RXTE-PCA observations of 1A 1118–61: timing and spectral studies during an outburst

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ABSTRACT

We report a detailed timing and spectral analysis of Rossi X-ray Timing Explorer Proportional Counter Array (RXTE-PCA) data obtained from observations during the outburst of a transient X-ray pulsar 1A 1118–61 in 2009 January. The pulse profile showed significant evolution during the outburst and also significant energy dependence – a double-peaked profile up to 10 keV and a single peak at higher energy. We have also detected quasi-periodic oscillations (QPOs) at 0.07–0.09 Hz. The rms value of the QPO is 5.2 per cent, and it shows a significant energy dependence with highest rms of 7 per cent at 9 keV. The QPO frequency changed from 0.09 to 0.07 Hz within 10 d. The magnetic field strength calculated using the QPO frequency and the X-ray luminosity is in agreement with the magnetic field strength measured from the energy of the cyclotron absorption feature detected in this source. The 3–30 keV energy spectrum over the 2009 outburst of 1A 1118–61 can be well fitted with a partial covering power-law model with a high-energy cut-off and an iron fluorescence line emission. The pulse phase resolved spectral analysis shows that the partial covering and high-energy cut-off model parameters have significant changes with the pulse phase.

Key words: binaries: general – pulsars: individual: 1A 1118–61 – X-rays: binaries – X-rays: individual: 1A 1118–61 – X-rays: stars.

1 INTRODUCTION

The hard X-ray transient pulsar 1A 1118–61 was discovered with the Rotation Modulation Collimator (RMC) experiment on Ariel V in 1974 (Eyles et al. 1975). Pulsations were detected in this source with a period of 405.3 s (Ives, Sanford & Bell Burnell 1975) and the optical counterpart of this source was identified as He 3–640 = WRA 793 (Chevalier & Ilovaisky 1975) which is a highly reddened Be star. The star has a visual magnitude of \(V = 12.1\) and is classified as a O9.5IV–Ve (Janot-Pacheco, Ilovaisky & Chevalier 1981; Motch et al. 1988) with strong Balmer emission lines indicating the presence of an extended envelope. The UV spectrum shows many absorption features; especially the C iv line indicating a stellar outflow. The P Cygni profile gives a wind velocity in the range of \(1600 \pm 300\ \text{km s}^{-1}\) and the general spectral profile is similar to that of the optical counterparts of other transient systems (Coe & Payne 1985). The extinction value of \(A_v = 2.8 \pm 0.3\ \text{mag}\) suggested the distance to be 4 kpc. From the Corbet diagram (Corbet 1984) for high magnetic field accreting pulsars, the orbital period is expected to be around 350 d. The known correlation between the orbital period of Be star binaries and Hα EW of the optical companion also indicates a similar large orbital period (Reig, Fabregat & Coe 1997) for 1A 1118–61. However, recently, the detection of a 24-d binary period was reported by Staubert et al. (2011) using Rossi X-ray Timing Explorer Proportional Counter Array (RXTE/PCA) data.

Einstein and EXOSAT observations of this source were carried out in 1979 and 1985, respectively. During these observations, the source was in a quiescent state and the luminosity calculated from the EXOSAT/ME observations was \(0.5–3.0 \times 10^{34}\ \text{erg s}^{-1}\) at 3–7 kpc. This confirms that in the quiescent state, centrifugal inhibition of accretion was not complete. Three outbursts have so far been detected in this source. First outburst was in 1974 (Maraschi et al. 1976). The source had a second outburst that was first detected with Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory (CGRO) in 1991/1992. During this period the source had a peak flux of about 145 mCrab and a spin-down rate of 0.016 s d\(^{-1}\) (Coe et al. 1994). The source was also observed by the WATCH all-sky monitor on Granat (Lund, Brandt & Castro-Tirado 1992).

1A 1118–616 was in quiescence for \(\sim 20\) yr and became highly active in 2009 January. The main outburst lasted only for about \(\sim 20\) d. This third outburst, observed by Swift/XRT in 2009 January, revealed a pulsation period of 407.68 s (Mangano 2009), indicating...
a spin-down in between the outbursts. About three weeks after
the start of the outburst, the source was also observed with
the International Gamma-Ray Astrophysics Laboratory (INTEGRAL/
JEM-X/ISGRI) which detected a flaring activity after the main out-
burst (Leyder, Walter & Lubinski 2009). Many observations of this
source were carried out with RXTE/PCA during this period, and
the combined analysis of the RXTE-PCA and High Energy X-ray Tim-
ing Explorer (HEXTE) spectra revealed a cyclotron line absorption
feature at 55 keV which gives a magnetic field strength of \( 4.8 \times 10^{12} \) G for the neutron star (Doroshenko et al. 2010).

Most of the transient high mass X-ray binary (HMXB) pulsars
are known to have a Be star companion. In Be/X-ray binaries,
X-ray emission is thought to be due to the accretion of matter by
the neutron star from the slow, dense, radial outflow of the Be
star (Negueruela 1998). These systems are observed to exhibit two
different types of X-ray outbursts. One is short X-ray outbursts
(type I outbursts) lasting for a few days \( (L_X \leq 10^{36} - 10^{37} \text{erg s}^{-1}) \)
occurring in several successive binary orbits at orbital phase close
to the time of periastron passage and other is giant X-ray outbursts
(type II outbursts) lasting for several weeks \( (L_X \geq 10^{37} \text{erg s}^{-1}) \)
and may start at any orbital phase. The current outburst in 1A 1118–61
appears to be a type II outburst but of shorter duration and smaller
peak luminosity than the type II outbursts in most other Be/X-ray
binary pulsars.

We have carried out a detailed timing and spectral analysis of
the RXTE-PCA observation of this source during the 2009 January
outburst to detect any intensity or energy dependence of the pulse
profile, aperiodic variabilities and also to find a suitable spectral
model in the 3–30 keV band. One component of the aperiodic vari-
abilities seen in X-ray binaries is the quasi-periodic oscillations
(QPOs), generally thought to be related to the innermost regions
of the accretion disc. Any inhomogeneous matter distribution or
blobs of material in the inner disc may result in QPOs in the power
spectrum. This can give useful information about the interaction
between accretion disc and the central object at different intensity
levels. HMXB pulsars show QPOs only at low frequency, i.e. in the
range of 10 mHz up to about 1 Hz. Black hole X-ray binaries
and low magnetic field neutron stars show QPOs over a wide range
of frequency from a few Hz to a few hundred Hz. Studying QPOs
and their variations with energy and luminosity gives important clues
about the mechanism of QPO production. In Section 2, we describe
the observations and the data used in the present work. In Section
3, we present the pulsation analysis, the power density spectra, the
pulse phase averaged and pulse resolved spectroscopy using the
RXTE-PCA archival data followed by a discussion of the results
in Section 4.

2 OBSERVATIONS AND DATA

During the 2009 outburst of the pulsar 1A 1118–61, a series of
observations were carried out with RXTE. RXTE consists of two
non-imaging instruments: PCA and HEXTE and an All Sky Moni-
tor (ASM) that is sensitive to X-ray photons between 1.5 and 12 keV.
The data analysed in this paper are from observations carried out us-
ing the PCA detectors. The PCA consists of five Xenon proportional
counter units, sensitive in the energy range of 2–60 keV with a total
effective area of 6500 cm². A total of 144 ks of useful PCA data
was obtained from 26 pointings carried out during the outburst. For
most of the pointings only one or two Proportional Counter Units
(PCUs) were ON. The long-term light curves of 1A 1118–61 are shown in Fig. 1 for different energy bands. The top panel shows
the ASM light curve in 2–15 keV energy band with 1 d bin size;

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The top panel shows the RXTE-ASM light curve of 1A 1118–61 in the 2–15 keV energy band with 1 d bin size; the middle panel shows the RXTE-PCU2 light curve with a bin size same as spin period and the bottom panel shows the 15–50 keV light curve from the Swift-BAT all sky monitor with a 1 d bin size.

the middle panel shows the PCU2 light curve with a bin size the same as spin period and the bottom panel shows the 15–50 keV light curve from the Swift-BAT all-sky monitor with a 1-d bin size. For the timing analysis presented in the next section, we have used Standard 1 mode data of the PCA having 0.125 s time resolution and Good Xenon mode data. We have used Standard 2 mode data for spectral analysis, and the spectral fitting was performed using XSPEC v12.6.0.

3 TIMING ANALYSIS

3.1 Pulse profiles

We created 2–60 keV light curves of the source with a time resolu-
tion of 0.125 s from the Standard 1 mode data. To remove data
acquired during periods of Earth occultations and satellite unstable
pointing, we have created Good Time Intervals (GTI) by screening
the raw data with an offset of \( <0.02 \) and elevation angle \( >10° \).
Subsequently, the background count rate was subtracted from the
light curves. The 2009 outburst lasted for \( \approx 20 \) d starting around
MJD 54834 and reached its maximum at around MJD 54845. The
source count rate reached a peak value of about 600 c s\(^{-1}\) per PCU.
In all but the last few PCA observations, the pulsations at around
408 s is clearly seen in the light curves. To measure the pulse pe-
riod and its changes, we first carried out a barycentre correction
and then applied the pulse folding and \( \chi^2 \) maximization technique.
All the single data stretches were not long enough to measure the
pulse period with high enough accuracy to investigate the pulse pe-
riod evolution during this outburst. The most accurate pulse period
measurement we obtained from any single observation is 407.58 s
(MJD 54845). The pulse profile for each day was created by folding
Observations of 1A 1118–61 during an outburst

Figure 2. The pulse profiles of 1A 1118−61, in the 2–60 keV band, obtained on different days observed with RXTE-PCA during the outburst.

The pulse profile showed significant evolution in shape during the outburst. At the beginning of the outburst, the pulse profile is complex with a smaller peak before the main peak. As the outburst progressed, the amplitude of the second peak decreased and on some days the pulse profile appears to have a main peak, a narrow minimum offset by 0.5 spin phase with respect to the main peak and two steps in between the main peak and the minimum, like a shoulder. At the end of the outburst, the overall shape of the pulse profile is a simple sinusoid, but with many narrow spikes or flares.

To check for any energy dependence of the pulse profiles of 1A 1118−61, we created light curves using Good Xenon mode data. We selected the observation (Obs ID P94032/94032-04-02-07) carried out on 14 January near the peak of the outburst having the highest signal-to-noise ratio. The profiles generated for different energy ranges are shown in Fig. 3. At low energies, the pulse profile has two peaks with the main peak leading by a phase of about 0.4, a dip after the smaller peak and a step before the main peak. At high energy, the pulse is made of a single asymmetric peak aligned with the main peak in the low-energy pulse profile. The energy dependence of the pulse profile is seen to be very complex in 1A 1118–61. The smaller peak, seen quite clearly in low-energy range, becomes weaker with increasing energy and above 10 keV, instead of a peak, the minimum of the pulse profile occurs at this phase. The phase range at which the minimum and the step occur in the low-energy band grows in intensity with increasing energy and at high energy this becomes the leading part of the pulse peak. We investigated this complex energy dependence of the pulse profile by carrying out pulse phase resolved spectroscopy described later.

3.2 Power density spectrum

We created power density spectrum (PDS) from the 2–60 keV light curves of 1A 1118–61 using the FTOOL-POWSPEC. The light curves were divided into stretches of length 4096 s and the PDS obtained from each of these segments in one observation were averaged to produce the final PDS. The expected white noise level was subtracted and the PDS was normalized such that the integral gives the squared rms fractional variability. A peak at around 0.0025 Hz corresponding to the spin frequency and its harmonics is seen clearly.

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in all the PDS except in the last few observations. In addition to the main peak, a QPO feature is also seen at 0.09 Hz. The continuum of the power spectrum was fitted with a model consisting of a power-law component and a Lorentzian and the QPO feature was fitted by adding another Lorentzian. The frequency bins corresponding to the pulse frequency and its harmonics were avoided while fitting the continuum. The QPO feature was detected during the period 54841 to 54854 MJD. A representative power spectrum with the QPO feature is shown in Fig. 4.

The quality factor ($\nu/\text{FWHM}$) of the QPO feature was about 5.4 and the detection significance of the QPO feature, including data from all the days when the QPOs were detected, is 7$\sigma$. The rms fractional variability calculated from the background-subtracted data was 5.2 per cent. Using the event mode data, we have measured the energy dependence of the QPO rms which is shown in Fig. 5. The rms value of the QPO is found to increase up to 9 keV and then decrease. QPOs were detected on five different days and a plot of the QPO frequency and rms fractional variability on these days is shown in Fig. 6. The QPO frequency decreased from 0.09 to 0.07 Hz over a span of 10 d along with the decay of the outburst.

4 SPECTRAL ANALYSIS

4.1 Pulse phase-averaged spectroscopy

To study the spectral variations during the outburst, we selected observations carried out on January 07, 14, 20, 21, 24 and 30, covering the entire outburst. We used Standard 2 mode data collected with PCU2 detector only to extract the source spectrum. The background spectrum was simulated using the PCABACKEST tool and appropriate background models for bright sources provided by the RXTE guest observer facility (GOF) was used. We have used 0.5 per cent systematic error to account for the calibration uncertainties while fitting the spectra. We first tried to fit the 3–30 keV spectrum with a model consisting of an absorbed power law with a high-energy cut off and a Gaussian for the iron line emission. This did not give a satisfactory fit with reduced $\chi^2$ in the range 1.6–9.3. The addition of a blackbody component improved the fit, with reduced $\chi^2$ in the range 1.0–2.0 for all six spectra. The temperature of the blackbody component was obtained as about 0.18–0.36 keV, which is common for bright accretion-powered pulsars (Paul et al.
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4.2 Pulse phase resolved spectroscopy

The pulse profiles shown in Fig. 3 exhibit strong energy dependence. As we have argued, a low-temperature blackbody component cannot explain the features above 3 keV. So to investigate this in detail, we have performed pulse phase resolved spectroscopy of an observation made near the peak of the outburst (MJD 54845) which has the highest signal-to-noise ratio among all the RXTE-PCA observations. Energy spectra were extracted in 25 phase ranges and appropriate background subtraction was done. The partial covering model gave an acceptable fit for the spectra in all pulse phase bins. The iron line parameters and the first hydrogen column density were fixed to the phase-averaged value and the rest of the parameters were allowed to vary. We could not constrain the $E_{\text{fold}}$ and $E_{\text{cut}}$ values for phases 0.22 and 0.70. So we freeze the $E_{\text{cut}}$ and $E_{\text{fold}}$ parameter values to the phase-averaged values for these two phases. The variation of the free parameters with pulse phase is shown in Fig. 8. We found significant variation in all the spectral parameters. The second column density and the covering fraction varied by a large factor. However, we note that the variation of two of the parameters, the power-law normalization and the photon index, is correlated and may not be entirely true.

5 DISCUSSION

5.1 Quasi-periodic oscillations

QPOs have so far been detected in 19 accretion-powered high magnetic field pulsars which include mostly HMXBs and a few LMXBs, in both transient and persistent sources. In Table 2 we have listed the sources, the spin frequency $\nu_s$, the QPO frequency $\nu_{\text{QPO}}$ and its range, and the ratio of the two.

The most commonly used models for explaining the QPO mechanism are Keplerian frequency model (KFM), beat frequency model (BFM) and accretion flow instabilities. In the KFM, the QPOs arise due to inhomogeneities at the inner edge of the accretion disc modulating the light curve at the Keplerian frequency. In the BFM, the accretion flow on to the neutron star is modulated at the beat frequency between the Keplerian frequency of the inner edge of the accretion disc and the spin frequency $\nu_{\text{QPO}} = \nu_k - \nu_s$ (Shibazaki & Lamb 1987). The third model applies only to the sources that have...
The occurrence of QPOs in accretion-powered pulsars is quite complex. In some sources like 4U 1626–67, QPOs are detected most of the time while in some others, such as Cen X-3, QPOs are rare. Recently, in two transient pulsars (KS 1947+300 and 4U 1901+03) QPOs were observed only at the end of the outbursts when the source intensity had fallen to a few per cent of the peak of the outbursts (James et al. 2010, 2011). Some transient pulsars like XTE J1858+334 showed QPOs in all observations while some other transient pulsars like EXO 2030+375 showed QPOs in only some of the outbursts. In the 405 s recurrent transient pulsar 1A 1118−61, QPOs are observed in the range 0.07–0.09 Hz in most of the observations near the peak of the outburst. The frequency evolution of the QPO in 1A 1118−61 during the outburst and the presence of QPOs during most of the outburst make this source similar to the transient XTE J1858+334 (Mukherjee et al. 2006). In 1A 1118−61, the QPO frequency is higher than the spin frequency of the pulsar and can be explained in either KFM or BFM and since the QPO frequency is a few hundred times larger than the spin frequency, the radius at which the QPOs are generated is quite similar in the two models. We have

$$R_{QPO} = \left( \frac{GM}{4\pi^2 c^3 v_{QPO}} \right)^{1/3}$$

For an assumed neutron star mass of 1.4 M⊙, R_{QPO} = 9 × 10^{3} km.

The average 3–30 keV X-ray flux during the period of QPO detection is 1.95 × 10^{−9} erg cm^{−2} s^{−1}, which for a distance of 4 kpc corresponds to an X-ray luminosity of 0.37 × 10^{37} erg s^{−1}. The radius of the inner accretion disc can be expressed in terms of the luminosity and magnetic moment as (Frank, King & Raine 2002)

$$R_{\text{acc}} = 3 \times 10^{4} L_{\text{x}}^{1/3} \mu_{30}^{4/7},$$

where $L_{\text{x}}$ is the X-ray luminosity in units of 10^{37} erg s^{−1} and $\mu_{30}$ is the magnetic moment in units of 10^{30} cm^{3} G. Equating $R_{QPO}$ with $R_{\text{acc}}$, we determine a magnetic moment of $\mu_{30} = 3.38 \times 10^{41}$ cm^{3} G, which for a neutron star canonical radius of 10 km corresponds to a surface magnetic field strength of 3.38 × 10^{12} G. The magnetic field strength of the neutron star derived using the QPO frequency and the X-ray luminosity is in excellent agreement with the strength of the magnetic field obtained from the cyclotron line absorption feature (4.8 × 10^{12} G; Doroshenko et al. 2010).

5.2 Pulse profile evolution and energy dependence

Accretion-powered X-ray pulsars are known to show interesting intensity dependence of the pulse profile, both in transient and in persistent sources (Nagase 1989; Raichur & Paul 2010). A most remarkable example of pulse profile evolution was investigated in EXO 2030+375 with EXOSAT observations (Parmar, White & Stella 1989). The evolution of the pulse profile during the outbursts indicates changes in the accretion flow from the inner accretion disc to the neutron star, especially in the mass accretion rate. The X-ray beaming pattern may also change during the outburst depending on the density, dimensions and structure of the accretion column. The 2–60 keV pulse profiles of 1A 1118−61, presented here, also show a complex profile, and profile evolution, as the relatively short outburst reached its peak and then decayed. The pulse profiles shown in Fig. 2 are clearly intensity dependent, but it is not a simple function of intensity. For example, for similar count rates per PCU, the pulse profile is quite different during the rise of the outburst (2009 January 7–10; Fig. 2) and during the decay (2009 January 22–23; Fig. 2).

Most accretion-powered pulsars also show strong energy dependence of the pulse profile. In 1A 1118−61, the position of the main peak is at the same phase in all energies in the 2–30 keV band, but several other features including a second peak at low energy, a narrow dip in the low energy and a leading edge of the main peak at high energy are energy-dependent features clearly seen in energy-resolved pulse profiles (Fig. 3). An intriguing aspect is that the pulse shape change appears at around 10 keV. Strong energy dependence of pulse profiles – in other words strong pulse phase dependence of the energy spectrum – is known to be present also in magnetars (see Enoto et al. 2010, and references therein), and multi-component emission models are invoked there to describe the same. However, we find that multi-component spectral model for accretion-powered pulsars, including a low-temperature blackbody, cannot explain the change in pulse profile at around 10 keV. For pulse phase-averaged and pulse phase-resolved spectroscopy, we have therefore used a model that can fit features in the medium-energy band.

### Table 1. Best-fitting spectral parameters of 1A 1118−61.

| Parameter | Jan 07 | Jan 14 | Jan 20 | Jan 21 | Jan 24 | Jan 30 |
|-----------|--------|--------|--------|--------|--------|--------|
| N_H1 (10^{22} cm^{-2}) | 1.22 (fixed) | 1.22 (fixed) | 1.22 (fixed) | 1.22 (fixed) | 1.22 (fixed) | 1.22 (fixed) |
| N_H2 (10^{22} cm^{-2}) | 284^{+19}_{-18} | 216^{+20}_{-19} | 218^{+28}_{-29} | 371^{+12}_{-13} | 341^{+38}_{-36} | 639^{+95}_{-64} |
| CvFract | 0.15^{+0.03}_{-0.04} | 0.17 ± 0.02 | 0.15 ± 0.03 | 0.11 ± 0.05 | 0.26 ± 0.05 | 0.54^{+0.03}_{-0.04} |
| P_index | 0.50 ± 0.03 | 0.30 ± 0.02 | 0.46 ± 0.03 | 0.34 ± 0.05 | 0.55 ± 0.05 | 0.44^{+0.05}_{-0.08} |
| P_Ne - | 0.053^{+0.003}_{-0.002} | 0.083 ± 0.004 | 0.069 ± 0.004 | 0.053^{+0.003}_{-0.002} | 0.053 ± 0.002 | 0.037 ± 0.03 |
| E_cut (keV) | 4.96^{+0.10}_{-0.17} | 5.88^{+0.17}_{-0.19} | 5.84^{+0.22}_{-0.28} | 4.88^{+0.32}_{-0.28} | 4.76^{+0.25}_{-0.23} | 5.01^{+0.20}_{-0.23} |
| E_fold (keV) | 12.64^{+0.65}_{-0.59} | 12.38^{+0.28}_{-0.24} | 14.08 ± 0.48 | 13.12^{+0.74}_{-0.92} | 13.22^{+1.08}_{-1.16} | 8.35^{+0.60}_{-0.62} |
| E_Fe (keV) | 6.41 ± 0.06 | 6.42^{+0.07}_{-0.08} | 6.33^{+0.08}_{-0.09} | 6.30 ± 0.06 | 6.41 ± 0.08 | 6.17 ± 0.10 |
| Fe EqWidth (eV) | 84 | 41 | 52 | 78 | 86 | 86 |
| FeNorm | 1.34 | 1.34 | 1.27 | 1.76 | 1.05 | 0.57 |
| Total flux (3–30 keV) | 3.25 | 8.91 | 5.39 | 5.03 | 2.62 | 1.11 |
| Red-$\chi^2$/d.o.f | 0.76/47 | 0.78/47 | 0.77/47 | 0.96/47 | 0.67/47 | 1.36/47 |

* The minimum of N_H1 was fixed to the Galactic hydrogen column density of 1.22 × 10^{22} atoms cm^{-2} towards this source and was allowed to vary only to the higher side.

† 10^{-3} photons cm^{-2} s^{-1}.

‡ 10^{-9} erg cm^{-2} s^{-1} for 3–30 keV.

The luminosities close to the Eddington limit (Fortner, Lamb & Miller 1989).

The average 3–30 keV X-ray flux during the period of QPO detection is $1.95 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$, which for a distance of 4 kpc corresponds to an X-ray luminosity of $0.37 \times 10^{37}$ erg s$^{-1}$. The radius of the inner accretion disc can be expressed in terms of the luminosity and magnetic moment as (Frank, King & Raine 2002)
5.3 Pulse phase-averaged and pulse phase resolved spectra

The continuum spectra of accreting X-ray pulsars are often best described by a power law with a high-energy cut-off and interstellar absorption. In most cases, the presence of a Gaussian component, for iron line fluorescent emission, is also evident. Cyclotron resonance absorption features have also been detected in about 20 bright pulsars, usually at energies above 10 keV. In 1A 1118–61, Doroshenko et al. (2010) detected a cyclotron absorption feature at \( \sim 55 \) keV using the combined PCA and HEXTE data in the 4–120 keV band. Considering the complex energy dependence of the pulse profile and from pulse phase resolved spectroscopy, we find that a partial covering power-law model describes the data very well. With a partial covering model we do not see a feature at 8 keV. The 8 keV feature mentioned in Doroshenko et al. (2010) and several other contemporary papers probably has same reason that a very simple, single continuum model is used while the sources have complex absorption. If the 8 keV feature is an instrument artefact, it should have been seen in all kinds of sources. However, such a feature has not been reported in the X-ray spectrum of black hole binaries and is also not seen in the spectrum of the Crab Nebula (Kirsch et al. 2005; Weisskopf et al. 2010). We would also like to note here that at higher energy, the partial covering absorption model is the same as a simple power-law model, and thus the cyclotron absorption feature reported by Doroshenko et al. (2010) is not in question here. Lin et al. (2010) fitted the 0.5–10.0 keV energy spectrum of this source obtained with the Swift-XRT and found that in this limited energy band, the spectra are fitted best with two blackbody components.
However, since the source shows strong hard X-ray emission (as detected with Swift-BAT; Fig. 1) and the two blackbody model cannot produce the hard X-ray photons, this model is inappropriate for this pulsar as well as for any hard X-ray pulsar.

In the partial covering absorption model, a part of the continuum source is obscured, resulting in a harder spectrum (Wang et al. 2010). If the absorbing component is in the form of an accretion stream or is a part of the accretion column, it can be phase locked with the neutron star, resulting into a phase-dependent column density and covering fraction. The pulse phase resolved spectroscopy reported here shows a strong modulation of the partial covering fraction as well as the column density supporting such a scenario for this pulsar. We also notice a systematic variation of the cut-off energy value and the e-folding energy at the pulse phases with highest column density of the partial covering material. A similar energy dependence of the pulse profile and pulse phase dependence of the spectral parameters have recently been found in another accretion-powered transient pulsar GRO J1008-57 (Naik et al. 2011) in the broad-band data obtained with the Suzaku X-ray observatory.

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Table 2. List of QPO sources.

| Source          | Type         | $\nu_s$ (mHz) | $\nu_{\text{QPO}}$ (mHz) | $\nu_{\text{QPO}}/\nu_s$ | Reference$^a$ |
|-----------------|--------------|---------------|--------------------------|--------------------------|---------------|
| Transient pulsars |              |               |                          |                          |               |
| KS 1947+300     | HMXB/Be      | 53            | 20                       | 0.38                     | 1             |
| SAX J2103.5-4545| HMXB/Be?     | 2.79          | 44                       | 15.77                    | 2             |
| A0535+26        | HMXB/Be      | 9.7           | 50                       | 5.15                     | 3             |
| V0332+53        | HMXB/Be      | 229           | 51                       | 0.223                    | 4             |
| 4U 0115+63      | HMXB/Be      | 277           | 62                       | 0.224                    | 5             |
| 1A 1118-61      | HMXB/Be      | 2.5           | 92                       | 36.8                     | This work     |
| XTE J1858+34    | HMXB/Be      | 4.53          | 110                      | 24.3                     | 6             |
| 4U 1901+03      | HMXB/Be?     | 361.9         | 130                      | 0.359                    | 7             |
| EXO 2030+375    | HMXB/Be      | 24            | 200                      | 8.33                     | 8             |
| SWIFT J1626.6-5156 | HMXB/Be  | 65            | 1000                     | 15.38                    | 9             |
| XTE J0111.2-7317| HMXB/B0.5-B1Ve | 32            | 1270                     | 39.68                    | 10            |
| GRO J1744-28    | LMXB         | 2100          | 20000                    | 9.52                     | 11            |
| Persistent pulsars |              |               |                          |                          |               |
| SMC X-1         | HMXB/B0      | 1410          | 10                       | 0.0071                   | 12            |
| Her X-1         | LMXB         | 806           | 13                       | 0.016                    | 13            |
| LMC X-4         | HMXB/O-type  | 74            | 0.65–20                  | 0.0087–0.27              | 14            |
| Cen X-3         | HMXB/O-type  | 207           | 35                       | 0.17                     | 15,16         |
| 4U 1626–67      | LMXB         | 130           | 48                       | 0.37                     | 17,18         |
| X Per           | HMXB/Be      | 1.2           | 54                       | 45                       | 19            |
| 4U 1907+09      | HMXB/OB      | 2.27          | 69                       | 30.4                     | 20,21         |

$^a$References: (1) James et al. (2010); (2) Inam et al. (2004); (3) Finger, Wilson & Harmon (1996); (4) Takeshima et al. (1994); (5) Soong & Swank (1989); (6) Paul & Rao (1998); (7) James et al. (2011); (8) Angelini, Stella & Parmar (1989); (9) Reig et al. (2008); (10) Kaur et al. (2007); (11) Zhang et al. (1996); (12) Angelini, White & Stella (1991); (13) Moon & Eikenberry (2001b); (14) Moon & Eikenberry (2001a); (15) Takeshima et al. (1991); (16) Raichur & Paul (2008); (17) Shinoda et al. (1990); (18) Kaur et al. (2008); (19) Takeshima (1997); (20) in’t Zand, Baykal & Strohmayer (1998); (21) Mukerjee et al. (2001).
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The QPO discovery mentioned in this paper was presented at the 38th COSPAR Scientific Assembly, 2010 July, Bremen, Germany. After initial submission of this paper, discovery of the same has also been reported by Nespoli & Reig (2011).

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