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Short-term pulse frequency fluctuations of OAO 1657−415 from *RXTE* observations

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ABSTRACT

We present new X-ray observations of the high-mass X-ray binary (HMXRB) pulsar OAO 1657−415, obtained during one orbital period (10.44 d) with the *Rossi X-Ray Timing Explorer* (*RXTE*). Using the binary orbital parameters, obtained from Burst and Transient Source Experiment (BATSE) observations, we resolve the fluctuations in the pulse frequency at time-scales on the order of 1 d for the first time. Recent BATSE results by Baykal showed that OAO 1657−415 has spin-up/down trends in its pulse frequency time series, without any correlation with the X-ray luminosity at energies >20 keV. In the present *RXTE* observations the source is found to be in an extended phase of spin-down. We also find a gradual increase in the X-ray luminosity which is correlated with a marginal spin-up episode. The marginal correlation between the gradual spin-up (or decrease in spin-down rate) and increase in X-ray luminosity suggests that OAO 1657−415 is observed during a stable accretion episode where the prograde accretion disc is formed.

Key words: accretion, accretion discs – binaries: eclipsing – pulsars: individual: OAO 1657−415 – X-rays: stars.

1 INTRODUCTION

The high-mass X-ray binary source HMXRB source OAO 1657−415 (OAO 1653−40) was first detected by the *Copernicus* satellite (Polidan et al. 1978) in the 4–9 keV range. The *HEAO-1* observations also showed 38.22-s pulsations in the 1–40 keV and 40–80 keV bands (White & Pravdo 1979; Byrne et al. 1981). Observations with *Ginga* and *GRANAT* (Kamata et al. 1990; Gilfanov et al. 1991; Mereghetti et al. 1991; Sunyaev et al. 1991) have found pulse period changes. BATSE observations of this source with the *Compton Gamma Ray Observatory* (*CGRO*) showed that OAO 1657−415 is in a $10^{\rm d}\!.44$ binary orbit with an X-ray eclipse by a stellar companion (Chakrabarty et al. 1993). The observed orbital parameters imply that the companion is a supergiant of spectral class B0–B6. The correlations between X-ray flux and pulse frequency derivatives ($\dot{\nu}$) fluctuations were investigated by using the previously published pulse frequencies and BATSE measurements (Baykal 1997). These correlations suggested that the formation of episodic accretion discs in the case of a stellar wind is the possible accretion mechanism.

In this paper, we present the short-term pulse frequency fluctuations and X-ray fluxes of OAO 1657−415 in the light of recent *RXTE* observations. We have employed background subtraction by using the background models for the *RXTE*/PCA (Proportional Counter Array) instrument and Galactic ridge emission in the 2–50 keV range. Our X-ray flux and pulse frequency measurements find an increase in the X-ray flux which is correlated with the decrease in the spin-down rate (or marginal spin-up trend).

2 OBSERVATION AND DATA ANALYSIS

OAO 1657−415 was observed during 1997 August 20–27 within the guest observer programme of *RXTE* with proposal observation ID 20113. *RXTE* pointings of the source are separated from each other by approximately 6 h with a total observation span of 75 ks. The results presented here are based on data collected with the PCA (Jahoda et al. 1996) and the High Energy X-ray Timing Experiment (HEXTE, Rothschild et al. 1998). The PCA instrument consists of an array of five proportional counters operating in the 2–60 keV energy range, with a total effective area of approximately 7000 cm^2 and a field of view ~1° full width at half-maximum (FWHM). The HEXTE instrument consists of two independent clusters of detectors, each cluster containing four NaI(Tl)/CsI(Na) phoswich scintillation counters sharing a common ~1° FWHM field of view. The field of view of each cluster is switched on- and off-source to provide background measurements. The net open area of the seven detectors is 1400 cm^2 and each detector covers the energy range 15–250 keV.

2.1 X-ray light curves and spectra

Background light curves and pulse-height amplitudes are

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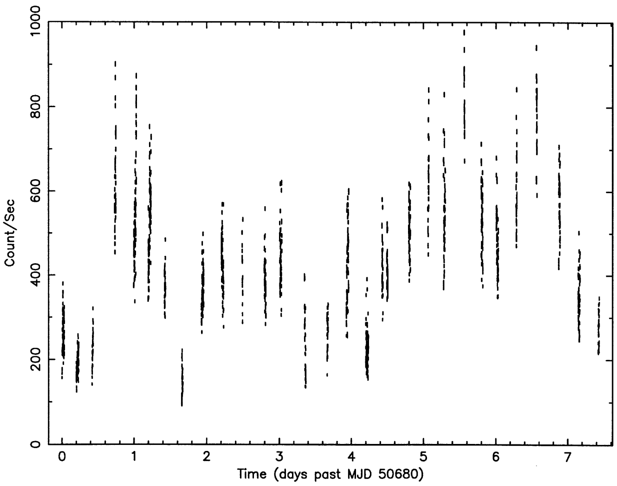

Figure 1. The total (5 PCU) *RXTE*/PCA background-subtracted X-ray light curve in the 2–50 keV energy range.

Table 1. Spectral fit parameters for *RXTE* observations.[a]

N_H (10^{21} cm^{-2})	12.94 ± 0.38
Fe line centre energy (keV)	6.65 ± 0.03
Fe linewidth (keV)	0.40 ± 0.06
Fe line intensity (photon cm^{-2} s^{-1})	$(2.77 \pm 0.31) \times 10^{-3}$
Photon index	1.07 ± 0.03
Cut-off energy (keV)	12.82 ± 0.29
Folding energy (keV)	29.37 ± 0.98
Power-law norm. (cm^{-2} at 1 keV)	$(5.96 \pm 0.37 \times 10^{-2}$
Reduced χ^2	1.28 (d.o.f = 178)

[a] Uncertainties in the spectral fit parameters denote single-parameter 1σ errors.

generated by using the background estimator models based upon the rate of very large events (VLE), spacecraft activation and cosmic X-ray emission with the standard PCA analysis tools. The background light curves are subtracted from the source light curve obtained from the Good Xenon event data (Fig. 1). Since the source is close to the Galactic centre, Galactic ridge data were extracted from archival *RXTE* observations. Observations pointed at directions a few degrees away from the source are collected. The background spectra for the Galactic ridge data were generated using PCA analysis tools. After the instrument background is removed from the Galactic ridge data, the residual spectra are used as a background for the X-ray spectra of OAO 1657−415. The source spectrum was calculated using the same PCA background estimator models. (It should be noted that ~3 per cent systematic errors are used in spectral fitting of PCA data.) For the HEXTE data the background subtraction is straightforward since the HEXTE detectors are rocking in 16-s intervals. Standard FTOOLS software for *RXTE* is used for the data reduction and for the deadtime correction. We have used power laws with high-energy cut-off models together with a 6.65-keV Gaussian emission line which was found in previous *Ginga* observations (Kamata et al. 1990). We have found no evidence for any deviation from a power-law model with high-energy cut-off that might be attributable to a cyclotron feature. Table 1 presents the spectral parameters of the X-ray spectra. Fig. 2 presents the joint X-ray spectra of *RXTE*/PCA and HEXTE detectors. The power-law index, and the cut-off and e-folding energies are significantly different from those measured by *Ginga*, the power law steeper, but extending to higher energy. The broader energy band of the PCA and HEXTE combination better constrains the higher energy spectra, but the spectrum may vary intrinsically.

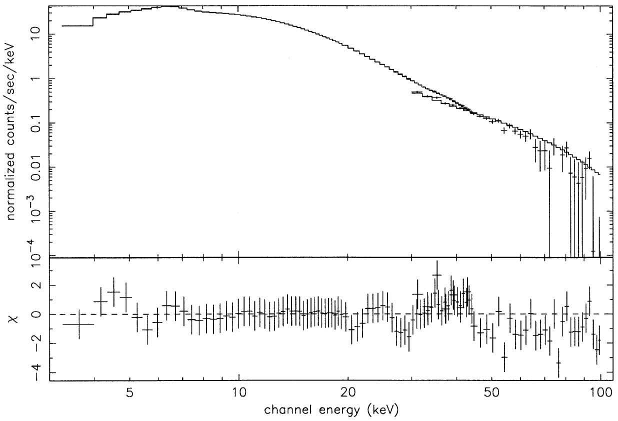

Figure 2. The *RXTE*/PCA-HEXTE spectra of OAO 1657−415. (Note that HEXTE spectra are the summed spectra of cluster 1 and cluster 2.) The lower panel shows the residuals of the fit in terms of χ^2 values.

Table 2. Timing solution of OAO 1657−415 for *RXTE* observations.[a]

Orbital epoch (MJD)	48 515.99(5)[b]
P_{orbit} (d)	10.448 09(30)[b]
$a_x \sin i$ (light-second)	106.0(5)[b]
e	0.104(5)[b]
w	93(5)[b]
Epoch (MJD)	50 683.954 00(2)
Pulse frequency (Hz)	0.026 775 618(4)
Pulse freq. deriv. (Hz s^{-1})	$-3.27(9) \times 10^{-12}$

[a] Confidence intervals are quoted at the 1σ level.
[b] Orbital parameters are taken from Bildsten et al. (1997). P_{orbit} = orbital period, $a_x \sin i$ = projected semimajor axis, e = eccentricity, w = longitude of periastron.

2.2 Pulse timing of OAO 1657−415

The background-subtracted light curves are corrected with respect to the barycentre of the Solar system. Using the binary orbital parameters of OAO 1657−415 from BATSE observations (Bildsten et al. 1997), the light curves are also corrected for binary motion of OAO 1657−415 (see Table 2). A long power spectrum was used to estimate the average pulse frequency. This pulse frequency is consistent with BATSE pulse frequency records at the same time (obtained through HEASARC http://cossc.gsfc.nasa.gov). In order to resolve the pulse arrival times and pulse frequencies at shorter time-scales, 29 pulse arrival times were generated (one pulse arrival time for each *RXTE* orbit). Pulse arrival times are found by folding the light-curve data into one average pulse for each *RXTE* orbit, folding all light curves into one master pulse, and cross-correlating the master pulse with each of the 29 average pulses. In the pulse timing analysis, we have used the method of harmonic representation of pulse profiles, as proposed by Deeter & Boynton (1985). In this method, pulse profiles are expressed in terms of harmonic series and cross-correlated with the master pulse profile. The maximum value of the cross-correlation is analytically well defined and does not depend on the phase binning of the pulses. The master pulse with 40 phase bins was represented by their harmonics (Deeter & Boynton 1985) and cross-correlated with harmonic representations of pulse profiles from segments of the data.

The pulse profiles for OAO 1657−415 are variable. This affects the pulse timing. In order to estimate the errors in the arrival times, the light curve of each *RXTE* orbit is divided into approximately 10–15 equal subsets and new arrival times are estimated. The average variances in the arrival times are computed and treated as errors of arrival times. The pulse arrival times are represented in Fig. 3. The residual pulse arrival times may arise from the change of the pulse frequency during the observation (or intrinsic pulse frequency derivative) and from the errors of orbital parameters (Deeter, Boynton & Pravdo 1981),

$$\begin{aligned}\delta\phi = {}& \phi_{\mathrm{o}} + \delta\nu(t - t_{\mathrm{o}}) + \tfrac{1}{2}\dot{\nu}(t - t_{\mathrm{o}})^2 \\ & + \nu\delta\left(\frac{a\sin i}{c}\right)\sin l_n - \nu\frac{2\pi\delta T_{\pi/2}}{P_{\mathrm{orbit}}}\frac{a\sin i}{c}\cos l_n \\ & + \nu\frac{2\pi}{P_{\mathrm{orbit}}^2}\frac{a\sin i}{c}\delta P_{\mathrm{orbit}}(t_n - T_{\pi/2})\cos l_n. \qquad (1)\end{aligned}$$

Here $\delta\phi$ is the pulse phase offset deduced from the pulse timing analysis; t_{o} is the mid-time of the observation; ϕ_{o} is the phase offset at t_{o}; $\delta\nu$ is the deviation from the mean pulse frequency (or additive correction to the pulse frequency); $\dot{\nu}$ is the pulse frequency derivative of the source; $(a\sin i)/c$ is the light traveltime for projected semimajor axis; $T_{\pi/2}$ is the epoch when the mean orbital longitude is equal to 90°; P_{orbit} is the orbital period; δ denotes the errors of these parameters; and $l_n = 2\pi(t_n - T_{\pi/2})/P_{\mathrm{orbit}} + \pi/2$ is the mean orbital longitude at t_n. The above expression is fitted to the pulse arrival times data. Table 2 presents the timing solution of OAO 1657−415 from our *RXTE* observations. The pulse frequency derivative obtained from the quadratic trend of the pulse timing analysis is $\dot{\nu}_{RXTE} = -(3.27 \pm 0.09) \times 10^{-12}\,\mathrm{Hz\,s^{-1}}$. The average pulse frequency derivative we deduce from the pulse frequency history of BATSE archival data is $-(3.1 \pm 0.2) \times 10^{-12}\,\mathrm{Hz\,s^{-1}}$, consistent at the 1σ level.

The pulse frequency records of OAO 1657−415 have shown that the source has stochastic spin-up/down trends (Baykal 1997; Bildsten et al. 1997) at time-scales longer than weeks. In intervals between stochastic changes, OAO 1657−415 shows secular spin-up or spin-down trends with lower values of noise strength (Baykal 1997). Our observations detect the source spinning down, on average. There are local deviations from quadratic trends which can be interpreted as very short-term fluctuations (see Fig. 3). The torque noise analysis of OAO 1657−415 from the BATSE observations (Baykal 1997) showed that pulse frequency fluctuations at shorter than ~8 d are almost not detectable because of the measurement noise. However *RXTE* observations yield significant fluctuations around the average quadratic trend (or spin-down rate), as shown in Fig. 3. In *RXTE* observations we are able to construct pulses for time intervals as short as a few hundred seconds. This yields better timing at shorter time-scales. Therefore the fluctuations in arrival times less than ~8 d are resolved.

2.3 Torque and X-ray luminosity changes of OAO 1657−415

The X-ray flux and pulse frequency derivative correlations of OAO 1657−415 were investigated by using the BATSE archival data base (Baykal 1997). BATSE pulse flux at 20–60 keV and pulse frequency series have shown no correlation between X-ray flux and pulse frequency derivatives. A strong correlation between specific angular momentum (l) and pulse frequency derivatives was found instead. These correlations implied that the specific angular momentum is directional, sometimes positive and sometimes negative ($\pm l$), and that sometimes the flow is radial. These results suggested the formation of temporary accretion discs in the case of stellar wind accretion and the short-term disc reversals are quite possible. In the analysis of BATSE data, the shortest time-scales for resolving the significant pulse frequency fluctuations were of the order of 8 d.

In the present work, in order to resolve pulse frequencies at shorter time-scales, we used high counting statistics of *RXTE*/PCA detectors and obtained pulse arrival times at approximately 6 h intervals. For each four or five pulse arrival times, we fitted a straight-line segment, and using the slope of this line we estimated a correction to the average pulse frequency, i.e. $\delta\phi = \phi_{\mathrm{o}} + \delta\nu(t - t_{\mathrm{o}})$. In this way, we obtained pulse frequency records for each day roughly. In Fig. 4 we present the pulse frequency records estimated in this work. We accumulated the spectral data at 2–50 keV, corresponding to observations of pulse arrival times.

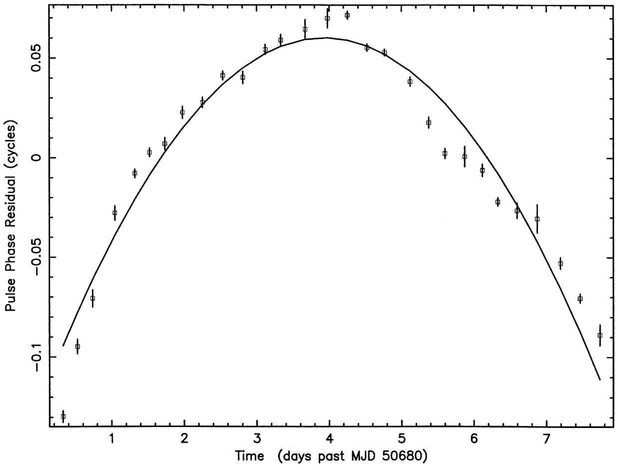

Figure 3. Phase offsets in pulse arrival times. Solid line denotes the best fit of arrival times.

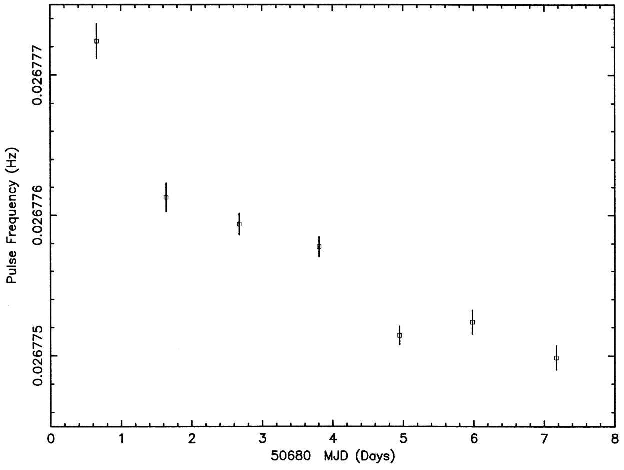

Figure 4. Pulse frequency measurements of OAO 1657−415, from *RXTE*/PCA observations.

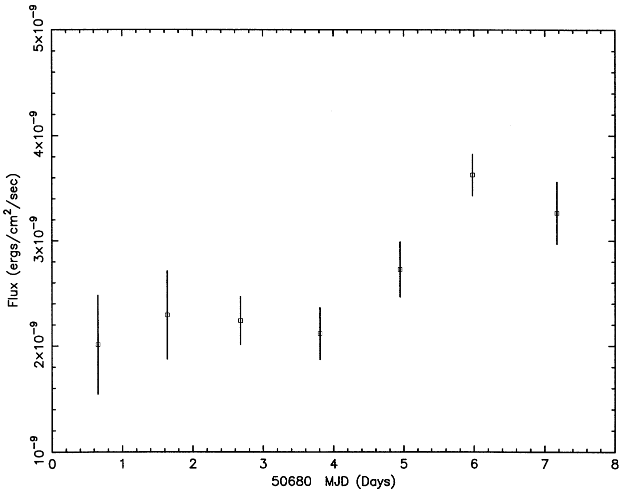

Figure 5. The 2–50 keV X-ray flux measurements of OAO 1657−415, from *RXTE*/PCA observations.

In each set of observations we fitted a power law with high-energy cut-off with a Gaussian emission line, then we estimate unabsorbed flux (or intrinsic pulsar flux). Fig. 5 presents the pulsar flux history during the *RXTE* observations. During the observation, bolometric X-ray flux increased roughly by 70 per cent. The spin-down rate is decreased and a marginal spin-up trend is seen. This is the first evidence in OAO 1657−415 to show positive marginal correlation between the X-ray flux and pulse frequency changes.

3 CONCLUSION

OAO 1657−415 has shown strong spin-up/down torques in its time history which cannot be explained by wind accretion (Baykal 1997). The formation of temporary accretion discs was therefore considered. If accretion on to the neutron star is from a Keplerian disc (Ghosh & Lamb 1979), the torque on the neutron star is given by

$$I\dot{\nu} = n(w_{\rm s})\dot{M} l_{\rm K}, \qquad (2)$$

where $l_{\rm K} = (GMr_{\rm o})^{1/2}$ is the specific angular momentum added by a Keplerian disc to the neutron star at the inner disc edge $r_{\rm o} \approx 0.5 r_{\rm A}$ where $r_{\rm A} = (2GM)^{-1/7}\mu^{4/7}\dot{M}^{-2/7}$ is the Alfvén radius, μ is the neutron star magnetic moment, $n(w_{\rm s}) \approx 1.4(1 - w_{\rm s}/w_{\rm c})/(1 - w_{\rm s})$ is a dimensionless function that measures the variation of the accretion torque as estimated by the fastness parameter

$$w_{\rm s} = \nu/\nu_{\rm K}(r_{\rm o}) = 2\pi P^{-1} G^{-1/2} M^{-5/7} \mu^{6/7} \dot{M}^{-3/7}.$$

Here $w_{\rm c}$ is the critical fastness parameter where the accretion torque is expected to vanish at $w_{\rm c} \sim 0.35$–0.85 depending on the structure of the disc. According to this model the torque will cause a spin-up if the neutron star is rotating slowly ($w_{\rm s} < w_{\rm c}$) in the same sense as the circulation in the disc, or a spin-down if it is rotating in the opposite sense. Even if the neutron star is rotating in the same sense as the disc flow, the torque will spin-down the neutron star if it is rotating too rapidly ($w_{\rm s} \gg w_{\rm c}$). In such a model one should see positive correlation between pulse frequency derivative ($\dot{\nu}$) and moderate mass accretion rate ($\dot{M}$) if the disc is rotating in the same sense as the neutron star (Baykal 1997).

Recent observations of accreting neutron stars have shown stochastic spin-up/down trends on time-scales from days to a few years (Bildsten et al. 1997). Some of the sources switch from spin-up to spin-down states without showing great changes in their mass accretion rates (Bildsten et al. 1997). These unusual behaviours led Nelson et al. (1997) to the possibility of retrograde circulation of accretion discs. GX 4+1 shows correlation between the X-ray flux and the spin-down rate (Chakrabarty et al. 1997), which may suggest a retrograde accretion disc. In our *RXTE* observations, OAO 1657−415 has shown marginal correlation with accretion rate and pulse frequency change. This positive correlation strongly suggests that the disc formed in the spin-down episode is in the prograde direction. From the BATSE observations, it was concluded that the pulse frequency derivatives and X-ray flux were not well correlated and that 8 d was the minimum for the correlation time-scale (Baykal 1997). This *RXTE* observation implies that the time-scale of correlation is short, only a few days. To see the exact nature of correlations between X-ray flux and pulse frequency derivatives, an even more extensive broad-band X-ray observation should be carried out.

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