the detector response function. The observed spectrum and the folded model along with the residual to the model fit are shown in the middle and the bottom panel of the same figure.

4. Discussion

The transient X-ray pulsars in which QPOs have been detected, are the high mass X-ray binaries (HMXB) EXO 2030+375 (Angelini et al. 1989), A 0535+262 (Finger et al. 1996), 4U 0115+63 (Soong & Swank 1989) and V 0332+53 (Takeshima et al. 1994) and the LMXB GRO J1744-28 (Zhang et al. 1996; See Finger 1998 for a review of the QPO in transient X-ray pulsars). QPOs have also been observed in some of the persistent HMXB sources: Cen X-3 (Takeshima et al. 1991), SMC X-1 (Angelini et al. 1991), X Persei (Takeshima 1997) and 4U 1907+09 (in'tZand et al. 1998) and the LMXB 4U 1626-67 (Shinoda et al. 1990; Kommers et al. 1998). Both the Keplerian frequency model (in which the QPOs are produced because some inhomogeneous structure in the Keplerian disk attenuates the pulsar beam regularly) and the beat frequency model (in which the material influx to the pulsar from the disk is modulated at the Keplerian frequency) are in very good aggrement with the observations in EXO 2030+375 and A 0535+262. In 4U 0115+63, V 0332+52, Cen X-3, 4U 1626-67 and SMC X-1 however, the QPO frequency is found to be lower than the pulsation frequency hence the Keplerian frequency model is not applicable in these sources because if the Keplerian frequency at the magnetospheric boundary is less than the spin frequency, centrifugal inhibition of mass accretion will take place. For V 0332+52 the beat frequency model may also be inapplicable because the magnetospheric boundary calculated from the QPO properties and from observed luminosity are in disagreement in this source. In the LMXB transient pulsar GRO J1744-28, large change in X-ray flux was found to be associated with a very little change in the QPO frequency which ruled out both the Keplerian and the beat frequency models for QPOs in this source (Zhang et al. 1996). The beat frequency model is applicable in many sources though there is no convincing evidence of positive correlation between the QPO frequency and the X-ray luminosity in some of them.

According to the beat frequency model, the QPOs are a result of beat phenomena between the rotation of the innermost part of the disk and the spin of the neutron star. The Keplerian rotation frequency ν_K of the disk at the magnetosphere boundary, the rotation frequency of the neutron star ν_S and the QPO frequency ν_{QPO} are related as $\nu_{QPO} = \nu_K - \nu_S$. Assuming that the QPOs are produced as a result of this phenomena, the Keplerian rotational frequency of the innermost part of the disk is just sum of the QPO frequency and the rotation frequency of the pulsar. For an assumed mass of 1.4 $M_\odot$, this can be related to the magnetospheric radius r_M of the X-ray pulsar.

In XTE J1858+034, we find that $\nu_{QPO} = 0.11 \pm 0.01$ Hz, $\nu_S = 0.0045$ Hz and the radius of the magnetospheric boundary is calculated to be

$$r_M = \left(\frac{GM}{4\pi^2\nu_K^2}\right)^{\frac{1}{3}} = 6.5\ 10^8 \left(\frac{M}{M_\odot}\right)^{\frac{1}{3}} \mathrm{cm} \qquad (1)$$

where M is the mass of the neutron star.

The pulse averaged X-ray flux in the 1.3-100 keV band is 6.5 10^{-10} erg cm^{-2} s^{-1} which, for a distance of r_{kpc}, amounts to an X-ray luminosity L_X of 7.9 10^{34} r_{kpc}^2 erg s^{-1}. For a standard accretion disk with disk axis parallel to the magnetic field axis and dipole magnetic field structure of the neutron star, the radius of the inner transition zone can also be expressed as (Frank et al. 1992)

$$r_M = 2.9 \times 10^8 \left(\frac{M}{M_\odot}\right)^{\frac{1}{7}} R_6^{-\frac{2}{7}} L_{37}^{-\frac{2}{7}} \mu_{30}^{\frac{4}{7}} \qquad (2)$$

where, R_6 is the radius of the neutron star in unit of 10^6 cm, L_{37} is X-ray luminosity in unit of 10^{37} erg and μ_{30} is magnetic moment in unit of 10^{30} cm^3 Gauss.

Combining the above two equations, and using M = 1.4 $M_\odot$, R_6 = 1, the magnetic moment μ_{30} of the pulsar is calculated to be $\sim 0.4 \times 10^{30}$ r_{kpc}, which for a neutron star radius of 10^6 cm, is equivalent to a magnetic field of 0.8×10^{12} r_{kpc} Gauss.

If origin of the QPOs in this source is the magnetospheric boundary, the QPOs cannot arise from the modulation of X-rays emitted from the accretion disk because for a magnetospheric radius of 3×10^8 cm the disk temperature is rather low to emit in X-rays. The X-ray modulation at the QPO frequency can arise either because some inhomogeneous structure in the Keplerian disk attenuates the pulsar beam regularly at its rotation frequency, or the material influx to the pulsar from the disk is modulated at the Keplerian frequency. The fact that the strength of the QPO is greater at higher energies indicates that the latter is likely to be the case for XTE J1858+034. A detailed analysis (which is currently in progress) of the QPO feature as a function of pulse phase and energy will help in firmly deciding one of the two alternatives for the QPO phenomenon.

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References

Angelini L., Stella L., Parmar A. N., 1989, ApJ 346, 906
Angelini L., Stella L., White N. E., 1991, ApJ 371, 332
Finger M. H., 1998, Adv. Space Res. (in press)
Finger M. H., Wilson R. B., Harmon B. A., 1996, ApJ 459, 288
Frank J., King A., Raine D. 1992, "Accretion Power in Astrophysics", Cambridge Astrophysics Series, p122
in'tZand J. J. M., Baykal A., Strohmayer T. E., 1998, ApJ 496, 386
Jahoda K., Swank J. H., Giles A. B. et al., 1996, SPIE 2808, 59
Kommers J. M., Chakrabarty D., Lewin W. H. G., 1998, ApJ 497, L33
Marshall F. E., Chakrabarty D., Finger M. H., 1998, IAUC 6828
Remillard R., Levine A., 1998, IAUC 6826
Shinoda K., Kii T., Mitsuda K., Nagase F., Tanaka Y., 1990, PASJ 42, L27
Soong Y., Swank J. H., 1989, The 23rd ESLAB Symposium on Two Topics in X-ray Astronomy. Vol. 1: X-ray Binaries p617
Takeshima T., 1997, BAAS 191, 111.04
Takeshima T., Dotani T., Mitsuda K., Nagase F., 1991, PASJ 43, L43
Takeshima T., Dotani T., Mitsuda K., Nagase F., 1994, ApJ 436, 871
Takeshima T., Corbet R. H. D., Marshall F. E., Swank J. H., Chakrabarty D., 1998, IAUC 6826
Valinia A., Marshal F. E., 1998, ApJ (in press)
Zhang W., Morgan E. H., Jahoda K., et al., 1996, ApJ 469, L29