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Search for pulsations in the LMXB EXO 0748–676

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Abstract We present here results from our search for X-ray pulsations of the neutron star in the low mass X-ray binary EXO 0748–676 at a frequency near the burst-oscillation frequency of 44.7 Hz. Using the observations made with the Proportional Counter Array onboard the Rossi X-ray Timing Explorer, we did not find any pulsations in the frequency band of 44.4 Hz to 45.0 Hz and obtained a 3σ upper limit of 0.47% on the pulsed fraction for any possible underlying pulsation in this frequency band. We also discuss the importance of EXO 0748–676 as a promising source for the detection of Gravitational Waves.

Key words: X-ray: neutron stars — X-ray binaries: individual (EXO 0748–676)

1 INTRODUCTION

Gravitational Wave (GW) emission is an alluring phenomenon, whose detection has eluded physicists and astrophysicists so far. The direct detection of GWs is technically a very challenging task. Accreting neutron stars in Low Mass X-ray Binary (LMXB) systems, by virtue of their rapid oscillations, are potential sources for the detection of GWs (Watts et al. 2008). Due to various reasons, such as magnetic deformation (Cutler 2002; Haskell et al. 2008) and crustal mountains (Bildsten 1998; Haskell et al. 2006; Vigelius & Melatos 2008), these compact objects can develop a quadrupolar asymmetry which leads to GW emission. The GW emission is also believed to limit the spin frequency up to which the neutron stars can be spun-up by accretion (Chakrabarty et al. 2003). In addition to being an important class of potential sources for GW detection, any detection of GWs from these sources may also provide important information about the structure and geometry of neutron stars. It can also be an important tool to understand the interaction of the neutron star with its accretion disk.

Detection of GWs associated with spinning neutron stars will be an arduous job since it requires huge computational power. The major hurdles include low accretion rates and uncertainty in the measurement of spin and orbital parameters of most of the associated astrophysical sources (Watts et al. 2008; Watts & Krishnan 2009). There are sources like Sco X-1, which are quite bright, but whose spin and orbital parameters are poorly constrained. In case of sources emanating weak signals, the data should be folded in order to increase their signal to noise ratio. However, this folding requires a priori and well constrained ephemeris for spin and orbital parameters. If the pulse and orbit ephemeris are accurately known, it will require only a single trial to search for gravitational waves. However, when parameters are poorly constrained, a large number of trials are required and hence the searches become computationally untenable.

Among the galactic sources, the LMXBs harboring rapidly spinning neutron stars are the best targets for GW searches with LIGO and VIRGO (Abadie et al. 2010; Abbott et al. 2010; Sengupta et al. 2010). Among all LMXBs, the spin and orbital parameters and their evolution are best constrained in the accreting millisecond pulsars. Hence, the least amount of computational resources will be required for the search for gravitational waves from these sources. However, the accreting millisecond pulsars are transient systems, active only during short outbursts and the long term mass accretion rate is not high enough for detectable GW emission. The magnitude of long term average flux from most accretion powered millisecond pulsars is on the order of 10^{-11} erg cm^{-2} s^{-1}, which is much smaller than that of Sco X-1 (on the order of 10^{-7} erg cm^{-2} s^{-1}).

The next best collection of sources are the burst oscillation sources and the kHz QPO sources (Watts et al. 2008; Watts & Krishnan 2009). However, the number of trial searches required in these sources can go up to 35 orders of magnitude, depending on the number of constrained parameters.

Among the persistent LMXBs, EXO 0748–676 is a promising source for the detection of GWs. It has been extensively studied since its discovery in 1985 (Parmar et al. 1985). Future monitoring of timing properties of this source, during the operation of Advanced LIGO (Smith & LIGO Scientific Collaboration 2009; Harry & the LIGO Scientific Collaboration 2010) will be possible with the large area X-ray detectors of *ASTROSAT* (Paul & The LAXPC Team 2009). Being an eclipsing source in a binary orbit with a period of 3.82 hr (Parmar et al. 1986), the orbital period, period evolution timescale and mid-eclipse time are measured with good accuracy over a time scale of more than 20 years (Wolff et al. 2009). The source also shows irregular X-ray dips (Parmar et al. 1986; Wolff et al. 2002). The mass of the neutron star (Cottam et al. 2002; Pearson et al. 2006; Özel 2006; Muñoz-Darias et al. 2009) and its companion (Parmar et al. 1986) are also known with reasonable accuracy.

Since its discovery, EXO 0748–676 has been regularly monitored by various satellites. Most of the observations reveal a persistent luminosity of $\sim 10^{36} - 10^{37}$ (D/7.4 kpc)^2 erg s^{-1}. The long term 2–20 keV average flux is $\sim 2 \times 10^{-10}$ erg cm^{-2} s^{-1} (Wolff et al. 2008a). It entered a quiescent phase in 2008, with a decline of up to two orders of magnitude in the flux level (Wolff et al. 2008a,b; Hynes & Jones 2008). The source has also repeatedly shown several Type-I X-ray bursts (Gottwald et al. 1986; Parmar et al. 1986; Wolff et al. 2002). Burst oscillations at 44.7 Hz (with 3% rms amplitude) were discovered by Villarreal & Strohmayer (2004) from the summed power spectra of 38 thermonuclear bursts, who associated these oscillations with the spin frequency of the neutron star and thereby explained the narrowness in the spectral line broadening. However, Galloway et al. (2010) recently found another millisecond oscillation feature at 552 Hz (with 15% rms amplitude) during individual thermonuclear X-ray bursts, separated by about a year. The actual spin period of the neutron star is therefore uncertain.

In the present work, we have tried to verify whether the 44.7 Hz burst oscillations, seen during the thermonuclear bursts, can be associated with the spin frequency of the neutron star. A positive result would also allow measurement of the semi-amplitude of the binary orbit, and monitoring of the spin and orbital parameters of this source would make a deep search for GW emission possible by allowing a long integration of GW data.

2 OBSERVATIONS AND ANALYSIS

The data used in this work were obtained from observations made with the Proportional Counter Array (PCA: Jahoda et al. 1996) onboard the Rossi X-Ray Timing Explorer (*RXTE*: Bradt et al. 1993), on 1997 August 17 (Observation ID: 20082–01–02–00). The total exposure time was 37 ks, covering about three binary orbits. All five Proportional Counter Units (PCUs) were ON during the observation. The data were collected from the Science event mode (E_125μs_64M_0_1s), having a time resolution of 125 μs and 64 binned energy channels. The raw events were filtered using the SEFILTER and SEEXTRCT tool of the $ftools$ (version V6.5.1) package of HEASOFT. The

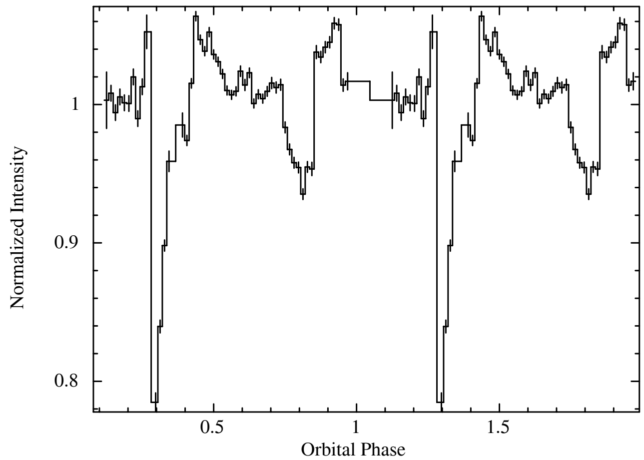

Fig. 1 Folded light curve of EXO 0748−676, obtained from observations made with *RXTE*-PCA. The light curve was folded into 64 phasebins with a period of 13766.78824 s. Two cycles are shown for clarity.

average source and background count rates during the observation were ∼155 and ∼45 count s^{-1}, respectively, i.e. the source was about four times more intense as compared to the background. The light curve was barycentered using the *ftool*-FXBARY.

Figure 1 shows the barycentered light curve of EXO 0748–676, folded into 64 orbital phasebins with a period of 13766.78824 s (Wolff et al. 2009). The folded light curve was normalized by dividing the count rate by the average source intensity. The folded light curve shows irregular dips along with a total eclipse lasting for about 0.04 orbital phase, i.e. 550 s.

For a neutron star in a binary system, the arrival times of the pulses vary with the orbital motion of the pulsar. When the pulsar is at $T_{\pi/2}$ (the farthest point in the orbit from the observer, also referred to as the superior conjunction), the photon takes a longer time (by $\frac{a_x \sin i}{c}$) to arrive (here, i is the source inclination angle and $a_x \sin i$ is the projected semimajor axis). Therefore, assuming a circular orbit for this LMXB, the time delay of photon arrival time caused by the orbital motion can be expressed as

$$t_{\mathrm{arrival}} = t_{\mathrm{emission}} + \frac{a_x \sin i}{c} \cos\left[\frac{2\pi(t_{\mathrm{emission}} - T_{\pi/2})}{P_{\mathrm{orbital}}}\right], \tag{1}$$

where P_{orbital} is the orbital period of the binary system.

In order to search for pulsations in EXO 0748–676, we first corrected the arrival time of the photons for different assumed values of $a_x \sin i$. Based on the known values of the mass function and the mass of the neutron star and its companion (Muñoz-Darias et al. 2009), the value of $a_x \sin i$ is expected to be around 730 lt-ms. The light curve was corrected for $a_x \sin i$ over a wide range of 100–1200 lt-ms, with a resolution of 2 lt-ms, which is about 10% of the pulse period around which the search was made.

After each correction of the light curve for the orbital motion, we searched for pulsations using the pulse folding and χ^2 maximization *ftool*-EFSEARCH. This is a well established technique and has been successfully used to determine the spin period and orbital parameters in various sources (Jain et al. 2007, 2010; Jain, Dutta & Paul 2007; Jain, Paul & Dutta 2010). The burst oscillations from EXO 0748–676 have been reported to be centered at 44.7±0.06 Hz (Villarreal & Strohmayer

2004; Villarreal & Strohmayer 2004). This indicates that the neutron star's spin frequency probably lies between 0.02234 and 0.02240 s. Using the *ftool*-EFSEARCH, the light curves were folded into 16 phasebins. We searched for 300 000 trial periods, with a resolution of 1×10^{-9} s and centered at 0.02237 s. This enabled us to search for a period over a range which is five times larger than the expected range for the neutron star's spin period with a maximum pulse phase smearing of 10%. Each folded light curve was fitted with a constant and its χ^2 value was determined. Under this analysis procedure, if the trial period and the $a_x \sin i$ value are not correct, then the folded profile is smeared and the χ^2 of the fit will be small, close to the number of phasebins. However, if the trial period is correct, the pulse profile is reproduced correctly and a constant fit is expected to give a high χ^2. Therefore, the trial period corresponding to a large χ^2 will represent the true pulse period in the light curve, if one exists. In this process, the $a_x \sin i$ will also be determined.

Figure 2 shows a few samples of the χ^2 distribution with the trial spin periods for different values of $a_x \sin i$. The value of $a_x \sin i$ used for orbital correction is mentioned in each case. We did not find a significantly high χ^2 for any spin period in the entire range of $a_x \sin i$. This is shown in Figure 3, where a histogram has been plotted which shows the number of times a specific χ^2 occurs for all the 300 000 trial spin periods. Histograms were created for the entire range of $a_x \sin i$ and were overlaid. A distribution centered at a χ^2 of about 14–15 is seen in each case. A large deviation from this curve will indicate detection of a spin period for the neutron star. As seen in Figure 3, a χ^2 of about 70 is seen in a few cases, which is an offset from the χ^2 distribution curve. However, detection significance of these deviations is poor, as can be seen in Figure 2.

In order to put an upper limit on the pulse amplitude present, if there is one, we corrected the light curve for the orbital motion with an arbitrary $a_x \sin i$. The light curve was then folded with a

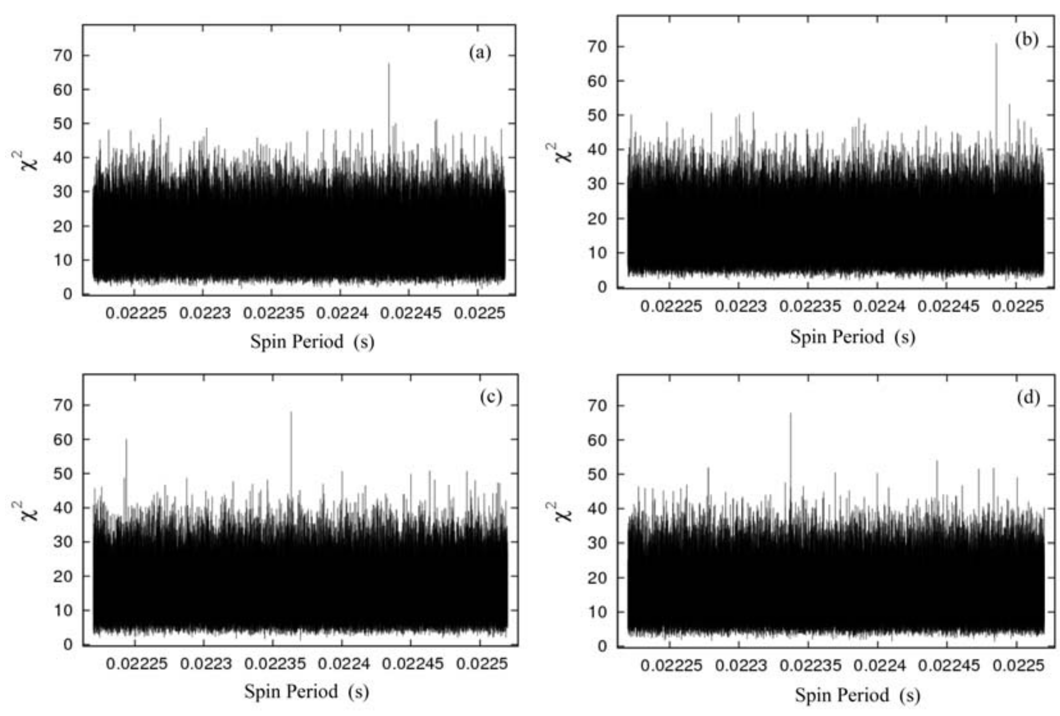

Fig. 2 A sample of χ^2 variation with trial spin periods for different values of $a_x \sin i = 400$ lt-ms (a), 708 lt-ms (b), 806 lt-ms (c) and 864 lt-ms (d), from EXO 0748−676.

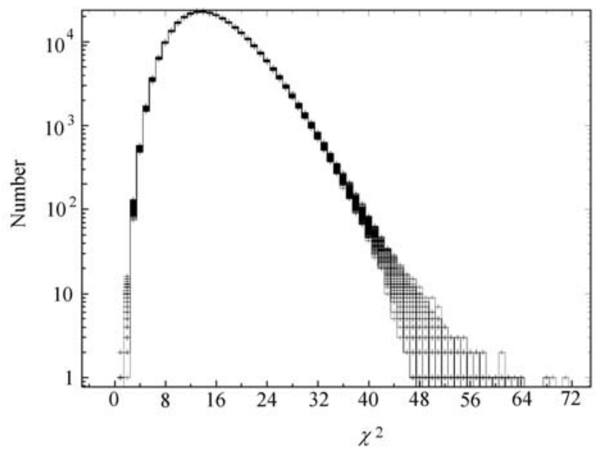

Fig. 3 Histogram showing the variation of χ^2 for 300 000 trial spin periods of EXO 0748–676 and for the entire range of $a_x \sin i$.

period of 0.00237 s. A model consisting of a sine curve was fit to the folded profile. This gave a 3σ upper limit of 0.47% for the pulse amplitude.

3 DISCUSSION

We have presented results from an X-ray timing analysis of the eclipsing LMXB, EXO 0748–676, in which we searched for pulsations at frequencies around the 44.7 Hz burst oscillations in this source observed during some Type-I X-ray bursts (Villarreal & Strohmayer 2004). We conclude that there is an absence of any pulsations around the reported burst oscillation frequency. We have determined a 3σ upper limit of 0.47% for the pulse amplitude.

Recently, Galloway et al. (2010) reported another burst oscillation feature at 552 Hz, which has higher detection significance and could be the true oscillation frequency. In order to detect pulsations around 552 Hz during non-burst episodes, a similar analysis, as explained above, is ongoing.

As mentioned before, the detection of GWs is a technically difficult task. The foremost candidate sources for the detection of GWs are the neutron stars in LMXBs, where asymmetries are induced in the neutron star crust by accretion. The prerequisites of a potential target for GW searches are the strength of the signal and well constrained orbital and spin parameters. Sources like Sco X-1 and GX 17+2 may have a large GW amplitude, owing to their high X-ray flux and mass accretion rates ($\sim 3\times10^{-9}\,M_{\odot}$ yr^{-1} – $2\times10^{-8}\,M_{\odot}$ yr^{-1}, Strohmayer & Bildsten 2003). However, the orbital and spin parameters are poorly constrained. The accretion powered millisecond pulsars have well constrained orbital and spin parameters, but these are transient sources, and have low long-term average accretion rates (with magnitudes less than $10^{-11}\,M_{\odot}$ yr^{-1}, Strohmayer & Bildsten 2003).

EXO 0748–676 is definitely a promising source for the detection of GWs. The long-term mass accretion rate of EXO 0748–676 is quite high ($\sim 2.9 \times 10^{-10}\,M_{\odot}$ yr^{-1}, Wolff et al. 2005) and most of the orbital parameters are well constrained. If pulsations are detected, they will make this source an ideal candidate for the search of GW emission.

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