CHAPTER 5. CONCLUSIONS AND OUTLOOK

We present a concise summary of the work presented in the thesis.

1. From the orbital studies of persistent sources we have the following conclusions:

   (a) Pulse profiles of both Cen X-3 and SMC X-1 show energy dependence.

   (b) The accuracy of pulse timing analysis of Cen X-3 and SMC X-1 is limited by orbital phase dependent changes of the pulse profile. Absorption coefficient of X-ray photons is energy dependent, soft X-ray photons being affected the most by absorption. The absorption column density has an orbital phase dependence, with higher absorption column density at orbital phases close to the eclipse. The absorption of soft X-ray photons is affected by this varying column density, which introduces small orbital phase dependent variations in the pulse profile. This effect is shown in Cen X-3 and also SMC X-1 during its low flux state. Measurement of the very small eccentricity of the orbit is affected by this.

   (c) Analysis of the high flux state observation of SMC X-1 in 2000 has allowed us to estimate the eccentricity ($e = 0.00021 \pm 0.00001$) and angle of periastron ($\omega = -43^{o}.23 \pm 8^{0}.99$) of SMC X-1 orbit for the first time.

   (d) Estimate for the rate of change of orbital period in both Cen X-3 and SMC X-1 has improved by an order of magnitude by including the new measurements of mid-eclipse times derived from our pulse timing analysis.

   (e) Our work of 4U 1538–52 has confirmed that this system has an eccentric orbit ($e = 0.18 \pm 0.01$) and shows no orbital evolution as was claimed previously. We also see that the angle of periastron ω has changed from 1997 to 2003 observation which could be due to apsidal motion. The rate of apsidal motion would then be $\dot{\omega} = -3^o.8 \pm 2^o.2 yr^{-1}$. This system is similar to SMC X-1 both having similar orbital periods of 3.8 days and mass of the companion star of about $15 M_{\odot}$. SMC X-1 has an almost eccentric orbit and shows orbital evolution due to tidal interaction between the neutron star and the companion star. On the other hand 4U 1538–52 has an eccentric orbit and does not show any observable orbital evolution. Therefore we conclude that this is a relatively young system compared to other persistent sources like SMC X-1.

2. From the spin period analysis of transient systems we conclude that :

   (a) All the three transient sources studied show pulse profile evolution with progress of the outburst. Therefore we use spin period analysis to measure the orbit of these sources for the present epoch.

   (b) From the analysis of 1999 and 2000 outburst of 4U 0115+63, including the earlier T_{ω} and ω measurements, we have for the first time measured the rate of apsidal motion. The rate of apsidal motion we measure for this system is $\dot{\omega} = 0^o.06 \pm 0^o.01$. Using the companion star mass, radius and rotational velocity given by Negueruela et al. (1997), we find the apsidal motion constant $k = 0.1$. This is higher than the usual apsidal motion constant quoted in literature for a $18 M_{\odot}$ star.

   (c) The spin period analysis of the 2004 outburst of V0332+53 has given the correct orbital parameters of this system. The correct orbital period as measured by the 2004 outburst data is $P_{orb} = 36.50 \pm 0.29$ which is 2 days more than earlier orbital period measurements done with sparse data. Also the $a_x \sin i$ measured is 82.49 $lt-sec$ which is 1.7 times greater than the $a_x \sin i$ reported by Stella et al. (1985).

   (d) The 1999 outburst of 2S 1417-624 observed by RXTE has allowed us to measure the orbital parameters of this system. We find that the 1999 orbit element measurements are in confirmation with the 1994 outburst measurements except for $a_x \sin i$ and ω. If the change in ω is due to apsidal motion then the rate of change of ω is

$\dot{\omega} = -0^o.29 yr^{-1}$.

3. Our study of long term flux variations in Cen X-3 has convincingly proved that the observed long term X-ray variations are not due to a varying mass accretion rate. The results of our studies are summarised below:

   (a) Cen X-3 long term X-ray light curve shows aperiodic flux variations in the energy bands 1.5-3 keV, 3-5 keV and 5-12 keV. The source switches from high to low state randomly which last between a few to upto 110 days. There is no periodicity in the long term intensity variations. The peak flux during the bursts is larger by upto a factor of 40 compared to the low state flux.

   (b) In the high state, Cen X-3 has two distinct spectral modes and during each outburst the source goes through flux changes via only one of the two spectral modes. There is no significant spectral evolution during each outburst.

   (c) Binary orbital modulation shows dependence on the flux state of the source. During high state, the eclipse is sharp which is more gradual during intermediate states. In the low state a uniform orbital modulation is seen.

   (d) Measurement of pulsed X-ray flux in different flux states of Cen X-3 is consistent with the X-ray flux having two components, one with a large pulsed fraction and a second unpulsed component that dominates in the low state.

   (e) To explain the intensity variations in Cen X-3, we propose that the long term intensity variations in Cen X-3 are mostly due to aperiodic obscuration of the compact source by the accretion disk. The unpulsed X-ray emission from an extended region appears to be due to scattering of the X-rays from the central source by an obscuring material in our line of sight.

   (f) QPO studies of Cen X-3 show that the Cen X-3 central QPO frequency do not depend on the source flux state. This is very consistent with the scenario proposed here that the changing flux of Cen X-3 is not due to a changing mass accretion rate.

5.1 Future Work

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. This requires X-ray detectors with large effective area and good timing accuracy. Proposed X-ray detectors like the LAXPC (Large Area X-ray Proportional Counter) of the ASTROSAT mission are very suitable for such a study. LAXPC is proposed to have a 10 microsecond time resolution with an effective area of 6000 cm^2 in the energy range of 5-30 keV. It can also be used to study the fast persistent pulsars and their orbital evolution.

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. The proposed Scanning Sky Monitor (SSM) of the ASTROSAT mission and the MAXI mission will be ideal for such studies. The SSM is similar to ASM and will be dedicated to monitor the X-ray sky regularly. Cen X-3 shows spectral mode changes, but we have not been able to do detailed study of this change in spectral mode due to no observations by PCA during the hard state of Cen X-3. ASTROSAT also has LAXPC which can be used for detail spectral studies when the SSM monitoring indicates a spectral mode change. The MAXI mission has more sensitivity than the existing ASM onboard RXTE. It is proposed to scan 90 to 90% of the sky every 96 minutes in an energy range of 2 to 30 keV. These 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.

APPENDIX A. Appendix I

When the eccentricity of binary orbit is small, the epoch defined by periastron T_ω is poorly determined (Luyten 1936). The epoch of mean longitude l, defined as the time when the mean longitude is zero, is more convinient to use (Sterne 1941). To define the binary orbit as a function of l, the line-of-sight displacement z is expanded with mean longitude l as the argument. The coefficients of the Fourier series depend on the eccentricity e and longitude of periastron ω (Deeter, Boynton and Pravdo 1981, Russell 1902, Wilsing 1893). We give the detail calculations to derive the line-of-sight displacement as a function of l in this appendix. For an orbit with finite eccentricity such that ω is defined, the mean longitude l is related to mean anomaly M by $l = M + \omega$. The line of sight displacement z is given by,

$$\begin{aligned} z &= r\sin(\nu+\omega)\sin i \\ &= r\cos\nu\sin i\sin\omega + r\sin\nu\sin i\cos\omega \qquad \text{(A.1)} \\ & \qquad \text{(A.2)} \end{aligned}$$

$r\cos\omega$ and $r\sin\omega$ are given by,

$$\begin{aligned} r\cos\nu &= \frac{3}{2}ae + a\left(1 - \frac{3}{8}e^2 + \frac{5}{192}e^4 - .....\right)\cos M \\ &\quad + \frac{1}{2}ae\left(1 - \frac{2}{3}e^2 + \frac{1}{8}e^4 - ....\right)\cos 2M \\ &\quad +..... \qquad \text{(A.3)} \\ r\sin\nu &= a\left(1 - \frac{5}{8}e^2 - \frac{11}{192}e^4 - ....\right)\sin M \end{aligned}$$

$$+\frac{1}{2}ae\left(1-\frac{5}{6}e^2+\frac{1}{12}e^4\right)\sin 2M$$
$$+..... \tag{A.4}$$

Neglecting the terms depending on higher power of eccentricity and using $t_n = z/c$ and $x = a\sin i/c$ we get,

$$\begin{aligned} t_n &= x\sin(M+\omega)+\frac{3}{2}xe\sin\omega+\frac{1}{2}xe\sin(2M+\omega) \\ &= x\sin l+\frac{3}{2}xe\sin\omega+\frac{1}{2}xe\sin(2l-\omega) \\ &= x\sin l+\frac{3}{2}xe\ \sin\omega+\frac{1}{2}xe\ \cos\omega\ \sin 2l-\frac{1}{2}xe\ \sin\omega\ \cos 2l \end{aligned} \tag{A.5}$$

where the first term is f_{orb} and the last three terms are the terms due to e and ω which were initially dropped as discussed in Chapter 2. When terms due to differential correction to initial orbital elements are added to Equation A.5, we get equation 2.4.

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List Of Publications

1. Raichur, H., Paul, B., 2008, MNRAS, 387, 439
2. Raichur, H., Paul, B., 2008, ApJ
3. Mukherjee, U., Raichur, H., Paul, B., Naik, S., Bhatt, N., 2006 JapA, 27, 411
4. Raichur, H., Paul, B., Naik, S., Bhatt, N., 2006, AdSpR, 38, 2785
5. Paul, B., Raichur, H., Mukherjee, U., 2005, A&A, 442, 15
6. Orbital evolution and eccentricity measurements in Cen X-3 and SMC X-1

In preparation

7. Orbital elements and apsidal motion measurements of Be-/X-ray binaries

In preparation

Other publications :

1. Kaur, R., Paul, B., Raichur, H. 2007, ApJ, 660, 1409
2. Jain, C., Paul, B., Joshi, K., Dutta, A., Raichur, H. 2007, JApA, 2007, 28, 4
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4. Mukherjee, U., Bapna, S., Raichur, H., Paul, B., Jaaffrey, S.N.A., 2006, JapA, 27, 25