Detection of a variable QPO at \(\sim 41\) mHz in the Be/X-ray transient pulsar 4U 0115+634

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ABSTRACT

We report the detection of quasi-periodic oscillation (QPO) at \(\sim 41\) mHz in the transient high-mass Be/X-ray binary pulsar 4U 0115+634 using data from the Rossi X-Ray Timing Explorer (RXTE) observatory. The observations used in the present work were carried out during X-ray outbursts in 1999 March–April, 2004 September–October and 2008 March–April. This frequency of the newly detected QPO was found to vary in 27–46 mHz range. This \(\sim 41\) mHz QPO was detected in four of the 36 pointed RXTE Proportional Counter Array (PCA) observations during 1999 outburst whereas during 2004 and 2008 outbursts, it was detected in four and three times out of 33 and 26 observations, respectively. Though QPOs at \(\sim 2\) mHz and \(\sim 62\) mHz were reported earlier, the \(\sim 41\) mHz QPO and its first harmonic were detected for the first time in this pulsar. There are three RXTE/PCA observations where multiple QPOs were detected in the power-density spectrum of 4U 0115+634. Simultaneous presence of multiple QPOs is rarely seen in accretion-powered X-ray pulsars. Spectral analysis of all the pointed RXTE/PCA observations revealed that the 3–30 keV energy spectrum was well described by Negative and Positive power law with EXPonential (NPEX) cut-off continuum model along with interstellar absorption and cyclotron absorption components. During the three X-ray outbursts, however, no systematic variation in any of the spectral parameters other than the earlier reported anti-correlation between cyclotron absorption energy and luminosity was seen. Presence of any systematic variation of QPO frequency and rms of QPO with source flux were also investigated yielding negative results.

Key words: stars: individual: 4U 0115+634 – X-rays: binaries – X-rays: stars.

1 INTRODUCTION

Be/X-ray binaries (BeXBs) represent the largest sub-class of high-mass X-ray binaries (HMXBs). BeXBs are known to consist of a neutron star and a non-supergiant OB star (luminosity class of III, IV or V) showing Balmer lines in the emission spectrum (Reig 2011). The optical companion in BeXB systems (Be star) is still on the main sequence. The neutron star in these systems is generally in moderate eccentric \((e \geq 0.3)\) and wide orbit with orbital period in range of 16–400 d. Mass transfer from the optical companion to the neutron star takes place through the equatorial circumstellar disc around the Be star. Though the neutron star spends most of the time away from the Be circumstellar disc, during the periastron passage, abrupt mass accretion takes place resulting in periodic X-ray outbursts, known as Type I outbursts. The peak luminosity during these periodic outbursts is moderate \((L_X \leq 10^{35} - 10^{37} \text{ erg s}^{-1})\); Stella, White & Rosner 1986). The duration of these outbursts is in the range of a few days to a few tens of days. The BeXBs occasionally show giant outbursts, known as Type II outbursts. These outbursts are caused by the enhanced episodic outflow of the Be star. The peak luminosity during Type II outbursts is estimated to be as high as \(10^{38} \text{ erg s}^{-1}\) or more (Stella et al. 1986; Negueruela et al. 1998). These outbursts are irregular and not linked with the binary orbit of the system. The neutron stars in most of the BeXB systems are found to be accretion-powered pulsars. The pulse period of these pulsars is in the range of a few seconds to several hundreds of seconds. The X-ray spectrum of these pulsars is found to be hard. For a brief review on the temporal and spectral properties of transient BeXB pulsars, refer to Paul & Naik (2011).

The Be/X-ray transient pulsars 4U 0115+634 was discovered during the UHURU satellite survey (Giacconi et al. 1972; Forman et al. 1978). Using the survey data, the pulsation of the transient pulsar was first estimated to be 3.6 s (Cominsky et al. 1978). A few years after the discovery, a new outburst was detected with SAS3 during 1977 December to 1978 January. Using the precise position of the

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pulsar obtained from the SAS3, ArielV and HEAO-1 observations (Cominsky et al. 1978; Johnston et al. 1978), the optical counterpart was identified to be a strongly reddened Be star with a visual magnitude $V \sim 15.5$ and named as V635 Cas (Johns et al. 1978; Hutchings & Crampton 1981). Timing observations of the pulsar with SAS3 were used to estimate orbital parameters of the binary system such as orbital period $P_{\text{orb}} = 24.31 \pm 0.02$ d, eccentricity of the orbit $e = 0.34 \pm 0.01$, projected semimajor axis $a \sin i = 140 \pm 0.16$ lt-sec, $\omega = 47.66 \pm 0.17$, mass function $f(M) \approx 5 M_{\odot}$ and time of periastron passage $\tau = 2443540.95 \pm 0.01$ d (Rappaport et al. 1978). The distance to the pulsar 4U 0115+63 was estimated to be 7–8 kpc (Negueruela & Okazaki 2001). A detailed study of optical and X-ray emissions from the binary system showed that the Type II outbursts in this pulsar were detected at an interval of about every three years (Whitlock, Roussel-Dupre & Friedhorsky 1989).

This was explained in terms of instabilities in the circumstellar disc due to radiative warping (Negueruela et al. 2001). The continuum spectrum of the pulsar was well described by a power-law model with high-energy cut-off (Rose et al. 1979; White, Swank & Holt 1983). A cyclotron resonance scattering feature (CRSF) at $\sim 23$ keV was first detected in the HEAO-1 A4 spectra of pulsar during an outburst (Wheaton et al. 1979) which was later suggested to be the first harmonic resonance, with the fundamental resonance at $\sim 11$ keV (White et al. 1983). This was later confirmed with Ginga observation of the pulsar (Nagase et al. 1991). Second, third and fourth harmonics of the CRSF are later detected in the pulsar spectrum from Rossi X-Ray Timing Explorer (RXTE) and BeppoSAX observations (Heindl et al. 1999; Santangelo et al. 1999). A close monitoring of the 1999 March–April outburst of the pulsar with RXTE confirmed the luminosity dependence of the CRSF in 4U 0115+634 which was interpreted as a result of the decrease in height of the accretion column, in response to a decrease in the mass accretion rate (Nakajima et al. 2006). Similar anti-correlation between the CRSF energy and X-ray luminosity has been seen in other binary X-ray pulsars such as A0535+262, Her X-1 (Terada et al. 2006; Mihara et al. 2007; Enoto et al. 2008, and references therein), etc. HEAO-1 observation of the pulsar 4U 0115+634, during an outburst, reported possible presence of quasi-periodic oscillations (QPOs) at 62 mHz (Soong & Swank 1989). Apart from the 62-mHz QPO, another low-frequency QPO at 2 mHz was detected in RXTE observations of the pulsar during 1999 March–April outburst (Heindl et al. 1999). These QPOs were explained as due to the obscuration of the neutron star by hot matter in the accretion disc. The blobs of hot matter in the inner accretion disc are understood to be because of the inhomogeneities caused by the interactions of the neutron star magnetosphere and the accretion disc.

In the present work, we have investigated the timing and spectral properties of the transient X-ray pulsar 4U 0115+634 using observations made with the RXTE/PCA and report the detection of variable QPO features detected during three X-ray outbursts in 1999 March, 2004 September and 2008 April.

2 OBSERVATION AND DATA ANALYSIS

RXTE was launched on 1995 December 31 with the main objective of timing studies of celestial X-ray sources. It made great contributions towards the understanding of high-energy astrophysics by means of its unrivaled timing resolution. We have used the RXTE observations of transient BeXB pulsar 4U 0115+634 during three of its Type II outbursts. RXTE, which is now decommissioned, had three sets of major instruments. The All-Sky Monitor (ASM) was sensitive in 1.5–12 keV energy range (Levine et al. 1996). The Proportional Counter Array (PCA), which was consisting of five xenon-filled proportional counter detectors, was sensitive in 2–60 keV energy range. The effective area, energy resolution and time resolution of PCA were $\sim 6500$ cm$^2$ at 6 keV, $\le 18$ per cent at 6 keV and 1 $\mu$s, respectively. A detailed description of the PCA instrument can be found in Jahoda et al. (1996). The third instrument, High Energy X-ray Timing Experiment (HEXTE), was operating in 15–250 keV energy range (Rothschild et al. 1998).

2.1 Timing analysis

The RXTE/ASM light curve of 4U 0115+634 from 1996 January to 2011 December is shown in Fig. 1. During above duration, i.e. entire lifetime of the RXTE observatory, only four major outbursts were detected in the pulsar. Out of the four outbursts, during 2000 outburst, the pulsar was monitored only three times and hence the data were not used in our present analysis. However, the pulsar was extensively monitored during the other three outbursts. For our timing analysis, we used data from all PCA observations during

![Figure 1](https://academic.oup.com/mnras/article-abstract/434/3/2458/1041109)

**Figure 1.** RXTE/ASM one-day-averaged light curve of the transient pulsar 4U 0115+634 in 1.5–12 keV energy range from 1996 January 5 (MJD 50087) to 2011 December 31 (MJD 55926). During entire observing period of RXTE, only four major outbursts were detected in the ASM light curve. RXTE/PCA observations during 1999, 2004 and 2008 outbursts were analysed to investigate the QPOs features in the pulsar.
the 1999 March–April, 2004 September–October and 2008 March–April outbursts (as marked in Fig. 1). In this work, we analysed a total of 95 publicly available RXTE/PCA observations (36 during 1999 March–April outburst, 33 during 2004 September–October outburst and 26 during 2008 March–April outburst). A brief log of the observations is given in Table 1. In this work, we used PCA data from these observations to study the evolution of QPO. Data reduction was carried out by using the software package FTOOLS, whereas data analysis was done by using the HEASOFT package (version 6.11).

Using the standard 1 mode PCA data, we extracted light curves in 2–60 keV energy range with a time resolution of 0.125 s from all the RXTE-pointed observations during the 1999, 2004 and 2008 outbursts. While extracting the source light curves, we found that a different number of proportional counter units (PCUs) were on during different dates of observations. Corresponding background light curves were created by using the modelled background event data (as provided by the instrument team). Background-subtracted average source count rates at peak of the 1999, 2004 and 2008 outbursts were found to be ~1238 counts s$^{-1}$, ~1170 counts s$^{-1}$ and ~1115 counts s$^{-1}$ per PCU, respectively. Data from all available PCUs were used in our analysis. Power-density spectra (PDS) were generated from each of the light curves obtained from the RXTE observations of the pulsar during 1999, 2004 and 2008 outbursts by using the FTOOLS package powspec. To detect the presence/absence of QPO, PDS were created for small segments of duration 512 s and averaged over the total number of available segments in the individual light curves. The PDS were normalized to subtract the white noise level. These normalized PDS were used to estimate the squared rms fractional variability by integrating over a certain frequency range. All the PDS were then examined for the presence/absence of QPOs in a wide frequency range (~1 mHz to ~1 Hz).

We found that the 3.6 s regular pulsations of the pulsar and its harmonics were present in the PDS obtained from all the RXTE/PCA observations. Apart from these pulsations and corresponding harmonics, the PDS from 72 RXTE/PCA observations during the three outbursts of the pulsar were featureless. However, in some cases, very prominent QPO features at ~41 mHz were detected, though the strength was variable during other observations. To estimate the frequency of the QPO, we fitted the PDS (for 1999 March 25 observation) with two continuum components such as a power law and a Lorentzian. The peaks corresponding to the spin frequency of the pulsar and its harmonics were ignored while fitting the PDS continuum. The fit clearly showed the presence of a Gaussian feature at ~41 mHz (shown in Figs 2 and 3). This ~41 mHz QPO in the transient pulsar 4U 0115+634 is detected for the first time here, though QPOs at ~2 mHz (Heindl et al. 1999) and the possibility of the presence of QPO at ~62 mHz (Soong & Swank 1989) were reported earlier. We obtained the ratio of the amplitude and uncertainty of the Gaussian component and found that the QPO feature is more than 3σ detection level. It may be noted that the exposures of individual RXTE/PCA observations were not very large (poor signal-to-noise ratio) which enhanced the error in the Gaussian component and degraded the significance level of the QPO feature. However, the feature can be clearly seen in the PDS as shown in one of the observations (Fig. 2). While careful examining this ~41 mHz QPO during the three outbursts, it is found that the QPO frequency is variable in the range of 27–46 mHz and the significance level of

### Table 1. List of RXTE/PCA observations during 1999, 2004 and 2008 outbursts.

| Year of outburst | Observation series | No. of IDs | Total exposure (ks) |
|------------------|--------------------|------------|---------------------|
| 1999             | P40051             | 15         | 74.6                |
|                  | P40070             | 5          | 117.2               |
|                  | P40411             | 16         | 23.4                |
| 2004             | P90014             | 16         | 40.8                |
|                  | P90089             | 17         | 65                  |
| 2008             | P93032             | 26         | 228.9               |
the QPO was always in the range of $3\sigma$–$8\sigma$. Apart from this newly detected $\sim 41$ mHz QPO, the other two QPOs were also detected in the PDS of some of the RXTE/PCA pointed observations of the pulsar. While carefully investigating all the RXTE observations of 4U 0115+634 during 1999, 2004 and 2008 outbursts, the presence of multiple QPOs was detected in the PDS of a few epochs. Out of 95 pointed RXTE observations, multiple QPOs were seen only in three occasions viz. 2004 September 22 (QPOs at $\sim 2$ mHz and $\sim 41$ mHz), 2004 October 4 (QPOs at $\sim 2$ mHz and $\sim 62$ mHz) and 2008 April 6 (QPOs at $\sim 41$ mHz and $\sim 62$ mHz). Apart from the presence of multiple QPOs at three epochs, we also detected $\sim 41$ mHz QPO and its first harmonic on two occasions such as 2004 September 30 and 2008 March 26. Fig. 4 shows the presence of $\sim 41$ mHz and $\sim 62$ mHz QPOs on 2008 April 6 whereas Fig. 5 shows the presence of $\sim 41$ mHz QPO and its first harmonic in the PDS of 2008 March 26 observation. These findings i.e. presence of multiple QPOs at a particular epoch and the detection of QPOs and its harmonics are very rarely seen in accretion-powered X-ray pulsars.

We calculated the quality factor $Q$ [QPO central frequency $\nu$/FWHM (full width at half-maximum)] of all the three QPOs detected during 1999, 2004 and 2008 outbursts and found to be in the range of 3–12 apart from three cases where it is in the range of 15–20. The estimated value of $Q$ is comparable to that in other HMXBs (4–10). Conventionally, a local maximum in the PDS is interpreted as a QPO when the quality factor $Q$ is more than 2 (van der Klis 2000). The high value of $Q$ ($\geq 2$) for the peak at $\sim 41$ mHz in the PDS of 4U 0115+634 also confirms the feature to be a QPO. The rms values of the detected QPOs in the RXTE/PCA observations were estimated and found to be in the range of 4–8 per cent except the two observation of 1999 outburst where the rms value of 2 mHz QPO is quite high, $\sim 17$ per cent. Comparisons between the QPO parameters with the flux of the pulsar are given in next section. One-day-averaged 1.5–12.0 keV RXTE/ASM light curves of the pulsar during the 1999, 2004 and 2008 outbursts are shown in Fig. 6. In each panel, the day of RXTE observations used in present work are marked with vertical lines at the top. Solid squares, asterisks and arrow marks in each panel represent the observations in which QPOs at $\sim 2$ mHz, $\sim 41$ mHz and $\sim 62$ mHz are detected, respectively. In second and third panels, the ○ marks represent the presence of newly detected $\sim 41$ mHz QPO and its first harmonic in the PDS of the pulsar. Out of a total of 95 RXTE observations, we found QPOs in 23 observations.

2.2 Spectral analysis

To investigate the changes in spectral parameters during the 1999, 2004 and 2008 outbursts and then compare these changes with the QPO parameters, we carried out spectral analysis of the available RXTE/PCA observations of the pulsar during above outbursts. As majority of the observations are not long enough, data from HETE instruments were not used in our analysis. Out of 33 (1999 outburst), 33 (2004 outburst) and 26 (2008 outburst) pointed RXTE observations of the pulsar, spectral analysis were carried out for 29, 27 and 24 observations, respectively. Standard-2 mode PCA data from all the RXTE/PCA observations were used to create source spectrum. Standard procedures were applied for the data selection, background estimation and response matrix generation (Naik & Paul 2003). Data from available PCUs were added together and response matrices were generated accordingly. We restricted our analysis to the 3–30 keV energy range. Though the RXTE observations of the pulsar during 1999 outburst were analysed to investigate the luminosity dependence of CRSFs (Nakajima et al. 2006), we used these observations in the context of understanding the change in spectral parameters and also QPO parameters with source flux. We used the same spectral continuum model as used by Nakajima et al. (2006) such as the Negative and Positive power-law with EXponential (NPEX) cut-off model along with the CRSF while fitting the pulsar spectra during all three outbursts. The NPEX model is known to be the approximation of the unsaturated thermally Comptonized plasma (Makishima et al. 1999). As described by Nakajima et al. (2006), a CRSF at $\sim 11$ keV and its harmonic are seen in the
The energy spectrum of 4U 0115−RXTE for each energy bin for the one-day-averaged RXTE/ASM light curves of the transient Be/X-ray binary pulsar 4U 0115+634 during 1999 March–April (left-hand panel), 2004 September–October (middle panel) and 2008 March–April (right-hand panel) outbursts. The vertical lines at the top of each panel indicate the RXTE/PCA pointed observations of the pulsar. The solid squares, vertical arrows and asterisks in each panels indicate the observations in which QPOs at ~41 mHz were detected, respectively. The ‘○’ symbols in the second and third panels show the presence of newly detected ~41 mHz QPO and its first harmonic in the power-density spectra of the pulsar. There are a few observations during which the presence of multiple QPOs in the PDS was also seen and marked in the figure.

The energy spectrum of the pulsar obtained from the RXTE/PCA observation on 1999 March 14, along with the best-fitting model comprising of NPEX continuum model and CRSF. The bottom panel shows the contributions of the residuals to the χ² for each energy bin for the best-fitting NPEX continuum model.

3–30 keV energy spectra of the pulsar. The CRSF energy was found to vary inversely with the pulsar luminosity which was interpreted as a result of decrease in the accretion column height due to the decrease in mass accretion rate (Nakajima et al. 2006).

As a detailed study on the luminosity dependence of CRSF is already done, we attempted to investigate the change in other parameters with the source flux during above three outbursts. A representative energy spectrum of the pulsar obtained from the RXTE observation on 1999 March 14 is shown in Fig. 7 along with the best-fitting model and the residuals. We estimated source flux in 3–30 keV energy range along with the power-law photon index, high-energy cut-off and equivalent hydrogen column density (N_H) for all the 80 observations during three outbursts. Considering the energy range of spectral fitting (i.e. 3–30 keV), the value of estimated hydrogen column density may not be accurate enough to draw any reliable conclusion. Random variation was seen in the values of power-law photon index with 3–30 keV source flux during 1999 and 2008 outbursts. Similar variation in the values of photon index with the pulsar luminosity was reported earlier during the 1999 outburst earlier (see table 4 of Nakajima et al. 2006). However, during 2004 outburst, the photon index was found to be high at low source flux level. This should be noted here that during 2004 outburst, the pulsar was monitored with RXTE/PCA even after the outburst (quiescent phase). The high value of power-law photon index during quiescent phase suggests that the pulsar spectrum was relatively hard compared to that during the outburst phase. In Fig. 8, we plotted the values of power-law photon index and the rms (per cent) of QPOs with the estimated source flux in 3–30 keV energy range during all three outbursts. It was found that the rms (per cent) of the QPO was variable in 3–8 per cent range during all three outbursts except ~17 per cent rms value of 2 mHz strong QPOs of 1999 outburst. However, there was no systematic variation in the values of QPO rms during all three outbursts.

3 DISCUSSION

The frequency of the QPOs detected in accretion-powered X-ray pulsars generally falls in the range of ~1 mHz to ~40 Hz (Psaltis 2006). Among these binary pulsars, the QPO features are detected more in transient sources compared to the persistent ones. In most of the transient BeXB pulsars, the detected QPOs are found to be transient in nature. For example, in the case of KS 1947+300, the QPO feature was not seen in the data during 2000 and 2002 outbursts, whereas it appeared at the end of the 2001 outburst (James et al. 2010). In 4U 0115+634, the QPO features were not detected in all of the RXTE observations during 1999, 2004 and 2008 outbursts (present work). Transient HMXB pulsars in which QPOs have been detected are EXO 2030+375 (Angelini, Stella & Parmar 1989), 4U 0115+63 (Soong & Swank 1989), V0332+53 (Takeshima et al. 1994), A0535+262 (Finger, Wilson & Harmon 1996), SAX J2103.5+4545 (Inam et al. 2004), XTE J1858+034 (Mukherjee et al. 2006), XTE J0111.2−7317 (Kaur et al. 2007), MAXI J1409−619 (Kaur et al. 2010), KS 1947+300 (James et al. 2010), 4U 1901+03 (James et al. 2011), IA 1118−61 (Devasia et al. 2011a) and GX 301−4 (Devasia et al. 2011b). However, there are only very few cases of accretion-powered X-ray pulsar such as SMC X-1 (Wojdowski et al. 1998), Her X-1, 4U 1626−67, LMC X-4 (see table 1 of Shirakawa & Lai 2002) and 4U 0115+63 (present work) where multiple QPOs are seen.
Another unique thing we detected in this work is the presence of multiple QPOs simultaneously in the same observation at three occasions.

QPOs in accretion-powered X-ray binary pulsars are thought to be due to the motion of the inhomogeneously distributed matter in the inner part of the accretion disc. The detection of QPOs, therefore, provides useful information on the radius of the inner accretion disc and the interaction between accretion disc and the neutron star. Several models have been proposed to explain the QPO features in the PDS of accretion-powered X-ray pulsars. According to the magnetospheric beat frequency model, the observed QPO frequency ($\nu_{\text{QPO}}$) represents the beat between the coherent spin frequency of the pulsar ($\nu_s$) and the Keplerian frequency ($\nu_K$) at the inner disc radius, i.e. $\nu_{\text{QPO}} = \nu_K(r_{in}) - \nu_s$, at the magnetospheric boundary of the pulsar (Alpar & Shaham 1985; Lamb et al. 1985). According to this model, interactions between the neutron star magnetosphere and its accretion disc result in fluctuations in the plasma density at the inner edge of the disc which rotates with the local Keplerian frequency $\nu_K(r_{in})$. As the magnetic field lines of the neutron star rotate with its spin frequency $\nu_s$, the fluctuation in plasma reappears with a frequency that is the beat frequency as given above. In Keplerian-frequency model, on the other hand, the QPOs arise because of the modulation of the X-rays by inhomogeneously distributed matter in the inner accretion disc at the Keplerian frequency (van der Klis et al. 1987). According to this model, the observed QPO frequency is the same as the frequency of the Keplerian motion at the inner accretion disc [i.e. $\nu_{\text{QPO}} = \nu_K(r_{in})$]. When the spin frequency of the pulsar is higher than the Keplerian frequency at the outer edge of the accretion disc, mass accretion on to the neutron star is stopped at the magnetospheric boundary by centrifugal inhibition of accretion (Stella et al. 1986) resulting in the onset of propeller effect. Keplerian-frequency model, therefore, can be applicable only when the QPO frequency is above the neutron star spin frequency, as seen in transient BeXB pulsars such as EXO 2030+375 (Angelini et al. 1989), A0535+262 (Finger et al. 1996), XTE J0111.27317 (Kaur et al. 2007), etc. However, in the case of 4U 0115+634, frequency of all three QPOs (earlier reported QPOs at $\sim$2 mHz and $\sim$62 mHz and newly detected QPO at $\sim$41 mHz) is found to be less than the spin frequency of the pulsar. Therefore, the Keplerian-frequency model is not suitable to explain the presence of QPO in the transient pulsar 4U 0115+634.

Third model proposed to explain the low-frequency QPO features in strongly magnetized ($\sim$10^{12} G) accretion-powered X-ray pulsars is the magnetic disc precession model (Shirakawa & Lai 2002). According to this model, the presence of QPOs in binary pulsars is due to the magnetically driven disc warping/precession near the inner edge of the disc at the magnetospheric boundary. The magnetic torques due to interactions of the stellar field and the induced electric currents in the disc are responsible for warping and precession of the disc. This model was used to explain the mHz QPO detected in the accretion-powered pulsar 4U 1626–67 along with several others (Shirakawa & Lai 2002). This model was also attempted to explain the QPOs in the transient pulsar 4U 0115+634 in terms of the presence of magnetically driven disc warping/precession around the neutron star.

4 Conclusion

We reported the detection of a $\sim$41 mHz QPO for the first time in the transient pulsar 4U 0115+634. These newly detected QPOs were present more frequently in decline phase of outbursts as compared to the rising phase (Fig. 6). These $\sim$41 mHz QPOs were found to be variable in 27–46 mHz frequency range. Apart from the newly detected $\sim$41 mHz QPO, QPOs at $\sim$2 mHz and $\sim$62 mHz were also detected at several other occasions. However, there was no correlation between the QPO parameters and source flux during above three outbursts in the pulsar. In this work, we have detected the presence of multiple QPOs in the PDS of the pulsar only on three occasions viz. on 2004 September 22 (QPOs at $\sim$2 mHz and $\sim$41 mHz), 2004 October 04 (QPOs at $\sim$2 mHz and $\sim$62 mHz) and 2008 April 06 (QPOs at $\sim$41 mHz and $\sim$62 mHz), whereas $\sim$41 mHz QPO and its first harmonic were detected on 2004 September 30 and 2008 March 26. The presence of multiple QPOs and QPOs with its harmonics in a single observation is very rarely seen in accretion-powered X-ray pulsars.

Figure 8. Change in the QPO rms (per cent) and power-law photon index with source flux (in 10^{-8} erg cm^{-2} s^{-1} units) in 3–30 keV energy range. The open circles, solid triangles and solid squares in the top three panels represent the rms values for QPOs at $\sim$2 mHz, $\sim$41 mHz and $\sim$62 mHz, respectively. The left-hand, middle and right-hand panels are for 1999, 2004 and 2008 outbursts, respectively.
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