Orbital Evolution and Super-orbital flux variations in X-ray Binary Pulsars

by

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DECLARATION

I hereby declare that the work presented in this thesis is entirely original and has been carried out by me at the Raman Research Institute and Tata Institute of Fundamental Research under the auspices of the Joint Astronomy Program of the department of Phyisics, Indian Institute of Science. I further declare that this has not formed the basis for the award of any degree, diploma, membership, associateship or similar title of any University or Institution.

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Dedicated to

My Parents

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SUMMARY

X-ray binaries are binary stellar systems containing a compact object and a normal companion star which are gravitationally bound and rotate about a common center of mass. The compact object accretes matter from the companion star. The accreted matter may have a high angular momentum and hence follow a Keplarian orbit about the compact object. It slowly spirals inward as its angular momentum is redistributed via viscous forces and forms an accreting disk before being finally accreted onto the compact object. The compact object that is accreting matter may either be a neutron star or a black hole. X-ray binaries can be broadly classified into two classes depending on the mass of the companion star. Low Mass X-ray Binaries (LMXBs) have companion star masses $M_c < 1M_\odot$ and accrete mass via Roche lobe overflow of the companion star. High Mass X-ray Binaries (HMXBs) have companion star masses $M_c > 10M_\odot$ and in these systems the compact object accretes matter from the high velocity stellar winds of the companion star.

For the work and results that are presented in the thesis we have studied the orbital evolution, apsidal motion and long term flux variations in High mass X-ray binaries which have a neutron star compact object with very high magnetic field of the order of $B \sim 10^{12}\ G$. Due to the high magnetic field, the accretion disk is disrupted at the Alfven radius where the magnetic field pressure equals the ram pressure of the infalling matter. From that boundary, the flow of the infalling matter will be guided by the magnetic field lines. The infalling matter will follow these lines, finally falling onto the magnetic poles with velocity nearly equal to the free fall velocity and form an accretion column over the magnetic poles. A hot spot is formed at both the magnetic poles and high energy photons are emitted from these regions. Inverse Compton scattering of these photons by high energy electrons in the accretion column can produce hard X-rays. If the optical depth of the accretion column is low, the radiation comes along the magnetic axis forming a pencil beam whereas if the optical depth is high, radiation escapes tangential to the accretion column forming a fan beam. Since the neutron star is rotating about its rotation axis, the radiation beam directed along magnetic axis non-aligned with the rotation axis will sweep across the sky. Whenever this beam of rotating radiation is

aligned with the line of sight, a pulse of X-ray radiation is detected. Hence these systems are also called X-ray Binary Pulsars (XBP). These pulses are emitted at equal intervals of time, where the time between the emission of two pulses is the spin period of the neutron star. But since the neutron star is in a binary orbit, the arrival time of pulses as recorded by an observer will be delayed or advanced due to the motion of the neutron star. When the neutron star is moving towards the observer, the pulses arrive faster and when the neutron star is moving away from the observer, the pulses are delayed. These delays or advances of the arrival time of pulses can be measured accurately which allows us to measure the orbital elements ($a_x \sin i$, P_{orb}, e, ω, T_ω) of the neutron star orbit.

The neutron star orbit may evolve with time due to mass loss from the system, mass transfer from the companion star onto the neutron star and due to tidal interaction between the neutron star and the companion star. Gravitational wave radiation may also cause orbital evolution. However, in HMXBs this effect is likely to be much weaker compared to the effect of mass loss, mass exchange and tidal interaction.

Rossi X-ray Timing Explorer (RXTE) is an X-ray astronomy satellite launched in 1995 by NASA. It has two pointed instruments, the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE). PCA has a large effective area of 6500 sq cm and works in the energy range of 2-60 keV. It has a very good time resolution of 1 microsec. HEXTE observes in the energy range of 15-250 keV and has a time resolution of 8 microsec. RXTE also has an All Sky Monitor (ASM) which scans 80% of the sky in 90 minutes. We have used RXTE-PCA data for timing and spectral studies and ASM data for the long term flux variation studies of Cen X-3. The thesis presents details of our work, the analysis of the data, results of the analysis and our conclusions from these results. The first chapter of the thesis gives an overview of X-ray binaries, their orbital evolution and the instrument details of RXTE.

In the second chapter we have presented our work of timing analysis of three persistent sources, namely Cen X-3, SMC X-1 and 4U 1538–52. For the SMC X-1 system, we have for the first time measured the eccentricity and the angle of periastron (ω). We found that the accuracy of pulse timing analysis is limited by the dependence of pulse profile on orbital phase. The new measurement of the orbit ephemeris of Cen X-3 when combined with the previous measurements of orbit ephemeris obtained by observations from other X-ray missions, gave an improved measurement of the rate of orbital decay $\dot{P}_{orb}/P_{orb} \sim -1.8 \times 10^{-6} yr^{-1}$. A long observation of SMC X-1 made by RXTE in 2000 during the high state of SMC X-1 allowed us to measure the very small orbit eccentricity $e \sim 0.00021$ in this system. SMC X-1 was again observed for a long time by RXTE during 2003 during its low state. The SMC X-1 pulse fraction depends on the flux state of the source such that the pulse fraction decreases with decrease in the source flux. Thus the 2003 observations of SMC X-1 have higher error in measurement of pulse arrival times compared to the 2000 observations and could not be used to measure the eccentricity of the orbit. But combining the orbital ephemeris of SMC X-1 measured using the 2000 and the 2003 observation with the epoch history allowed us to improve the measurement of rate of orbit decay by an order of magnitude compared to previous observations $\dot{P}_{orb}/P_{orb} \sim -3.4 \times 10^{-6} yr^{-1}$.

We observed 4U 1538–52 with RXTE under the guest observer program to measure the orbital evolution of this system. From observations of this system with *BeppoSAX*, a circular orbit similar to the SMC X-1 system was inferred. 4U1538–52 was observed with RXTE again in 1997 and analysis of this observation showed it to have eccentric orbit with a marginal evidence for an orbital decay. Our analysis carried out using the 2003 RXTE observation data confirmed that the orbit is eccentric with $e \sim 0.18$. But the new orbital ephemeris measured clearly shows that the orbit is not evolving with time as reported earlier. We have derived an upper limit on the rate of change of orbital period of this system to be $\dot{P}_{orb}/P_{orb} = 2.5 \times 10^{-6} yr^{-1}$. 4U 1538–52 is similar to SMC X-1 in many respects, both have similar orbital period of $P_{orb}(SMC\ X-1) = 3.89$ days and $P_{orb}(4U1538-52) = 3.72$ days and companion star mass. But tidal interactions between the neutron star and the companion star have almost circularised the orbit of SMC X-1 where as the orbit of 4U 1538–52 is quite eccentric. Therefore we conclude that 4U 1538–52 is a young system and hence the orbit has not circularised by tidal interaction.

The neutron star orbit also precesses due to tidal interaction and rotation of the companion star, which causes the longitude of periastron ω to change with time. The rate of change of ω can be measured by comparing the orbital elements of the neutron star orbit measured at different epochs of time. This rate of change of ω is directly related to the mass distribution of the companion star and hence the apsidal motion constant that are predicted by the theoretical models for stellar structure. Therefore measuring $\dot{\omega}$ will be a direct test for the stellar structure models. But ω can be measured only when the orbit is eccentric and for this purpose the Be-star/X-ray binary pulsars are the most suitable objects. The Be-star/X-ray binary pulsars are transient systems and have wide eccentric orbits of $P_{orb} > 10$ days. The Be-stars are fast rotating stars with rotational velocity near to the break-up velocity. They eject matter along their equator in a circumstellar disk. When the neutron star intercepts this circumstellar disk during its periastron passage, the rate of mass accretion increases and the system becomes bright in X-rays. These short outburst are called the type-I X-ray bursts. The Be-star also has episodes of high mass ejection when the neutron star may accrete a larger amount of matter and can be seen over several binary orbits. These long duration outbursts are called type-II X-ray bursts. In the third chapter of the the thesis we have reported the analysis and results of three Be-/X-ray binary pulsars we have studied, namely 4U 0115+62, V0332+52 and 2S 1417-624 which were observed by RXTE during their respective type-II bursts.

The X-ray pulse profiles of the Be-/X-ray systems evolve as a function of the source flux. Generally a simple single peaked pulse profile is seen during the onset of the outburst, which evolves into a more complex multiple peaked pulse profile as the source flux increases. The pulse profile again returns to the simple single peaked profile as the outburst fades off and the source flux decreases to persistent X-ray flux levels. Also due to varying mass accretion rate, the spin period evolves during the outburst. Both these factors together reduce the accuracy of measuring the arrival time of pulses. Hence we have used the instantaneous spin period measurements to deduce the orbital parameters of these system. The apparent spin period (P_{spin}) of the neutron star is modified by the radial velocity of the neutron star due to Doppler effect. The radial velocity of neutron star is dependant on the neutron star orbit and hence measurement of the spin period of the neutron star at different orbital phases allows us to determine the orbital elements.

4U 0115+63 was observed with the RXTE during two of its recent type II outbursts in 1999 and 2004. We measured the orbital parameters during both these outbursts independently. We combined the previous measurements of ω with our two measurements and measure the rate of apsidal motion of the system to be $\dot{\omega} \sim 0^o.06\ yr^{-1}$. V0332+52 was seen in outburst during 2004. During its previous outburst of 1983 only nine spin period measurements had been obtained and the orbital parameters measured from them were erroneous. We have measured the orbital parameters of this system accurately and determined the correct projected semi-major axis $a_x \sin i$ and orbital period. The new orbit parameters can now be used to compare with future orbital element measurements to estimate any apsidal motion and/or orbital evolution in this system. We also used the 1999 outburst of 2S 1417–624 to accurately measure the orbital parameters of this system.

We have also investigated the long term flux variations in the X-ray light curves of X-ray Binaries. Our studies on the flux variations observed in Cen X-3 are described in the fourth chapter of the thesis. Long term light curves of X-ray binaries show variations due to many reasons. Periodic variations of few milliseconds to a few hours in the light curve are seen due to spin of the neutron star. Light curves show variations due to motion of the neutron star in its orbit at timescales of few minutes to several days. Many sources also show quasi periodic variations in their X-ray light curves at timescales smaller than the neutron star orbital period which are believed to arise due to some material inhomogeneity orbiting the neutron star. These variations are called quasi periodic oscillations (QPOs). QPOs in X-ray binaries are observed between a frequency range of few millihertz to a few kilohertz. Long term X-ray light curves of many sources also reveal flux variations at time scales greater than the respective orbital period of the source. These variations are called superorbital variations. Systems like Her X-1, LMC X-4, 2S0114+650, SS 433, XTE J1716–389, 4U 1820–303 and Cyg X-1 show periodic superorbital variations whereas other systems like SMC X-1, GRS 1747-312, Cyg X-2, LMC X-3 and the Rapid Burster show quasi periodic superorbital flux variations. These superorbital flux variations are understood as arising either due to a changing mass accretion rate which could be aperiodic in nature or as due to obscuration of the central X-ray source by a tilted, warped and precessing accretion disk. Many theoretical models have been proposed to explain the disk precession. The long term flux variations in the X-ray light curves of bright persistent X-ray binaries like Her X-1, SMC X-1 and LMC X-4 have been understood to be due to a periodic (in case of Her X-1 and LMC X-4) or a quasi periodic (for SMC X-1) precession of a warped accretion disk.

We analysed the light curves of Cen X-3 obtained with the RXTE-ASM. The Cen X-3 light curves show aperiodic X-ray flux variations in all the energy bands of 1.5-3, 3-5 and 5-12 keV. The high and low states last for a few to upto a hundred days. The source also shows two spectral modes during the observations carried out with the ASM. The source was in a hard state during December 2000 to April 2004. At first look the aperiodic variations seen in Cen X-3 light curves seem to be arising due to a changing mass accretion rate. To investigate the cause of these aperiodic flux variations of Cen X-3 we studied the orbital modulation and the pulsed fraction as a function of source flux state. In the high state, the eclipse ingress and egress are found to be sharp whereas in the intermediate state, the transitions are more gradual. In the low state, instead of eclipse ingress and egress, the light curve shows a smooth intensity variation with orbital phase. The orbital modulation of the X-ray light curve in the low state shows that the X-ray emission observed in this state is from an extended object. The intensity dependent orbital modulations indicate that the different intensity states of Cen X-3 are primarily due to varying degree of obscuration. Measurements of the pulsed fraction in different intensity states are consistent with the X-ray emission of Cen X-3 having two components, one highly varying component with a constant pulsed fraction and a relatively stable component that is unpulsed and in the low state, the unpulsed component becomes dominant. The observed X-ray emission in the low state is likely to be due to scattering of X-rays from the stellar wind of the companion star. Though we can not ascertain the origin and nature of the obscuring material that causes the aperiodic long term intensity variation, we point out that a precessing accretion disk driven by radiative forces is a distinct possibility.

We also studied the QPOs in Cen X-3 that are seen at 40 mHz. The QPOs are explained by the Beat Frequency Model (BFM) as arising due to the beat between the Keplarian frequency of the inner accretion disk and the spin of the neutron star. Thus when the mass accretion rate is high the inner disk radius decreases, increasing the Keplarian frequency and hence the observed QPO frequency and vise versa when the mass accretion rate decreases. Thus if the flux variations of Cen X-3 were due to a changing mass accretion rate then the observed QPO frequency should have a positive correlation with the observed X-ray flux of the source. But we find in our study that the QPO frequency does not have any correlation with the observed X-ray flux and the QPO frequencies does not follow the Frequency-Flux relation as expected in the Beat frequency model. Thus the QPO behaviour is in agreement that the observed X-ray flux does not indicate the true X-ray intensity state and hence the mass accretion rate in Cen X-3. Therefore, we conclude that X-ray variations of Cen X-3 are not due to changing mass accretion rate but due to varying obscuration of the central X-ray source, possibly by an accretion disk which precesses aperiodically.

The conclusions from our studies presented in chapter 2, 3 and 4 of the thesis are summarised in the final chapter. The improved measurements of the rate of change of orbital periods from our work can now help us to detect any small departures from a constant period derivative in the persistent HMXB systems. The improved measurements of the orbital elements of Be-/X-ray binaries can now be used to study orbital evolution and apsidal motion in these system. New outbursts of the transient systems observed by future satellites providing good timing accuracy and large effective area, like LAXPC (Large Area X-ray Proportional Counter) of the ASTROSAT mission will facilitate such studies. The long term X-ray light curves study as done for Cen X-3 can be extended to other X-ray binary systems observed by All Sky Monitor. The method of source flux state dependent studies developed to study the Cen X-3 system can be easily extended to other systems that show long term superorbital flux variations. These kind of studies can be done by future proposed X-ray missions like ASTROSAT which will have a Sky Monitor similar to ASM dedicated to monitor X-ray sources. More sensitive measurements of long term X-ray light curves with the MAXI mission will allow similar studies of a large number of X-ray binaries and we will be able to see if aperiodically precessing accretion disk is present in many X-ray binaries.

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