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RXTE/PCA Observations: "Variable QPOs for Transient Be/X-Ray Binary Pulsar EXO~2030+375"

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Abstract— We present results from study of timing properties and report the detection of variable quasi-periodic oscillations (QPO) between 0.36-0.74 Hz in the transient Be/X-ray binary pulsar EXO~2030+375 using RXTE/PCA observations. The observations used in the present work were carried out during the X-ray outbursts in 2006 (March-May-June-August-September-October-November) and 2011 (January-February-April-May-June-July-August-September-November-December). The 0.36-0.74 Hz variable QPOs in EXO~2030+375 were detected in seven Rossi Explorer Timing Experiment (RXTE) Proportional Counter Array (PCA) observations during the rising and declining phase of its giant outburst 2006 and normal outburst of 2011. However, these QPOs were never detected during other outbursts of the pulsar. Though QPO of 0.2 Hz were reported earlier in the pulsar, the 0.36-0.74 Hz variable 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— stars: neutron, pulsars: individual: EXO 2030+375 X-rays: stars

1 INTRODUCTION

Be/X-ray binaries consists the largest subclass of high mass X-ray binary systems in which the compact object is generally a neutron star (pulsar) whereas the companion is a B or O-type star. The binary optical companion lies well within the Roche lobe. In these binary systems, the objects are typically in a wide orbit having moderate eccentricity. The neutron star in this type of Be/X-ray binaries accrets matter while passing through the circumstellar disk of the companionBe star. Strong X-ray outbursts takes place when the abrupt accretion of matter onto the neutron star while passing through the circumstellar disk of the Be companion or during the periastron passage [23] The X-ray emission from the pulsar can be transiently enhanced by a factor more than ~10 during such outbursts. The neutron stars in the Be/X-ray binary systems are found to be accretion powered X-ray pulsars except a very few cases such as LS I+61303 [21].

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When the compact object interacts with the Be star's circumstellar disk following the standard model of a Be/X-ray binary ascribes the high-energy radiation to an accreting mechanism, gives rise to an X-ray outburst.

Mostly the Be/X-ray binaries are transient systems and their out bursts have been classified into two classes: type I and type II outbursts. Type I outbursts define the the X-ray variability of the transient BeXRB and also known as normal outbursts. The type I outbursts are regular and quasi-periodic outbursts normally close to periastron passage of the neutron star having peak luminosities ($L_x \le 10^{37}$ 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}) [3], [9]. Giant outbursts have no consistently preferred orbital phase [Wilson et al. 2008]. There are several models to define QPOs. According to Beat Frequency Model (BFM), QPOs arise from the modulation of accretion flow onto a weakly magnetized, rapidly rotating neutron star [2].

In our case, we studied one giant outburst during 2006 and another normal outburst during 2011 for the transient Be/X-Ray binary pulsar EXO~2030+375 and detected variable QPOs.

2 Be/X-Ray BINARY PULSAR EXO~2030+375

The HMXRB EXO~2030+375 is an X-ray transient binary system that consists of a neutron star orbiting a Be companion. It was discovered by EXOSAT in 1985 during a giant (or type II) X-ray outburst [24], [25]. This system shows both giant and normal outbursts. The pulsar is one of the most regularly monitored BeXRBs. The pulsar is extensively studied from the discovery date with different satellites CGRO/BATSE [32], RXTE [35], SWIFT [10], EXOSAT [32], and INTEGRAL [38].

The spin 42 s and orbital periods of 44.3-48.6 days of the pulsar were estimated using the EXOSAT observations in 1985. Stollberg [32] derived following orbital parameters of the binary system: orbital period Porb = 46.02±0.01 days, e =

0.36±0.02, ax sin i = 261±14 lt-sec, ω = 223◦ .5 ± 1◦ .8 and time of periastron passage τ = 2448936.8 ± 0.3 days while analyzing BATSE monitoring data of several consecutive outbursts of the pulsar EXO~2030+375 in 1992. An extensive monitoring campaign of EXO~2030+375 with BAT SE and RXTE showed that a normal outburst has been detected for nearly every periastron passage for ~13.5 years [37].
The counterpart of the pulsar found to be B0 Ve star in follow up observations in the optical and infrared bands [13], [20], [5]. During the giant outburst, EXO 2030+375 showed a QPO phenomenon with a frequency of ~0.2 Hz [2] interpreted as caused by the formation of an accretion disk.
In the present work, we have investigated the timing properties of the transient X-ray pulsar EXO~2030+375 using observations made with the RXTE and report the detection of QPO features detected during two X-ray outbursts in 2006 and 2011. The results obtained from the timing analysis of the RXTE/PCA observation are presented in this paper.

3 OBSERVATIONS AND DATA ANALYSIS

RXTE was launched on 1995 December 31 and the timing studies of celestial X-ray sources was its main objective. 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 EXO~2030+375 during two of its both types of outbursts. RXTE, which is now decommissioned, had three sets of major instruments classified as: (a) The all sky monitor (ASM), (b) PCA (Proportional Counter Array) and (c) High Energy Timing Experiment (HEXTE).
The 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 [14]. The third instrument, HEXTE was operating in 15-250 keV energy range [29].

We used standard 1 mode data, which provided binned data with a time resolution of 0.125 s, as all 256 channels were combined into one, to calculate the light curve and pulse periods.

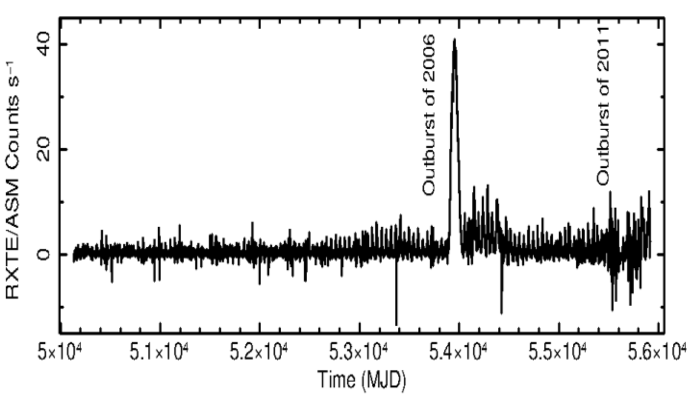

Figure 1 ASM one-day averaged light curve of the transient pulsar EXO~2030+375 in 1.5-12 keV energy range from 1996 February 2 (MJD 50133) to 2012 January 01 (MJD 55927). During entire observing period of RXTE, only four major outbursts were detected in the ASM light curve. RXTE/PCA observations during 2006 and 2011 outbursts were analyzed to investigate the QPO features in the pulsar.

Figure 1 represents the full RXTE-ASM curve from the beginning of the RXTE mission in 1996 to 2012. There is a big peak among the number of small peaks of periodic x-ray bursts of slightly varying amplitudes. The big x-ray peak refers to a well studied huge x-ray burst of 2006 observed by RXTE for EXO~2030+375 pulsars. The huge burst of 2006 is found with approximately three times time width and 4 times counting rate. This burst is identical to the other small periodic bursts of almost the same time width, but with sufficiently larger amplitude. This provides an opportunity for the comparative study of the x-ray system EXO~2030+375 with earlier studies.

The RXTE/ASM light curve of EXO~2030+375 from 1996 February to 2012 January is shown in figure 1. During above duration i.e. entire life time of the RXTE observatory, only one major outburst was detected in the pulsar. We used the data of 2006 and 2011 outbursts, were used in our present analysis.
We used data from all the PCA observations for our timing analysis during the 2006 and 2011 outbursts (as marked in figure 1). There were a total of 161 RXTE/PCA observations (103 during 2006 outburst and 58 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).
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, 2, 3, 4, 5.
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 2006 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. We found varying rms values between ~4%-17% (as shown in table no. 6). All the PDS were then examined for the presence/absence of QPOs in a wide frequency range (1 mHz to 4 Hz). We found that the 42 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. Variable QPOs between ~0.36-0.74 Hz (as shown in table no. 6) in the transient pulsar EXO~2030+375 are detected for the first time here though the QPO at 0.2 Hz was reported earlier.

Table 1 : Log of observations during 2006 (March-May-June-August-September)

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Observation ID	Date	MJD	Duration	Exposure	Average count	Pulse period	PCUs on
92067-01-01-00	22/03/06	53816	5589	3544	358.66±0.16	41.64	0,2,3
92760-01-01-01	23/03/06	53817	5989	4089	297.93±0.42	41.65	1,2,3
92067-01-01-03	24/03/06	53818	8654	5492	217.21±0.41	41.64	0,2
92067-01-01-10	24/03/06	53818	1806	1554	93.55±0.41	41.65	0,2
92067-01-01-11	25/03/06	53819	3935	1922	232.65±0.45	41.63	0,1,2
92067-01-01-02	25/03/06	53819	4520	2258	241.05±0.45	41.65	1,2
92067-01-01-04	25/03/06	53819	4074	1798	253.18±0.48	41.65	0,2
92067-01-01-05	26/03/06	53820	7803	5077	251.22±0.43	41.66	3
92067-01-01-06	27/03/06	53821	7845	4496	333.5±0.42	41.59	0,2
92067-01-02-00	07/05/06	53862	9173	5955	224.96±0.44	41.65	0,2
92067-01-02-01	08/05/06	53863	9819	5307	266.72±0.42	41.65	0,2
92067-01-02-03	0905/06	53864	4600	2400	208.72±0.32	41.64	0,1,2,3
92067-01-02-02	10/05/06	53865	8117	5416	241.50±0.40	41.64	0,2
92067-01-02-04	11/05/06	53866	7537	4786	368.75±0.53	41.64	0,2
92067-01-02-10	12/05/06	53867	2755	527	241.951±0.45	41.67	0,2
92067-01-02-11	13/05/06	53868	5290	2824	328.94±0.42	41.64	2
92067-01-03-00	22/06/06	53908	9152	5086	549.61±0.51	41.62	0,2,4
92067-01-03-10	23/06/06	53909	7716	4912	1976.65±0.56	41.63	2,3
92067-01-03-11	24/06/06	53910	10037	5798	1283.95±.05	41.63	0,2,3
92067-01-03-12	25/06/06	53911	8283	4977	2322.01±0.42	41.62	0,2,3,4
92067-01-03-13	26/06/06	53912	7906	5099	2452.08±0.71	41.64	0,1,2
92067-01-03-14	27/06/06	53913	9353	4769	2614.78±0.23	41.64	0,2,3
92067-01-04-00	07/08/06	53954	4681	2021	4935.18±0.24	41.64	0,1,2
92067-01-04-01	08/08/06	53955	3598	2096	5031.65±0.23	41.54	0,2
92067-01-04-03	10/08/06	53957	1470	1000	4943.43±0.43	41.57	0,1,2,3
92067-01-04-04	11/08/06	53958	1505	1014	6515.06±1.06	41.63	2,3
92066-13-01-00	25/08/06	53972	9990	6993	3180.72±0.36	41.52	0,1,2,3
92066-13-01-02	25/08/06	53972	21361	14064	3115.7±0.47	41.51	0,1,2,3
92066-13-01-01	26/08/06	53973	21677	13927	3445.9±0.76	41.51	0,1,2,3
92066-13-01-03	26/08/06	53973	16483	10534	4380.63±0.38	41.51	0,2,3
92066-13-01-04	26/08/06	53973	4377	2495	2857.34±0.19	41.52	1,2
92067-01-04-10	21/09/06	53999	1543	903	2571.48±2.47	41.46	2,3
92067-01-05-00	22/09/06	54000	1615	957	1204.22±2.22	41.45	2,4
92067-01-05-01	24/09/06	54002	3264	1957	1057.71±0.35	4144	2,4
92067-01-05-02	24/09/06	54002	2103	905	1012.48±1.48	41.46	2,3
92067-01-05-03	25/09/06	54003	2137	911	1045.86±1.86	41.45	0,1,2
92067-01-05-04	26/09/06	54004	3266	914	1016.21±1.21	41.48	0,2,3
92067-01-05-05	27/09/06	54005	1885	888	1528.44±2.44	41.34	0,1,2
92067-01-05-06	28/09/06	54006	2033	987	1466.05±2.05	41.47	0,2
92067-01-06-00	29/09/06	54007	2030	933	1447.67±2.67	41.47	0,2
92067-01-06-01	30/09/06	54008	3514	1118	852.15±0.26	41.45	0,1,2

Observation ID	Date	MJD	Duration	Exposure	Average count of light curve	Pulse period	PCUs on
92067-01-06-02	01/10/06	54009	2171	978	1087.80±1.80	41.48	0,2,3
92067-01-06-03	02/10/06	54010	1503	1152	1037.35±1.35	41.47	0,2
92067-01-06-04	03/10/06	54011	2331	1055	623.13±1.23	41.5	0,2,3
92067-01-06-05	04/10/06	54012	1749	956	841.70±0.6	41.5	0,2,3
92067-01-06-06	05/10/06	54013	2401	891	782.76±0.56	41.49	0,2,3
92067-01-07-00	06/10/06	54014	1986	885	782.76±0.56	41.48	0,2,3
92067-01-07-01	07/10/06	54015	3060	946	695.49±1.79	41.49	0,2,3
92067-01-07-02	08/10/06	54016	1305	972	869.46±1.13	41.48	0,1,2,3
92067-01-07-03	09/10/06	54017	3147	947	627.01±1.51	41.45	0,1,2
92067-01-07-04	10/10/06	54018	1780	912	185.53±0.73	41.47	2
92067-01-07-05	11/10/06	54019	3060	896	536.33±1.33	41.46	0,2,3
92067-01-07-06	12/10/06	54020	2082	983	338.14±0.94	41.46	0,2
92067-01-08-00	13/10/06	54021	1261	884	473.62±1.22	41.45	0,4
92067-01-08-01	14/10/06	54022	2785	905	296.45±1.05	41.46	0,2
92067-01-08-02	15/10/06	54023	1858	997	391.61±1.21	41.5	0,1,2
92067-01-08-03	16/10/06	54024	1375	991	355.48±0.98	41.5	0,2,4
92067-01-08-04	17/10/06	54025	3054	924	363.61±1.11	41.46	0,1,2
92067-01-08-05	18/10/06	54026	1080	944	199.22±0.52	41.49	0,2
92067-01-08-06	19/10/06	54027	1821	974	293.49±0.89	41.45	0,2,4
92067-01-09-00	20/10/06	54028	2592	1278	299.76±1.76	42.22	0,2,3
92067-01-09-01	21/10/06	52029	1726	931	268.76±0.86	41.45	0,2,3
92067-01-09-02	22/10/06	54030	3239	891	222.66±0.86	41.45	0,2,3
92067-01-09-03	23/10/06	54031	3314	1040	163.47±0.67	41.45	0,2
92067-01-09-04	24/10/06	54032	1892	921	145.93±0.53	41.48	0,2
92067-01-09-05	25/10/06	54033	1535	896	217.46±0.76	41.49	0,2,3
92067-01-09-06	26/10/06	54036	2807	994	135.90±2.00	40.25	0,1,2,3
92067-01-10-00	27/10/06	54036	2591	832	174.48±0.88	41.47	0,2,3
92067-01-10-01	28/10/06	54037	2540	1097	161.34±0.74	41.45	0,2,4
92067-01-10-02	29/10/06	54038	2579	1072	174.32±0.72	41.44	0,2,4
92067-01-10-03	30/10/06	54039	2950	1203	117.01±0.51	41.46	0,2
92067-01-10-04	31/10/06	54040	2086	960	168.94±0.74	41.41	0,2,2

Table 2 : Log of observation during 2006 October
Table 3 : Log of observations during 2006 November
Table 4 : Log of observations of 2011 (January-February-April-

Observation ID	Date	MJD	Duration	Exposure	Average count	Pulse period	PCUs on
96098-01-01-00	05/01/11	55566	1647	2455	270.77±0.67	41.3	2,1
96098-01-01-01	06/01/11	55567	2109	3246	304.5±0.53	41.32	0,2
96098-01-01-02	05/01/11	55566	2511	3045	266.12±0.65	41.3	4,2
96098-01-01-10	07/01/11	55568	2280	3296	149.55±0.62	41.31	2
96098-01-01-11	08/01/11	55569	1676	2923	166.54±0.24	41.34	2
96098-01-01-12	10/01/11	55571	3419	7515	300.82±0.02	41.32	4,2
96098-01-01-13	11/01/11	55572	2116	3408	276.36±0.45	41.32	0,2
96098-01-01-14	12/01/11	55573	3420	5289	243.57±0.09	41.32	1,2
96098-01-01-15	13/01/11	55574	2055	3154	89.96±0.35	41.32	2
96098-01-01-20	14/01/11	55575	2095	3276	172.12±0.52	41.33	2,0
96098-01-02-05	22/02/11	55673	1084	1927	370.67±0.90	41.37	2,1
96098-01-02-20	07/04/11	55658	1053	1589	77.21±0.54	41.3	2
96098-01-02-10	08/04/11	55659	1620	2950	225.49±0.50	41.3	2,4
96098-01-02-11	09/04/11	55660	2859	4023	296.98±0.02	41.3	1,2
96098-01-02-12	10/04/11	55661	1137	2337	152.62±0.62	41.34	2
96098-01-02-13	10/04/11	55661	2875	4063	141.94±0.38	41.31	2
96098-01-02-14	12/04/11	55663	2621	3246	306.01±0.29	41.32	0,2
96098-01-02-15	12/04/11	55663	1677	2507	342.11±0.41	41.33	0,2
96098-01-02-04	14/04/11	55665	1848	2606	258.60±0.50	41.31	0,2
96098-01-03-00	22/05/11	55703	2336	2921	67.24±0.13	41.29	2
96098-01-03-01	23/05/11	55704	3543	5020	256.48±0.39	41.3	1,2
96098-01-03-02	24/05/11	55705	3603	5149	252.97±0.77	41.31	2,4
96098-01-03-03	25/05/11	55706	2260	3306	168.22±0.01	41.31	2
96098-01-03-04	26/05/11	55707	2398	3135	173.62±0.52	41.3	2
96098-01-03-10	27/05/11	55708	2230	2593	169.92±0.36	41.39	2
96098-01-03-11	28/05/11	55709	2565	3332	158.74±0.21	41.33	2
96098-01-03-12	29/05/11	55710	1995	2812	152.32±0.42	41.33	2
96098-01-03-13	30/05/11	55711	2070	2962	124.89±0.34	41.32	2
96098-01-03-14	31/05/11	55712	1658	2412	106.11±0.41	41.34	2
96098-01-03-15	01/06/11	55713	1857	2782	215.75±0.25	41.31	0,2

May-June)

Table 5 : Log of observations during 2011 (July-August-September-November-December)

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Observation ID	Date	MJD	Duration	Exposure	Average count	Pulse period	PCUs on
96098-01-04-10	07/07/11	55749	2942	3727	314.51±0.01	41.32	2,3
96098-01-04-00	08/07/11	55750	3096	4658	296.68±0.09	41.31	1,2,3
96098-01-04-01	10/07/11	55752	2834	4461	402.09±0.12	41.31	1,2
96098-01-04-02	12/07/11	55753	3216	4929	500.85±0.15	41.32	1,2
96098-01-04-03	13/07/11	55755	2531	4341	181.53±0.25	41.31	2
96098-01-04-04	14/07/11	55756	1991	3207	353.34±0.14	41.3	0,2
96098-01-04-20	15/07/11	55757	4008	4505	1.51.18±0.34	41.3	2
96098-01-04-21	16/07/11	55758	2453	3106	109.33±0.13	41.31	2
96098-01-04-22	17/07/11	55759	3669	4695	224.88±0.23	41.3	1,2
96098-01-05-00	22/08/11	55795	2177	3531	116.41±0.41	41.3	0,2
96098-01-05-01	23/08/11	55796	1274	2587	245.87±0.87	41.32	1,2
96098-01-05-02	25/08/11	55798	2236	4220	310.96±0.23	41.31	1,2
96098-01-05-10	26/08/11	55799	2370	4123	167.72±0.32	41.31	2
96098-01-05-11	27/08/11	55800	1477	2513	378.09±1.1	41.3	1,2
96098-01-05-12	29/08/11	55802	2580	5347	314.81±0.41	41.32	1,2
96098-01-05-13	30/08/11	55803	1437	2140	251.40±0.70	41.35	0,2
96098-01-05-14	01/09/11	55805	1828	2729	76.16±0.31	41.32	2
96098-01-06-00	22/11/11	55887	3270	3885	121.94±0.54	41.29	2
96098-01-06-01	23/11/11	55888	2867	3366	226.36±0.24	41.3	2
96098-01-06-02	24/11/11	55889	1006	1447	296.92±0.92	41.29	1,2
96098-01-06-10	25/11/11	55890	2506	4251	329.86±0.36	41.31	0,2
96098-01-06-11	26/11/11	55891	2515	4978	416.49±0.49	41.92	0,2
96098-01-06-12	27/11/11	55892	2433	4665	173.5±0.62	41.31	2
96098-01-06-13	27/11/11	55892	2314	4545	176.02±0.23	41.34	2
96098-01-06-14	28/11/11	55893	1565	2798	145.50±0.20	41.31	2
96098-01-06-15	29/11/11	55894	2863	3798	313.82±0.45	41.31	0,2
96098-01-06-16	30/11/11	55895	1566	2976	288.77±0.87	41.32	0,2
96098-01-06-20	02/12/11	55897	2227	5233	168.43±0.61	41.31	0,2

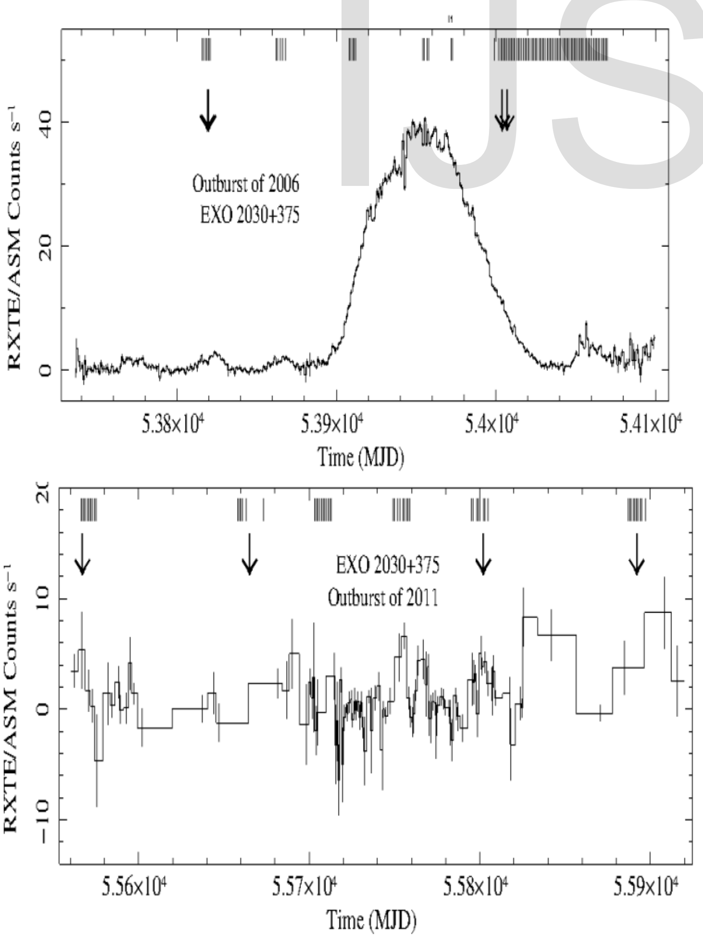
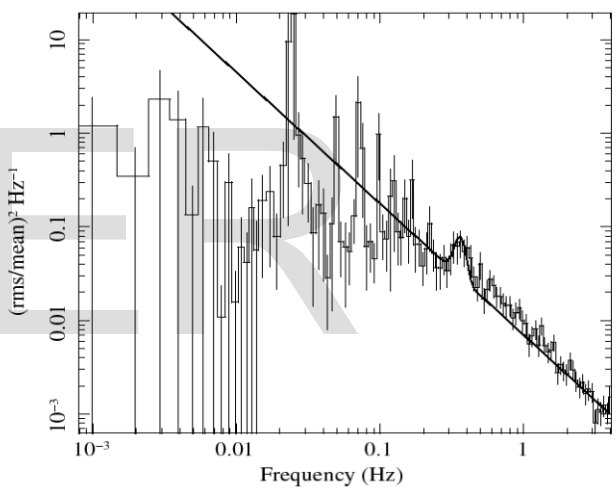


Figure 2 One-day averaged RXTE/ASM light curve of the transient Be/X-ray binary pulsar EXO~2030+375 during 2006 outburst (top panel) and 2011 outburst (lower panel). The vertical lines at the top of panel indicate the RXTE/PCA pointed observations of the pulsar whereas the vertical arrows indicate the 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 2006 (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 161 RXTE observations, we found the presence of QPOs in 7 observations (as shown in table no. 6). The log of observations are given in Table 1, 2, 3, 4, 5. The variable QPO between 0.36−0. 74 Hz (as shown in table no. 6) seen in the transient pulsar EXO~2030+375 were detected in a few of the observation during outbursts of 2006 and 2011. Figure 3 and figure 4 show QPOs for outburst of 2006 for different observations 92067-01-05-04 & 92067-01-06-00 respectively. Figure 5 & 6 show the representative PDS for the outburst of 2011 for observation IDs 96098-01-01-01 and 96098-01-02-04 respectively.



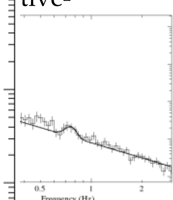


Figure 3 Representative PDS showing QPO for observation ID 92067-01-05-04 (MJD-54004, 2006 September 26)

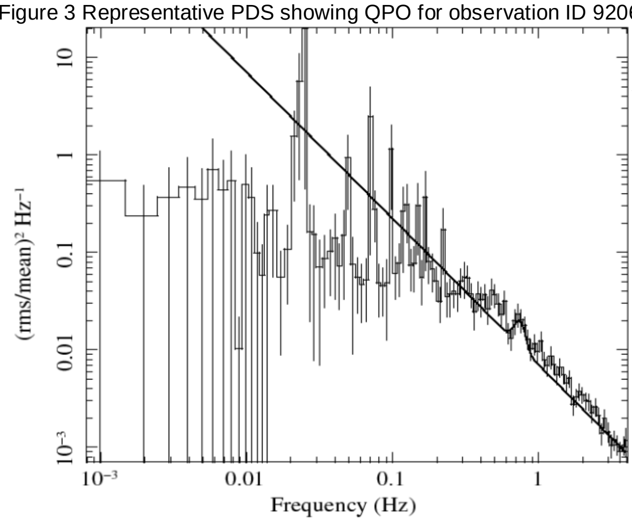


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Figure 4 Representative PDS showing QPO for observation 92067-01-06-00 of 2006 outburst (MJD-54007, 2006 September 29)

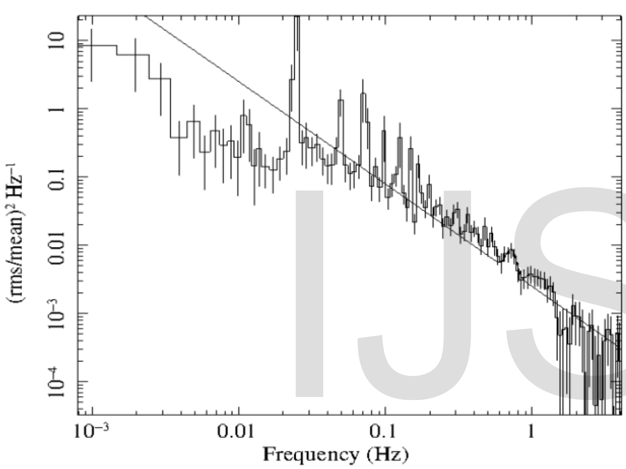

Figure 5 Representative PDS showing QPO for observation 96098-01-01-01 of 2011 outburst (MJD-55567, 2011 January 06)

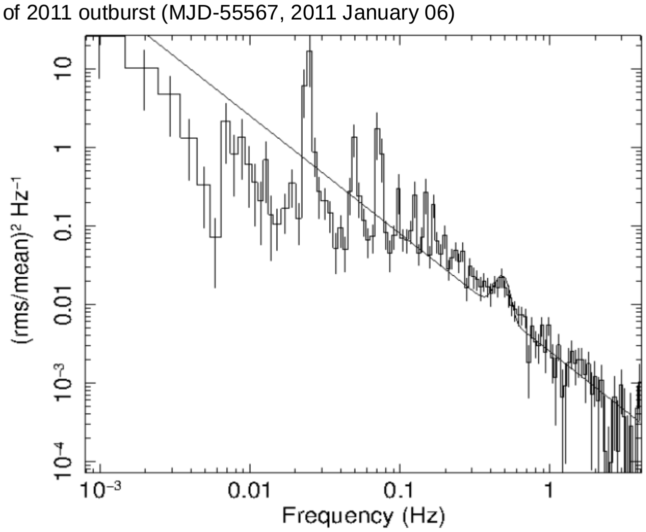

Figure 6 Representative PDS showing QPO for observation 96098-01-02-04 of 2011 outburst (MJD-55665, 2011 April 14)

Table no. 6 Log of results of QPO detected observations for Be/X-Ray binary pulsar EXO~2030+375

Observation ID	Date	MJD	Duration	Exposure	QPO frequency	rms %	Average light count counts	Pulse period
92760-01-01-02	25/03/06	53819	4520	2258	0.36±0.029	11.83%	277.21±0.34	41.65
92067-01-01-04	25/03/06	53819	4074	1798	0.52±0.036	12.08%	253.18+0.48	41.65
92067-01-05-04	26/09/06	54004	3266	914	0.36±0.035	17.00%	1016.21+1.21	41.48
92067-01-06-00	29/09/06	54007	2030	933	0.74±0.051	16.46%	1447.67+2.67	41.47
96098-01-01-01	06/01/11	55567	2109	3246	0.72±0.05	4.08%	304.5±0.36	41.32
96098-01-02-04	14/04/11	55665	1848	2606	0.48±0.08	5.34%	258.60+0.50	41.31
96098-01-05-12	29/08/11	55802	2580	5347	0.42±0.04	5.07%	314.81+.41	41.32

4 DISCUSSIONS

In the inner part of the accretion disk, due to the motion of the inhomogeneously distributed matter, gives rise evolution of QPOs in accretion powered X-ray binary pulsars. Best 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 [26] 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. Most of the transient Be/X-ray pulsars have detected QPOs to be transient in nature.

In EXO 2030+375, the QPO features were not detected in all of the RXTE observations during 2006 and 2011 outbursts (present work). Transient HMXB pulsars from which QPOs have been detected are KS~1947+300 [15], SAX~J2103.5+4545 [12], A0535+262 [8], V0332+53 [33], and 4U 0115+63 [31], XTE~J1858+034 [22], EXO~2030+375[2], XTE~J0111.2-7317 [17], 4U~1901+03 [16], 1A~1118-61 [6] and GX~301-4 [7].

The QPO features in the accretion powered X-ray pulsars has been explained using several models as : (i) Beat frequency model (BFM) (ii) Keplerian-frequency model (KFM) and third one (iii) 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[[1][18].

In the KFM model the modulation of the X-rays by inhomogeniously distributed matter in the inner accretion disk at the Keplerian frequency gives rise to QPOs [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 exceeds the Keplerian frequency, mass accretion on to the neutron star is stopped at the magnetospheric boundary by centrifugal inhibition of accretion [30]. This results 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 [2], A0535+262 [8], XTE~J0111.2−7317 [17] etc. However, in case of EXO~2030+375, frequency of all QPOs (earlier reported QPOs ~0. 2 Hz and newly detected variable QPO between ~0. 36−0. 74 Hz) 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 EXO~2030+375.

The predictions of both models are in good agreement with the measured values. It is not possible to exclude either of the two models due to the evident is based on the QPOs frequency.

The KFM has serious difficulties in accounting for the QPOs rms strength of ~4%-17%. In this model the gravitational energy released up to r_m avails the most signals to generate QPOs. This corresponds to ~0.2% of the source luminosity near the maximum of the outburst. QPOs could be generated if "blobs" orbiting near r_m quasi periodically obscure the central X-ray source in the KFM larger amplitude. This requires very high system inclination ((i ≥ 89°) which is not possible for EXO~2030+375. Alternatively, a larger amplitude QPOs signal at local Keplerian frequency might be generated when the X-Rays scatter in the direction of the observer at the τ ~1 surface of an oscillating accretion corona close to r_m [4]. In the BFM there is no such difficulty. The interaction between the magnetosphere and the inner accretion disk regions modulates the accretion rate at the QPOs frequency. In principle most of the gravitational energy released at the neutron star surface is available to generate the QPOs signal [18].

A number of models for QPOs does not involve the presence of a neutron star magnetosphere. QPOs might result from instabilities at the boundary between an accretion disk and the neutron star surface [11]. In our case of EXO~2030+375 these ideas are not applicable to the case of EXO 2030+375, where the magnetosphere prevents the formation of an accretion disk close to the neutron star surface. The ~0.36-0.74 Hz frequency of the QPOs from EXO 2030+375 is likely to be too small to result from non radial g-mode oscillations in the neutron star envelope.

5 CONCLUSION

In this paper, we performed timing analysis using the RXTE observation of the Be/X- ray transient pulsar EXO~2030+375 during the outbursts of 2006 (type I) and 2011 (type II). Temporal analysis performed with RXTE/PCA observations showed X-ray pulsations. The ~42 s pulsations were detected in the light curves. Our best fit period obtained is 41.317±0.001 s, in excellent agreement with previous results [24], [25], [28], [27], [36], [37].

Using Gaussian model to fit and analyze the PDS of X-ray pulsars and investigate their random variability, we have discovered variable QPOs between ~0.36-0.74 Hz of centroid frequency are in excellent agreement with the predictions of the BFM. In addition, this model is able to account for the observed ~4% to ~17 % QPOs fractional strength. These results provide the first quantitative confirmation of the BFM and show that the model can work in the presence of an accretion disk interacting with a rotating neutron star magnetosphere.

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