29th ASI Meeting
ASI Conference Series, 2011, Vol. 3, pp 29 – 33
Edited by Pushpa Khare & C. H. Ishwara-Chandra

Orbital evolution of X-ray binaries and quasi-periodic oscillations in X-ray pulsars

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Abstract. We have measured the orbital period derivatives in several high mass and low mass X-ray binaries. Mechanisms that could be responsible for the observed orbital evolution in these sources are briefly mentioned. We also describe studies of quasi-periodic oscillations in several X-ray pulsars and their relation with long term evolution of these systems and also the neutron star magnetic field strength.

Keywords : X-rays: binaries – X-rays: individual – pulsars: general

1. Introduction

X-ray binaries show periodic, aperiodic and quasi-periodic variabilities in a wide range of time scales. Here we summarize some progress made in X-ray binary studies in the recent years using different types of X-ray variabilities. First we describe the results from orbital evolution measurements made in low and high mass X-ray binaries using pulse timing and eclipse timing, whichever is appropriate for a given source. Then we describe some significant progress made in study of accretion powered pulsars using the low frequency quasi-periodic oscillations (QPO), including discovery of QPOs in several pulsars.

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2. Orbital evolution of X-ray binaries

The orbits of compact X-ray binaries can evolve due to various mechanisms like mass transfer between the two stars and mass loss from the companion, gravitational wave radiation (Verbunt 1993), tidal interaction between the components (Lecar et al. 1976), magnetic braking (Rappaport et al. 1983) and X-ray irradiated wind outflow (Ruderman et al. 1989). If the compact object is an accreting X-ray pulsar, the most accurate way of measuring orbital evolution is to make repeated measurements of the orbital parameters by pulse timing. In Fig. 1 we have shown evidence of orbital evolution in nine X-ray binaries. For some sources, the results were obtained by combining new measurements of orbit markers with earlier reported measurements of these sources.

Four of these sources are accreting X-ray pulsars with high mass companion stars (Cen X-3 and SMC X-1: Raichur et al. 2010a; LMC X-4: Naik & Paul 2004; 4U 1538-52: Mukherjee et al. 2006). In the first three sources, the orbital evolution time scale was found to be rather short, less than a million years. This indicates that the orbital evolution of these systems is mainly driven by tidal effect of the compact star on the companion. In 4U 1538-52, we determined a lower limit of the evolution time scale which is larger than the three systems described above. One interesting aspect of this source is that in spite of having a small orbital period of 3.75 days, the binary has significant ellipticity, indicative of it being a relatively young binary system. The close high mass X-ray binaries reported here are also progenitors of the double compact binaries that are the key systems in the fields of Short Gamma Ray Bursts and Gravitational Wave Emission from Merging Compact Stars.

Three of the sources are X-ray pulsars with low mass companion stars. In 4U 1822-37 (Jain et al. 2010a) and the millisecond X-ray pulsar SAX J1808.4-3658 (Jain et al. 2008) we measured positive orbital evolution with time scale of 5 and 73 million years respectively, both unexpectedly low. Though 4U 1822-37 is a pulsar, we found that as the light travel time across this binary is of the same order as the spin period of the neutron star, the pulse timing method has limited accuracy for determination of the orbital parameters. In contrast, a narrow, partial eclipse in this binary works as a better marker of the orbital phase. In a unique low mass accreting pulsar Her X-1 (Paul et al. 2004), from pulse timing measurement we have determined orbital period glitches with $\frac{\Delta P_{orb}}{P_{orb}}$ of about 10^{-7}.

We found a more convincing evidence of orbital period glitch in a low mass X-ray binary XTE J1710-281 by eclipse timing method (Jain et al. 2011). This source has a similar $\frac{\Delta P_{orb}}{P_{orb}}$ of about 10^{-7} and is the third source after EXO 0748-676 (Wolff et al. 2009) and Her X-1, in which the intriguing feature of orbital period glitch has been detected.

The remaining source in Fig. 1 is Cyg X-3, which is a high mass X-ray binary and the nature of its compact star is uncertain. It has an orbital period of about 4.8 hrs

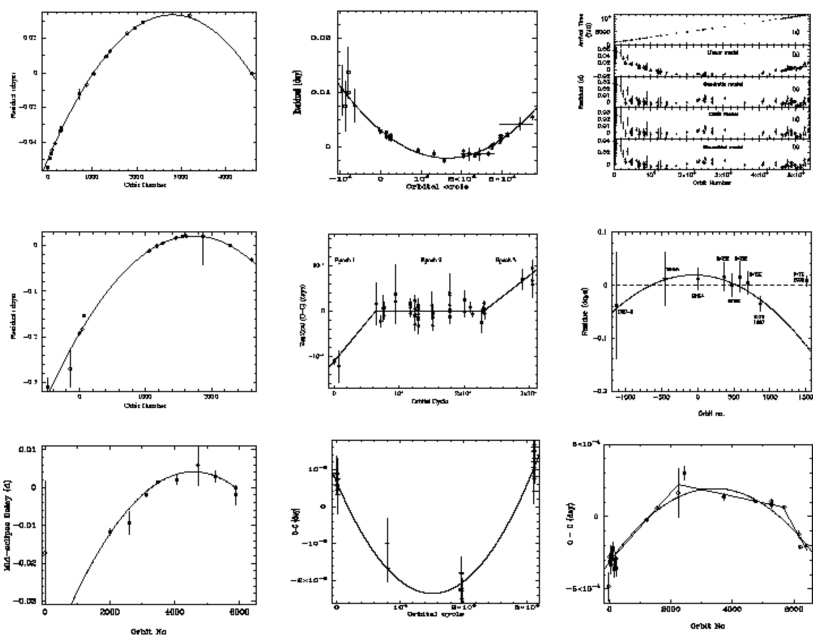

Figure 1. The mid-eclipse time measurements of various X-ray binaries are shown here after subtraction of a linear component. *Left column from top:* Cen X-3, SMC X-1, LMC X-4. *Middle column from top:* 4U 1822-37, XTE J1710-281, SAX J1808.4-3658. *Right column from top:* Cyg X-3, 4U 1538-52, Her X-1.

and shows a remarkably stable orbital period modulation. Using this modulation as a phase marker, we have measured the positive orbital period evolution of this binary (Singh et al. 2002). Cyg X-3 is the only X-ray binary in which a double derivative of the orbital period has also been measured.

Another remarkable result obtained from orbital evolution studies is detection of an apsidal advance in the Be X-ray binary 4U 0115+63 (Raichur et al. 2010b). Since this result was published, analysis of data from another recent outburst has further increased the significance of this detection.

3. Quasi-periodic oscillations in X-ray pulsars

QPO is an ubiquitous feature of different types of X-ray binaries. X-ray binaries with low magnetic field neutron stars and black holes show QPOs over a wide range of frequencies, from mHz to kHz. The accretion powered pulsars, on the other hand show QPOs over a narrow range of frequency, from about 20 mHz to 200 mHz with only a couple of exceptions: GRO J1748-288 (Zhang et al. 1996) and XTE 0111.2-7317 (Kaur et al. 2007). Though we had an ongoing programme from QPO search in

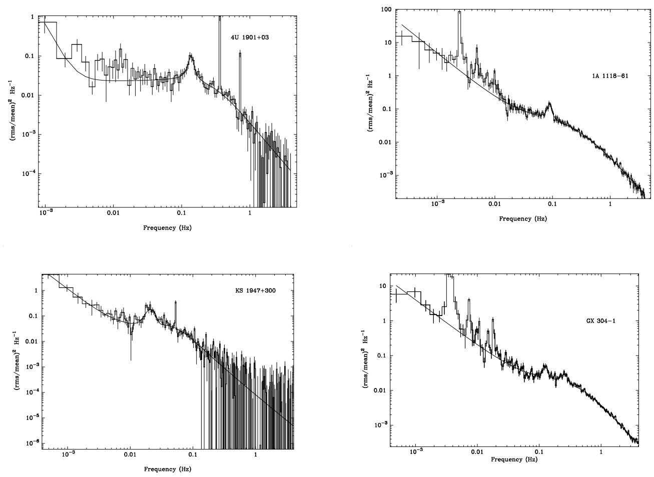

Figure 2. The power density spectra of four accretion powered X-ray pulsars are shown here (*top:* 4U 1901+03 and 1A 1118-61; *bottom:* KS 1947+300 and GX 304-1). The broad QPO features are seen in all sources along with the pulse frequency peaks and its harmonics.

accretion power X-ray pulsars starting with XTE J1858+034 (Paul & Rao 1998) there has been a sudden spurt of QPO discovery in accretion powered X-ray pulsars and the QPO features in four such sources, KS 1947+300 (James et al. 2010), 4U 1901+03 (James et al. 2011), 1A 1118-61 (Devasia et al. 2011a) and GX 304-1 (Devasia et al. 2011b) are shown in Fig. 2. In the first two sources the pulse frequency is higher than the QPO frequency while in the other two sources the opposite is true. The former two sources also showed QPOs only near the end of the two outbursts while QPOs were detected from the later two sources all along the outbursts. In GX 304-1 we have clearly detected a harmonic of the QPO feature, which makes it only the second X-ray pulsar after MAXI J1409-619 (Kaur et al. 2010) in which harmonics of a QPO feature have been detected.

The detection of QPO features and measurement of the QPO frequency allows an estimation of the inner radius of the accretion disk at which the QPOs are generally believed to originate. This, along with the bolometric X-ray luminosity provides a way to measure the magnetic field strength of the neutron star. The magnetic field strengths derived from QPOs in several such sources quite agree with the same derived from the cyclotron absorption features in the X-ray spectrum, when available. Thus in absence of cyclotron absorption features, the QPOs can be used to make a rough estimate of the magnetic field strength of high magnetic field neutron stars.

In addition to the discovery of QPOs, we have carried out an investigation of the long term behaviour of QPOs in accretion powered pulsars. In Cen X-3, we found the QPOs to be intermittent, and surprisingly always at the same frequency irrespective of the X-ray flux (Raichur & Paul 2008). In 4U 1626-67, we found the QPOs to be always present during its spin-down era with a slow evolution of the QPO frequency indicative of a slowly increasing inner disk radius (Kaur et al. 2008). This source had an abrupt turn over from spin-down to spin-up in late 2008 associated with a significant increase in X-ray luminosity. In subsequent observations, the QPOs were not found anymore (Jain et al. 2010b), indicating a change in the accretion mode.

Future prospects: Most of the results mentioned above were obtained from observations with the PCA instrument onboard the Rossi X-ray Timing Explorer, a set of large area X-ray proportional counter detectors. The LAXPC instrument of the upcoming Astrosat mission will provide a similar, large photon collecting over a wider energy band (Paul et al. 2009). Observations with Astrosat will therefore provide very good opportunity to make further progress in these areas.

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