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QPO Detection for HMXB Transient Pulsar 1A~0535+262 Observed with RXTE-PCA

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Abstract— We report the detection of quasi-periodic oscillations (QPO) at ~19 mHz and ~4 mHz in the transient high-mass Be/X-ray binary pulsar 1A~0535+262 using data from the RXTE observatory. The observations used in the present work were carried out during the X-ray outbursts in 2010 January-April-August and 2011 Feb-May-July-August. The ~19 mHz QPO in 1A~0535+262 was detected in two Rossi Explorer Timing Experiment (RXTE) Proportional Counter Array (PCA) observations during the declining phase of its 2010 January-April-August outburst and ~4 mHz QPO in 2011 Feb-May-July-August. However, this QPO was rarely detected during other two outbursts of the pulsar. Though QPOs between 27-72 mHz were reported earlier in the pulsar, the ~19 mHz and ~4 mHz QPOs were detected for the first time in this pulsar. The results of our analysis of RXTE data during two outbursts of the pulsar are presented in the paper.

Index Terms— X-rays: stars - neutron, pulsars - stars: individual - 1A~0535+262

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1 Introduction

X-ray binaries are combined system of a donor star and an accreting compact object either a black hole or a neutron star. The system with detected periodic pulsations is known as accreting X-ray pulsar and then compact object must be neutron star. Be/X-ray binaries represent the largest sub-class of high mass X-ray binaries (HMXB). About 2/3 of the identified HMXB systems fall into this category. Be/X-ray binaries are composition of neutron star and non-supergiant OB star (luminosity class of III, IV or V) showing emission lines in the spectrum [26]. Be star are rapidly objects having a quasi-Keplerian disk around their equator. The solid cause of disk formation is still under debate [33]. In these systems (Be star) the optical companion is still on the main sequence and neutron stars have wide orbit and moderate eccentricity. Periodic X-ray outbursts take place due to mass transfer from the optical companion to the neutron star.

Mostly the Be/X-ray binaries are transient systems and their out bursts have been classified into two classes: type I and type II out bursts. Type I outbursts define the The X-ray variability of the transient Be/XRB and also known as normal outbursts.

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The type I outbursts are regular and quasi-periodic outbursts normally close to periastron passage of the neutron star having peak luminosities ($L_x \leq 10^{37}$ erg/s^{-1}). The type II outbursts outburst reaching peak luminosities of the order of Eddington luminosity for a neutron star ($L_x \approx 10^{38}$ erg s^{-1}) [10]. Giant outbursts have no consistently preferred orbital phase [35]. For more detail study the review on the temporal and spectral properties of transient Be/X-ray binary pulsars [23].

Transient Be/X-ray binary pulsar 1A ~0535+262 was discovered by Arielv in 1975 [27], [5]. The pulsar has orbital period of ~111 days and pulse period of ~ 103 s in a eccentric orbit of ~0.47 [9]. Optical counter-part of the pulsar is O9.7 IIIe star 2 HDE 245770. This system shows both giant and normal outbursts. The pulsar is extensively studied from the discovery date with different satellites CGRO/BATSE, RXTE/ASM, SWIFT/BAT, FERMI/GBM and EERMI/LAT [1].

Both types of behavior (typeI and typeII) are possible for the eccentricity of the pulsar 1A0535+262 (e=0.47) as the disk expands and contracts between different as resonants radii [11],[6]. Moritani [20] studied high dispersion optical spectroscopic observations of the pulsar during and after 2009 December giant outburst. An anti correlation was found between the optical brightness and the H-alpha intensity during 2009 outburst [36]. During the 2011 February giant outburst and X-ray quiescent phases a ~12% reduction was found in the near -IR flux during the periastron passage of the neutron star [22].

Two cyclotron resonance scattering features were detected at 45 keV and 100 keV during the 1989 March/April giant outburst [17] and magnetic field of B~4x10^{12} G was detected. During the recent outburst (2009 and 2010) of the pulsar 1A~0535+262 first cyclotron line studies was presented by Caballero [4]. The Broad QPOs from 27 to 72 mHz were detected during the 1994 giant outburst [9]. A hard 30-70 mHz x-ray QPO was detected with GBM during the 2009 December gaint outburst pointed out that the large event that came after the 2009 December giant outburst does not follow the standard classification as earlier Type I or Type II outburst. These QPOs were explained as due to the obscuration of the neutron star by hot matter in the accretion disk.

In the present work, we have investigated the timing properties of the transient X-ray pulsar 1A~0535+262 using observations made with the RXTE and report the detection of QPO features detected during two X-ray outbursts in 2010 and 2011.

2 OBSERVATIONS 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 to our understanding of high energy astrophysics by means of its unrivaled timing resolution. We have used the RXTE observations of transient Be/X-ray binary pulsar 1A~0535+262 during two of its both types of 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 [19]. The 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 6500 cm^2 at 6 keV, 18 % at 6 keV and 1 s, respectively. A detailed description of the PCA instrument can be found in paper by Jahoda [13]. The third instrument, High Energy Timing Experiment (HEXTE) was operating in 15-250 keV energy range [28].

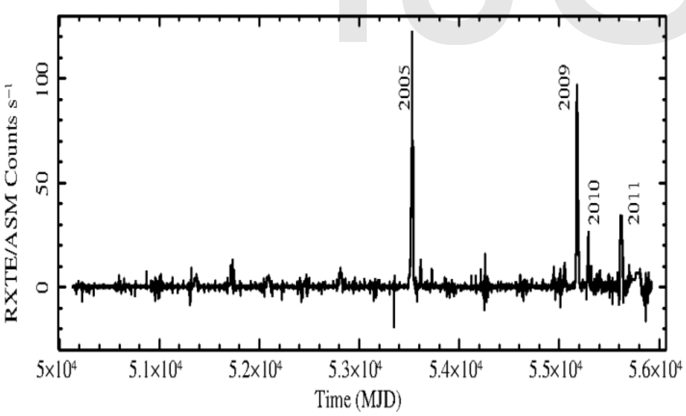

Figure 1 ASM one-day averaged light curve of the transient pulsar 1A~0535+262 in 1.5-12 keV energy range from 1996 January 5 (MJD 50087) to 2011 December 31 (MJD 55926). During entire observing period of RXTE, only four major outbursts were detected in the ASM light curve. RXTE/PCA observations during 2010 and 2011 outbursts were analyzed to investigate the QPO features in the pulsar.

The RXTE/ASM light curve of 1A~0535+262 from 1996 January to 2011 December is shown in figure 1. During above duration i.e. entire life time of the RXTE observatory, only four major outbursts were detected in the pulsar. Out of the four outbursts, we used the data of 2010 and 2011 outbursts, were used in our present analysis.

For our timing analysis, we used data from all the PCA observations during the 2010 and 2011 outbursts (as marked in figure 1). There were a total of 18 RXTE/PCA observations (14 during 2010 outburst and 4 during 2011 outburst). We used PCA data from above observations to study the evolution of QPO in this pulsar. Standard 1 mode data with a time resolution of 0.125 s were used in the present analysis. Data reduction was carried out by using the software package FTOOLS whereas data analysis was done by using the HEAsoft package (version 6.11).

Table 1 Observation detail of 1A~0535+262 for the 2010 and 2011 outbursts

S.No.	Observation ID	Date	MJD	Duration	Exposure	PCUs on	Average light curve Count rate
1	95431-01-03-00	2010-08-13	55421	11223	6707	0,1,2	120.12±0.18
2	95431-01-03-01	2010-08-15	55423	10066	6443	0,1, 2	79.52± 0.2
3	95431-01-03-02	2010-08-16	55424	9617	4755	0,1, 2	57.92±.63
4	95431-01-01-01	2010-08-02	55410	6038	3537	0,2,3	494.48±0.15
5	95347-02-01-01	2010-04-05	55291	4683	3528	2	1258.94±0.94
6	95347-02-01-00	2010-04-03	55289	5049	3479	2	1169.04±0.66
7	95431-01-01-00	2010-08-02	55410	5478	3362	1,2	607.84±0.53
8	95431-01-02-00	2010-08-07	55415	5435	3366	1	280.8±0.8
9	94323-05-05-00	2010-01-11	55207	5822	3360	2	43.11±0.19
10	94323-05-04-01	2010-01-04	55200	4430	3280	0,2	597.79±0.71
11	95347-02-01-02	2010-04-08	55294	4325	3117	2	138.67± 0.43
12	94323-05-04-02	2010-01-07	55203	4475	3026	1,2	257.38±0.9
13	94323-05-04-00	2010-01-02	55198	5440	2948	2	492.59± 0.56
14	94323-05-05-01	2010-01-14	55210	4361	2533	0,2	88.55±0.36
15	96421-01-01-00	2011-02-24	55616	11519	6681	0,2,4	5260.50±0.5
16	96421-01-02-00	2011-05-15	55696	6532	3073	2	30.02±0.16
17	96421-01-03-00	2011-07-28	55770	5754	3033	2, 3	26.68±0.25
18	96421-01-04-00	2011-08-22	55795	6115	2887	2	26.94±0.84

Observation detail with date, Modified Julian Days (MJD), duration of observation, exposure of observation, the PCUs on during the observation and averaged light curve counts with error are shown in table 1. Using the standard 1 mode PCA data, we extracted light curves with a time resolution of 0.125 s from all the RXTE pointed observations during the 2010 and 2011 outbursts. We generated power-density spectrum (PDS) from each of the light curves by using the FTOOLs package. The resulting PDS were normalized such that their integral gives the squared rms fractional variability. All the PDS were then examined for the presence/absence of QPOs in a wide frequency range (0.1 mHz to 1 Hz). We found that the 103 s regular pulsations of the pulsar and its harmonics were present in the PDS obtained for all the PCA observations. Apart from these pulsations and corresponding harmonics, the PDS from some RXTE/PCA observations during the two outbursts of the pulsar were featureless. These ~19 mHz and ~4 mHz QPOs in the transient pulsar 1A~0535+262 are detected for the first time here though the QPOs between 27-72 mHz were reported earlier.

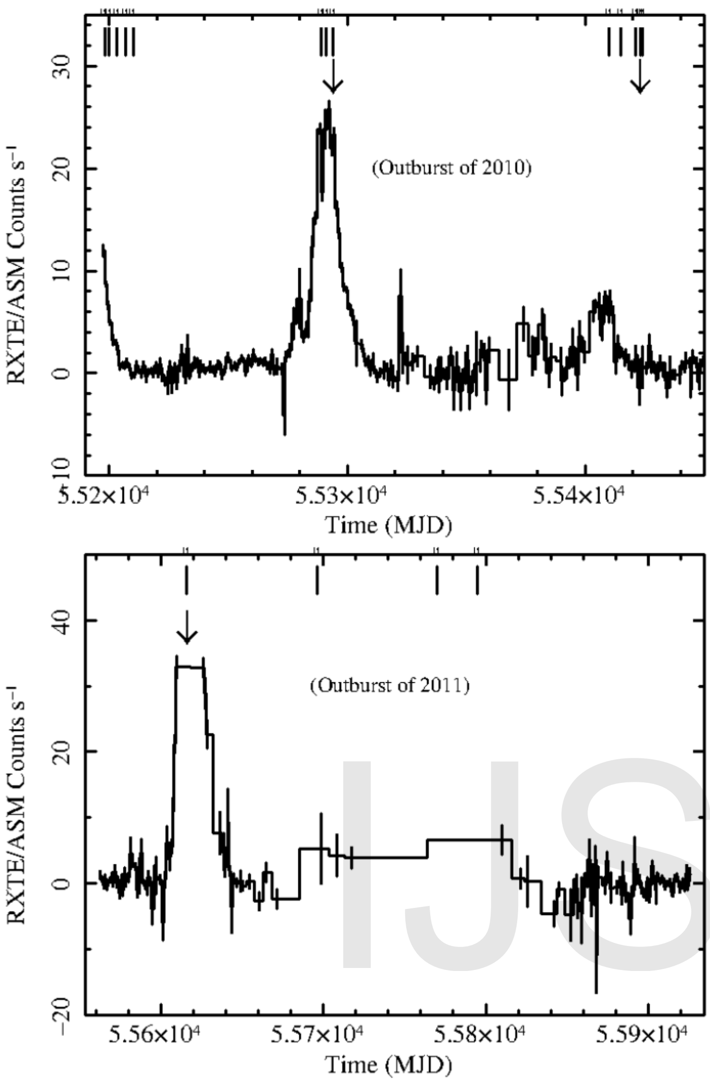

Figure 2 One-day averaged RXTE/ASM light curve of the transient Be/X-ray binary pulsar 1A~0535+262 during 2010 outburst (top panel) and 2011 outburst (lower panel). The vertical lines at the top of panel indicate the RXTE/PCA pointed observations of the pulsar whereas the vertical arrows indicate the observations when the QPOs were detected in the PCA data.

One-day averaged 1.5-12.0 keV RXTE/ASM light curves of the pulsar during the 2010 (upper panel) and 2011 (lower panel) outbursts are shown in figure 2. In each panels of the figure, the day of RXTE observations are marked with vertical lines and the observations in which the QPOs were detected are indicated with downward arrow marks in each panel. Out of a total of 18 RXTE observations, we found the presence of QPOs in 3 observations. The log of observations is given in Table 1. The ~19 mHz QPO seen in the transient pulsar 1A~0535+262 were detected in a few of the observation during 2010 outbursts and ~4 mHz QPO in 2011 outburst. Figure 3 and figure 4 show QPOs 2010 outburst for different observations 95431-01-03-01 & 95347-02-01-02 respectively . Figure 5 shows the representative PDS for the outburst of 2011 for observation ID 96421-01-01-00.

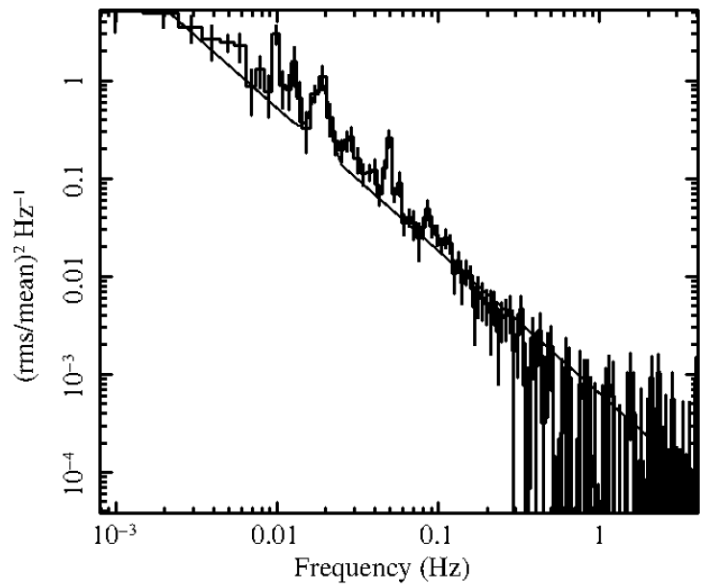

Figure 3 Representative PDS showing QPO for observation ID 95431-01-03-01 of 2010 outburst

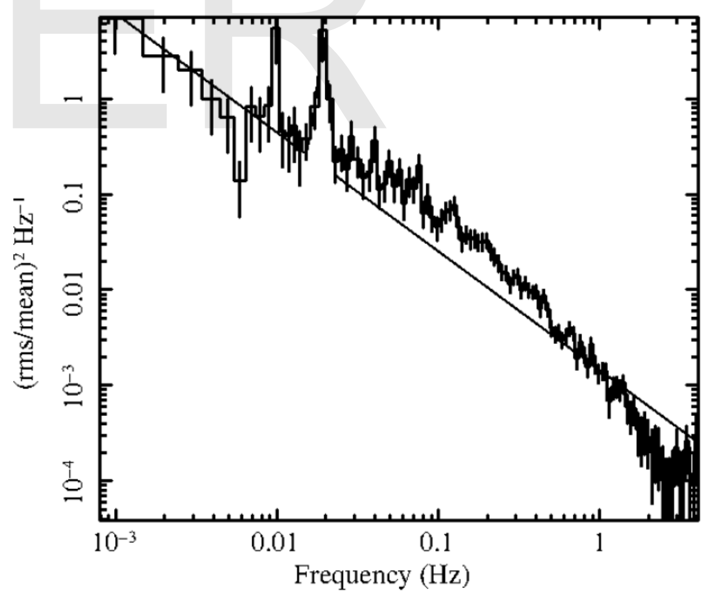

Figure 4 Representative PDS showing QPO for observation 95347-02-01-02 of 2010 outburst

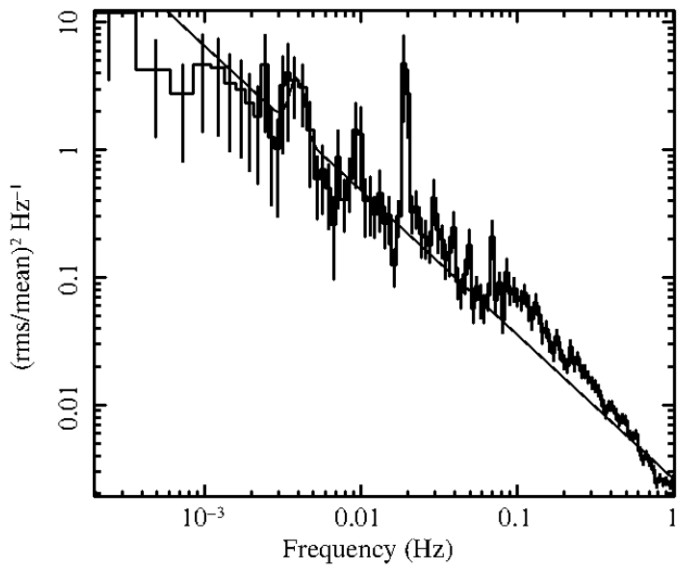

Figure 5 Representative PDS showing QPO for observation 96421-01-01-00 of 2011 outburst

3 DISCUSSIONS AND CONCLUSION

Due to the motion of the inhomogeneously distributed matter in the inner part of the accretion disk, results to evolution of QPOs in accretion powered X-ray binary pulsars. Useful information on the radius of the inner accretion disk and the interaction between the neutron star accretion disk can be found from detection of QPOs. According to Psaltis [25] the QPO frequency detected in accretion powered X-ray pulsars falls in the range of 1 mHz to 40 Hz. QPO features are detected more in transient sources compared to the persistent ones In accretion powered X-ray binary pulsars. In most of the transient Be/X-ray pulsars, the detected QPOs are found to be transient in nature. For example in case of KS~1947+300, the QPO feature was not seen in the data of 2000 and 2002 outbursts whereas it appeared at the end of the 2001 outburst [24].

In 1A~0535+262, the QPO features were not detected in all of the RXTE observations during 2010 and 2011 outbursts (present work). Transient HMXB pulsars from which QPOs have been detected are KS~1947+300 [14], SAX~J2103.5+4545 [12], A0535+262 [9], V0332+53 [32], and 4U 0115+63 [31], XTE~J1858+034[21], EXO~2030+375[3], XTE~J0111.2-7317[16], 4U~1901+03[15], 1A~1118-61[7] and GX~301-4 [8].

The QPO features in the PDS of accretion powered X-ray pulsars have been explained using several models as follows: (a) Beat frequency model (BFM) (b) Keplerian-frequency model (KFM) and third one (c) magnetic disk precession model (MDPM). According to the magnetospheric BFM model, the observed QPO frequency (ν_{QPO}) represent the beat between the coherent spin frequency of the pulsar (ν_s) and the Keplerian frequency (ν_K) at the inner disk radius i.e. $\nu_{QPO} = \nu_K(r_{in}) - \nu_s$, at the magnetospheric boundary of the pulsar[2],[18].

On the other hand, in the KFM model, QPOs arise because of the modulation of the X-rays by inhomogeniously distributed matter in the inner accretion disk at the Keplerian frequency [34]. The observed QPO frequency is same as the frequency of the Keplerian motion at the inner accretion disk (i.e. $\nu_{QPO} = \nu_K(r_{in})$. When the spin frequency of the pulsar is higher than the Keplerian frequency at the inner edge of the accretion disk, mass accretion on to the neutron star is stopped at the magnetospheric boundary by centrifugal inhibition of accretion [29] 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 Be/X-ray binary pulsars such as EXO~2030+375[3], A0535+262[9], XTE~J0111.2−7317 [16] etc. However, in case of 1A~0535+262, frequency of all QPOs (earlier reported QPOs between 27-72 mHz and newly detected QPO at ~19 mHz) are found to be greater than the spin frequency of the pulsar. Therefore, the Keplerian-frequency model is suitable to explain the presence of QPO in the transient pulsar 1A~0535+262.

Third model proposed to explain the low-frequency QPO features in strongly magnetized (10^{12} G) accretion powered X-ray pulsars is the magnetic disk precession model[30]. According to this model, the presence of QPOs in binary pulsars is due to the magnetically driven disk warping near the inner edge of the disk at the magnetospheric boundary. The magnetic torques due to interactions of the stellar field and the induced electric currents in the disk is responsible for warping and precession of the disk. This model was used the mHz QPO detected in the transient Be/X-ray pulsar 4U~1626-67 along with several others [30]. This model was also attempted to explain the QPO features in the transient pulsar 1A~0535+262 in terms of the presence of magnetically driven disk precession around the neutron star.

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