Flares, broadening of the pulse-frequency peak and quasi-periodic oscillations in the transient X-ray pulsar 4U 1901+03

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ABSTRACT
After a long quiescence of three decades, the transient X-ray pulsar 4U 1901+03 became highly active in 2003 February. From the analysis of a large number of Rossi X-ray Timing Explorer/Proportional Counter Array (RXTE/PCA) observations of this source, we report here the detection of X-ray flares, a broadening of the pulse-frequency feature and quasi-periodic oscillations (QPOs). The X-ray flares showed spectral changes, had a duration of 100–300 s, and were more frequent and stronger during the peak of the outburst. In most of the observations during the outburst we also detected a broadening of the pulse-frequency peak. We have also found intensity-dependent changes in the pulse profile at very short time-scales. This reveals a coupling between the periodic and the low-frequency aperiodic variabilities. In addition, near the end of the outburst we have detected a strong QPO feature centred at ∼0.135 Hz. The QPO feature is broad with a quality factor of 3.3 and with an rms value of 18.5±3.1 per cent. Using the QPO frequency and the X-ray luminosity during the QPO detection period we estimated the magnetic field strength of the neutron star as 0.31 × 10^{12} G which is consistent with the value inferred earlier under the assumption of spin equilibrium.

Key words: stars: individual: 4U 1901+03 – stars: neutron – pulsars: individual: 4U 1901+03 – X-rays: binaries – X-rays: stars.

1 INTRODUCTION
Most of the accretion powered X-ray pulsars belong to the class of high-mass X-ray binaries (HMXBs). The companion star may be a Be star or an OB supergiant. Most of the Be star sources are transients which are normally detected during outbursts. There are two kinds of outbursts, normal outburst (Type I) and giant outburst (Type II). Be stars have circumstellar discs and when the neutron star passes through the disc, it produces Type I outbursts. The Type II outbursts are produced during the episodes of large mass outflow from the Be star. Transient X-ray pulsars are excellent candidates to investigate properties of the accretion process that are intensity dependent.

The recurrent HMXB pulsar 4U 1901+03 was discovered by Uhuru and Vela 5B satellite in 1970–1971 which was the first detection of an outburst from this source (Forman, Tananbaum & Jones 1976; Friedhorsky & Terrell 1984). A second outburst in 2003 was reported by Rossi X-ray Timing Explorer/All Sky Monitor (RXTE/ASM). After the detection by ASM, detailed long-term observations of this source was carried out with the Proportional Counter Array (RXTE/PCA).

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RXTE observations revealed pulsations with a period of 2.763 s and variations in the pulse period indicated an orbital period of 22.58 d and eccentricity of about 0.035s of the binary system. No optical or IR counterpart has been found for this source (Galloway, Wang & Morgan 2005). 4U 1901+03 is included in the unusual class of X-ray binaries with wide orbits (Porb ≥ 20 d) but low eccentricity. The source was also observed in the hard X-ray band with the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) between 2003 March 10 and 2003 April 13 (Molkov, Lutovinov & Grebenev 2003). Chen et al. (2008) carried out a pulse-profile analysis of this source and found that the pulse profile is luminosity dependent. A phase-resolved spectroscopic study revealed a strong pulse phase dependence of the spectrum (Lei et al. 2009).

In the following sections, we present a detailed timing analysis of RXTE/PCA archival data of 4U 1901+03 and report the discovery of several interesting features including flares, a broadening of the spin-frequency peak and a QPO at ∼0.135 Hz.

2 OBSERVATIONS AND DATA REDUCTION
The HMXB pulsar 4U 1901+03 was observed with the RXTE in 2003 during an outburst after a long interval of quiescence. The RXTE/PCA observations started on 2003 February 10 and lasted for around 5 months. Though the RXTE/PCA has a large field of view...
of one square-degree, any contamination from nearby sources is negligible because there are no bright X-ray sources within 1° from this object. There were a total of 68 pointings during this time period and data are available for a total useful exposure of 398 ks. The PCA instrument of RXTE consists of five Proportional Counter Units (PCUs) covering an energy range of 2–60 keV with an effective area of 6500 cm². The ASM is sensitive to X-ray photons between 1.5 and 12 keV. Table 1 gives a log of the observations. For our timing analysis we used data from all the PCA observations and during most of the observations PCU0 and PCU2 were operational. The data reduction was performed using the software package FTOOLS version 6.5. The background count rate was simulated using the tool pcabackest and was subtracted from the total count rate. Appropriate background models are used for the background simulation. CALDB version 1.0.1 and PCARSP version 11.7 were used for the creation of the energy response matrix of the PCA detections.

### Table 1. Log of PCA observations.

| Year | Observation IDs | No. of pointings | Total durations (ks) |
|------|-----------------|------------------|----------------------|
| 2003 | P70068          | 5                | 111.8                |
|      | P70096          | 63               | 286.5                |

3 ANALYSIS AND RESULTS

#### 3.1 Light curve and flares

Many accretion powered pulsars show aperiodic variability, like flares, with time-scales of a few seconds to a few hundred seconds. Here we are presenting results from the analysis of data from the RXTE/PCA long-term observations of 4U 1901+03, in which we have detected a large number of X-ray flares.

One-day averaged ASM light curve is shown in the top panel of Fig. 1 for a 250-d period around the outburst. The outburst started around MJD 52660 and reached a maximum count rate of 18 s⁻¹ in the ASM detectors (about 240 mCrab; Galloway et al. 2005) and then it declined linearly reaching a count rate of about 1 count s⁻¹ at MJD 52840. We extracted light curves from all the 68 PCA observations with a time resolution of 0.125 s. The entire background-subtracted PCU2 light curve from all 68 observations is shown in the bottom panel of Fig. 1. This 2–60 keV light curve is generated with a time resolution of 200 s. The arrow marks in Fig. 1 indicate the periods of QPO detection described later.

In most of the observations carried out during the outburst, 4U 1901+03 exhibited X-ray flares. The flares occurred randomly with different recurrence times between a few hundred to thousand seconds and flare duration of 100–300 s. Pulsations are also clearly seen during the flares. Some of the flares had sharp rise and slow decay with multiple-peak structure. In Fig. 2 we have shown three light curves selected on the basis of intensity of flare activity and a fourth without flares but strong short-term variability. The light curves are plotted with a bin size equal to the spin period of ∼2.763 s so that the variability associated with the pulsation is omitted. At the peak of the flare, the luminosity is higher by a factor of up to 2.5. The flares are found to be more frequent and stronger near the peak of the outburst indicating a relation with the mass accretion rate.

We calculated the hardness ratios (soft hardness ratio: 6–10 keV/2–6 keV and hard hardness ratio: 10–30 keV/6–10 keV) of the light curves using the event mode data (Good Xenon mode) from the PCA. The hardness ratios of the data corresponding to panel (b) of Fig. 2 are shown in Fig. 3 along with the summed light curve in the bottom panel. During the flares, the soft hardness ratio is found to increase while the hard hardness ratio is seen to be decreasing. This implies that the flares are stronger in the medium-energy band which we have also found in the analysis of the flare spectrum described later. A detailed hardness-ratio analysis showed that all the flares have similar energy dependence.
Transient X-ray pulsar 4U 1901+03

3.2 Power-density spectrum

Quasi-periodic oscillations (QPOs) have been reported in many accretion powered pulsars, both HMXBs and low mass X-ray binaries (LMXBs; see James et al. 2010 for a complete list of the sources). In the accreting high magnetic field X-ray pulsars, the QPO appears as a broad peak in the power-density spectrum (PDS). We have carried out a timing analysis using data from all the RXTE/PCA observations to search for QPOs and other aperiodic features in this pulsar.

Standard 1 mode data of RXTE/PCA with a time resolution of 0.125 s was used for the timing analysis. We extracted light curves from all the archival data and created PDS using the ftool-pswSpec. The light curve was divided into stretches of length 1024 s and the power spectra obtained from two to five consecutive segments were averaged to produce a set of averaged PDS from which the expected white noise level was subtracted. The PDS was normalized such that the normalized integral gives the squared rms fractional variability.

For most of the observation period, the PDS was a featureless continuum except for the pulse peak and its harmonics. The PDS reveals no QPO feature during the time of the outburst but in many of the observations we detected a broadening of the spin-frequency peak. Near the end of the outburst, the broadening of the spin-frequency peak disappeared and a broad QPO feature at $\sim 0.135$ Hz appeared in the PDS. The three PDS with and without flares are shown in Fig. 4 (top panel: PDS for the period of flare; middle panel: non-flare; bottom panel: QPO detection). During the QPO detection we also detected a large pulsed fraction (up to 60 per cent) and a large rms (18 per cent) of the QPO. If these two features were to be from two different sources in the field of view, then even if the pulsating source was to be 100 per cent pulsed, the source with QPOs is required to have a rms of 45 per cent. This is much larger than any QPO feature in any type of X-ray binary. We, therefore, conclude that the QPO feature is indeed from the X-ray pulsar. The PDS with the QPO was fitted with a model consisting of a power law and Lorentzian for the continuum and a second Lorentzian for the QPO feature. The frequency bins corresponding to the pulse peak and its harmonics seen in Fig. 4 were ignored while fitting the continuum. Centre frequency of the QPO feature was found to change from a value of $0.143 \pm 0.003$ to $0.130 \pm 0.006$ Hz in 3 d.

Figure 2. Some representative RXTE/PCA light curves of 4U 1901+03. The bin size used here equals the spin period of the neutron star. The start time of the light curves are (a) 52685 15:34, (b) 52685 21:57, (c) 52689 13:08 and (d) 52686 18:25 MJD, respectively.

Figure 3. Background-subtracted RXTE/PCA light curves (Fig. 2b: 52685 21:57 MJD) and hardness ratios in two different energy band pairs are shown here.

Figure 4. Power-density spectra with broadening (top and middle panels) and without broadening of the pulse peak (bottom panel) are shown in this figure.
The QPO feature has a width of about 0.04 Hz and a quality factor of about 3.3. The significance of the detection of the QPO was different on different days varying from 6σ to 7σ. The background-corrected rms value of the QPO feature is 18 ± 3 per cent. We calculated the energy dependence of the QPO rms using the event mode data (Good Xenon mode) of the PCA and found that the QPO feature is not detectable above 11 keV.

A broadening of the X-ray pulse-frequency peak has been seen in several other sources (Lazzati & Stella 1997; Reig et al. 2006; Raichur & Paul 2008; Jain, Paul & Dutta 2010) and is thought to be due to a coupling of the low-frequency variations with the pulsation. To investigate this in detail, we have created intensity-dependent pulse profiles. Light curve from RXTE/PCA observations were first created with a bin size same as the pulse period. Using the X-ray intensity of each single pulse, separate intensity-dependent time windows were created and these windows were then used to obtain intensity-dependent pulse profiles of 4U 1901+03. The intensity-dependent pulse profiles obtained from two light curves, with and without flares (panels b and d in Fig. 2) are shown in the top two panels of Fig. 5. It is to be noted that broadening of the pulse-frequency peak is present in all the light curves shown in Fig. 2. In the bottom panel of Fig. 5 we have shown the intensity-selected pulse profiles during a period when the light curve shows a QPO feature but no broadening of the X-ray pulse-frequency peak. Note that the three PDS shown in Figs 4 and 5 are from the same set of light curves (top: flare, middle: non-flare and bottom: QPO).

In the top two panels of Fig. 5 one can clearly see that at low intensity, the pulse profile has two unequal peaks. At higher intensity, both the peaks become stronger, the dip before the main peak disappears while the dip after the main peak becomes more clear. The intensity dependence of the pulse profile appears to be quite similar for the flaring and non-flaring episodes. From the bottom panel of Fig. 5 we can see that the episode that does not show a pulse peak broadening also does not have any significant intensity dependence of the pulse profile.

### 3.3 Spectral analysis

We have done a spectral analysis of the source during the QPO detection, flaring and non-flaring state to investigate if there are any differences. Standard 2 data of the PCA were used for extraction of the energy spectrum in 2.5–25 keV energy band. All the three spectra were fitted with a model consisting of an absorption component, a power law with a high-energy cut-off and a Gaussian emission line. A systematic error of 0.5 per cent was added to the first and second spectra to account for the calibration uncertainties while the non-flaring spectrum required a systematic error of 1 per cent. The spectra, along with the respective best-fitting models and the residuals, are shown in Fig. 6 (top panel: spectrum for the period of flare; middle panel: non-flare; bottom panel: QPO detection). The best-fitting spectral parameters are given in Table 2 along with the reduced $\chi^2$ values. The spectrum taken when QPOs are present and broadening of spin-frequency peak is absent has a larger photon index and large value of the high-energy cut-off compared to the spectrum when QPOs are absent and spin-frequency peak shows a broadening. Non-flaring spectra give $\chi^2$ of 1.3 and 1.6, respectively, with 42 d.o.f. If we take a ratio of the flaring and the non-flaring spectrum, the medium-energy band of 6–10 keV shows the maximum difference. This is in accordance with the hardness ratio changes during the flares (Fig. 3). The flux measured in the 2–20 keV band during the time of the QPO detection is about $3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. The flux measured in the 2–20 keV band using the spectra shown in Fig. 6 during the time of flare and non-flare time are $7.7 \times 10^{-9}$ and $5.2 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$, respectively.

### 4 DISCUSSION

Detailed timing and spectral studies of 4U 1901+03 using this set of RXTE/PCA observations have been reported earlier. This includes timing and spectral evolution studies over the duration of the outburst, pulse-frequency evolution (Galloway et al. 2005), energy and luminosity dependence of the pulse profile (Chen et al. 2008) and pulse phase dependence of the energy spectrum (Lei et al. 2009). In the previous section we have reported some additional temporal studies, including the detection of an intensity dependence of the pulse profile at very short time-scales, probably for the first time in any short-period pulsar.

#### 4.1 Flares

X-ray flares of different duration, occurrence and flux enhancement have been reported in many accretion powered pulsars like GRO J1744−28 (Finger et al. 1996), SMC X-1 (Moon, Eikenberry & Wasserman 2003a), EXO 2030+375 (Parmar et al. 1989), LMC X-4 (Moon et al. 2001a; Moon, Eikenberry & Wasserman 2003b), 4U 1907+09 (in’t Zand, Baykal & Strohmayer 1998; Mukherjee et al. 2001), Vela X-1 (Kreykenbohm et al. 2008), SWIFT J1626.6−5156 (Reig et al. 2008), Her X-1 (Moon & Eikenberry 2001b) and 4U 1626−67 (McClintock et al. 1980).

The extremely large flux enhancements seen in GRO J1744−28 and the large flares in SMC X-1 are probably due to accretion disc instability similar to the bursts in the rapid burster. The large flares
Figure 6. The 2.5–25 keV spectra of 4U 1901+03 during X-ray flares (top), non-flares (middle) and during QPO detection (bottom) are shown here along with the respective best-fitting models consisting of absorption, power law, high-energy cut-off and Gaussian components. The lower panel in each figure shows the residual to the best-fitting models.
1626+67 (Kaur et al. 2008) in which QPOs are detected in most of the observations.

There are many models that have been proposed to explain the QPOs in X-ray binaries. Beat-frequency model (BFM) is generally considered as the most plausible model for QPOs in X-ray pulsars. In this model, blobs of matter entrained in the neutron star magnetic field which orbit with the Keplerian frequency of the inner edge of the accretion disc are accreted at a rate that is modulated by the rotating magnetic field (Alpar & Shaham 1985). It produces an aperiodic variability at the beat frequency between the pulsar spin frequency and the Keplerian frequency; \( v_{\text{QPO}} = v_k - v_s \). Another possible model is the Keplerian frequency model (KFM) in which the accretion disc contains structures that persist for a few cycles around the neutron star and modulate the X-ray flux by obscuration, i.e. \( v_{\text{QPO}} = v_k \) (van der Klis et al. 1987).

In the present source and some other sources like Cen X-3, 4U 0115+63, 4U 1626−67, Her X-1, LMC X-4, V 0332+52 (Koyama et al. 2000) and GRO J1744+67 (Kaur et al. 2008) in which QPOs are detected in most of these models is applicable in these sources. But in sources like 4U 1636−53 and KS 1947−20, the pulsar frequency is higher than the QPO frequency; hence the KFM is inapplicable. It is expected that centrifugal forces inhibit mass accretion if the Keplerian frequency at the inner disc radius is less than the spin frequency of the pulsar. The X-ray flux is proportional to the mass accretion rate, and the Keplerian frequency at the inner edge of the accretion disc is related to the X-ray flux (Finger 1998). So in both KFM and BFM we expect a positive correlation between QPO frequency and the luminosity which was, however, not seen in two sources V 0332+52 (Qu et al. 2005) and GRO J1744−28 (Zhang et al. 1996). So neither of these models is applicable in these sources. But in sources like A0535+262, EXO 2030+375 and XTE J1858+37 (Mukherjee et al. 2006) the QPO frequency depends on the X-ray intensity.

In the 2.7s pulsar 4U 1901+03, the QPO is detected at ~0.135 Hz during decline phase of the 2003 outburst. The same kind of QPO feature was also discovered in KS 1947+300, during its 2001 outburst. KS 1947+300 source has the smallest QPO frequency among all the transient pulsars (James et al. 2010). In 4U 1901+03, the QPO frequency is less than the spin frequency of the pulsar, so it can be explained by the BFM. Radius of the QPO production region can be estimated as

\[
R_{\text{QPO}} = \left( \frac{GM}{4\pi^2 v_k} \right)^{1/3}.
\]

For the BFM, the Keplerian frequency is \( v_k \approx 0.5 \) Hz. Assuming a neutron star mass of 1.4 M\(_\odot\), the inner radius of the accretion disc is obtained as 2.6 × 10\(^3\) km.

The 2–20 keV X-ray flux during the time of QPO detection is 1.3 × 10\(^{-10}\) erg cm\(^{-2}\) s\(^{-1}\). The total X-ray luminosity for the source is calculated to be about 1.6 × 10\(^{36}\) erg s\(^{-1}\) at 10 kpc. The magnetospheric radius of a neutron star can be expressed in terms of the luminosity and magnetic moment as (Frank, King & Raine 2002)

\[
R_m = 3 \times 10^8 L_\nu^{-2/7} \mu_{30}^{-4/7} \text{cm},
\]

where \( L_\nu \) 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\(^2\) G. Equating \( R_m \) with \( R_{\text{QPO}} \) we estimate the magnetic field as 0.31 × 10\(^{12}\) G. This is consistent with the value inferred by Galloway et al. (2005) by estimating magnetic field strength from spin equilibrium (0.3 × 10\(^{12}\) G). This is also within the bounds for the magnetic field derived from the upper and lower flux levels within which the source behaved as an X-ray pulsar. In the BFM, the expected QPO frequency range, for source luminosity between 5.8 × 10\(^{37}\) erg s\(^{-1}\) at the peak of the outburst and 0.16 × 10\(^{37}\) erg s\(^{-1}\) when the QPOs are detected, is 2.05–0.135 Hz. But only a 0.135-Hz QPO is detected in this source.

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