CHAPTER 3. Orbital evolution and apsidal motion studies: Transient sources

3.1 Introduction

In the previous chapter we described our study of persistent X-ray binary pulsars and their orbital evolution. In persistent systems, the companion star is an O/B type giant star of mass $M_c > 10M_\odot$ and the neutron star accretes matter from stellar wind of companion. Thus there is a steady accretion of matter onto the neutron star because of which the system is a persistent X-ray source. Also for persistent systems with small orbital periods, the tidal interaction between the neutron star and the companion star tries to circularise and synchronise the binary orbit, which is the case for Cen X-3 and SMC X-1.

In this chapter we will be discussing three Be/X-ray binaries, which are transient systems. All the three sources have wide and eccentric orbits of orbital period $P_{orb} > 20$ days. The companion is a Be-star, which differs from a normal B star. Its spectra has emission lines in the optical and infrared regions of the spectra. The emission lines are produced by a relatively cool circumstellar disk formed by material ejected from the Be-star. The causes for material ejection are poorly understood, the most possible reasons being fast rotation, magnetic fields and/or non-radial pulsations of the Be-star (Slettebak, 1988). The circumstellar disk itself is understood as a viscous decretion disk, which is similar to a viscous accretion disk but with an opposite sign of $\dot{M}$ (Lee et al 1991; Porter 1999; Okazaki 2001). The observed upper limit on the radial velocity in disks around Be star is 3 kms^{-1} (Hanuschik 2000) implying that the outflow in viscous decretion disc is highly subsonic near the star (Okazaki 1997, 2001). Since the mass of the neutron star is much smaller than that of the Be star, its presence will hardly affect the mass loss process from the Be star but the disk truncation radius could be governed by the presence of the neutron star. The interaction of the disk with the neutron star can also lead to its warping, tilting (due to variable X-ray irradiation) and precession.

X-ray emission from these systems is due to the accretion of the circumstellar material by the neutron star. Due to the varying geometry and physical conditions in the circumstellar disk, the Be/X-ray binaries show different states of X-ray activity (Stella et al. 1986). In quiescence, some of them show persistent low luminosity ($10^{32}\ ergs^{-1} \leq L_x \leq 10^{36}\ ergs^{-1}$) X-ray emission whereas some may show no detectable emission. Occasionally, they show series of periodic (type I) X-ray outbursts ($L_x \approx 10^{36} - 10^{37}\ ergs^{-1}$), separated by the orbital period of the neutron star. These type-I bursts are understood as occurring whenever the neutron star intercepts the circumstellar disk which causes increase in the mass accretion rate. This can happen when the neutron star is near the periastron point of the binary orbit and hence the periodicity seen in the type-I X-ray bursts are explained. More rarely, Be-/X-ray binaries also undergo giant (type II) X-ray outbursts ($L_x \geq 10^{37} ergs^{-1}$), which do not clearly correlate with the orbital motion. These are related to some episodic outbursts of the Be-star which results in higher mass being ejected. This results in higher mass accretion rate for the neutron star making it X-ray bright over a few orbital cycles. Type-II outbursts are preceded by increased optical activity of the Be-star.

The Be/X-ray transients are very good candidates to study apsidal motion of the binary orbit. Apsidal motion is the rate of change of the longitude of periastron of the orbit. This longitude of periastron is defined only when the orbit is eccentric. Hence for determination of apsidal motion it is essential that the orbit be eccentric. Due to the presence of the X-ray pulsars in these systems, the orbit of the binary can be measured accurately. The rate of apsidal motion is sensitive to the internal mass distribution and rotation velocity of the companion star. The Be-stars have very high rotational velocity which is just below the breaking point velocity. Hence large apsidal motion can be expected in the Be/X-ray transients. Also the neutron star can be essentially approximated to a point mass which will simplify the interpretation of the apsidal motion results.

Since these systems are X-ray bright only during times of increased mass accretion rate, the spin of the neutron star during an outburst may evolve. Thus timing analysis should take into account the neutron star spin up rate. This spin up rate may not be constant, in which case it will depend on the instantaneous luminosity of the source. In such a case one has to model $\dot{P}_{spin}$ as a function of instantaneous X-ray luminosity. This may not be simple at all times, and the orbit elements will be dependant on the model used for spin period modelling. Another important aspect to be noted is that many of these sources have a variable pulse profile. The pulse profile is a function of the X-ray luminosity, the exact dependence of which is not yet fully understood. Thus a unique time marker for timing analysis may be difficult to find in the pulse profile of these system, decreasing the accuracy with which one can determine the arrival time of pulses. However, the pulse profile evolution is slow. If one takes a data segment of a fraction of a day, the pulse period determined is not significantly affected by the profile evolution. Taking into consideration all these factors we have used the variability in the spin period due to the motion of the neutron star in its orbit to determine the orbital elements. The analysis technique is described below and the same technique is used for all the 3 pulsars which we have studied here.

3.2 Measuring orbital parameters using Doppler variation of spin period

The measured spin period of the neutron star is modified due to its orbital motion. The radial velocity will modulate the spin period (P_{spin}) of the neutron star through the Doppler effect as

$$P_{obs} = (P_{spin} + \dot{P}_{spin}\Delta t)\sqrt{\frac{1 + v_r/c}{1 - v_r/c}} \tag{3.1}$$

where $\dot{P}_{spin}$ is the rate of change of spin period and P_{obs} is the observed spin period. v_r is the velocity component along the line of sight of the neutron star and depends on the orbit elements. For the systems we are studying the relevant parameters describing the neutron star spin and orbit are

P_{spin} : Spin period of the neutron star

$\dot{P}_{spin}$: Rate of change of spin period

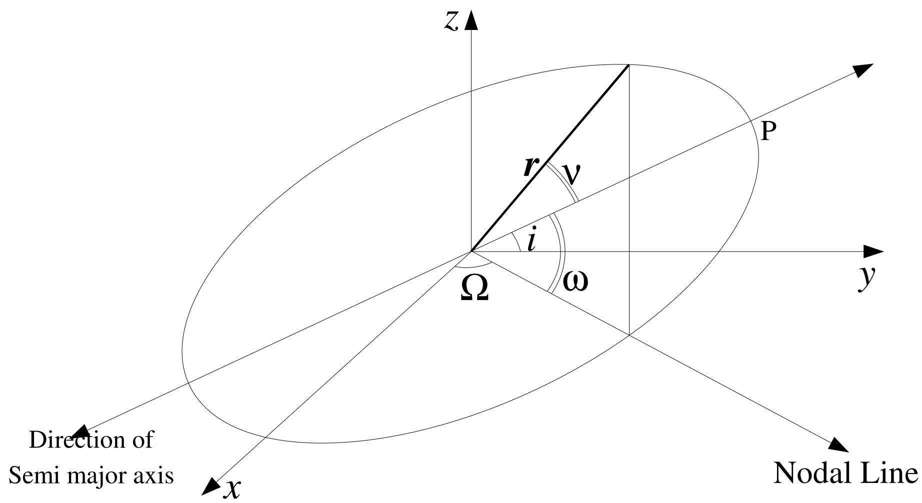

Figure 3.1 Figure shows the orbit of the neutron star inclined at an angle i with respect to the plane normal to the line of sight. The direction of line of sight is along the z-axis. ω is the angle between the nodal line and the line joining the center of the orbit to the periastron point P. r is the distance of any point on the eccentric orbit from the center of the orbit and ν is the true anomaly of that point.

$a_x \sin i$: Projected semi-major axis

e : eccentricity of the orbit

ω : Longitude of periastron

T_ω : Time of periastron passage

P_{orb} : Orbital period

The instantaneous position of the neutron star in an eccentric orbit inclined at an angle i to the plane perpendicular to the observers line of sight is given by (see first chapter for details) :

$$r = \frac{a(1-e^2)}{1+e\cos\nu} \tag{3.2}$$

where ν is the eccentric anomaly. Projection of r along the line of sight is (see Figure 3.1)

$$z = rsin(\nu + \omega)\sin i \tag{3.3}$$

Line of sight component of the velocity is then given by $\dot{z}$

$$\dot{z} = v_r = \sin i[\sin(\nu + \omega)\dot{r} + r\cos(\nu + \omega)\dot{\nu}] \tag{3.4}$$

where

$$\dot{\nu} = \frac{2\pi a^2(1 - e^2)^{1/2}}{r^2 P_{orb}}$$

$$\dot{r} = \frac{re\sin\nu}{1 + e\cos\nu}\dot{\nu}$$

Therefore velocity (v_r) is given by

$$v_r = \frac{2\pi a_x \sin i}{(1 - e^2)^{1/2} P_{orb}}(\cos(\nu + \omega) + e\cos\omega) \tag{3.5}$$

Spin period measurements at different orbital phases can thus be used to solve equation 3.1 along with equation 3.5 and the relation between true anomaly, eccentric anomaly and mean anomaly given in Chapter 1. There are seven free parameters to be solved which completely describe the neutron star orbit. In cases where the history of T_ω is known, the orbital period P_{orb} is held fixed and the new T_ω is used along with the earlier reported T_ω's to estimate P_{orb} with a greater accuracy. The method for this is same as that described for E_n in the last chapter.

3.3 4U 0115+63

The hard X-ray transient 4U 0115+63 is one of the best-studied Be/X-ray binary systems (Campana 1996; Negueruela et al. 1997). It was first reported in the *Uhuru* satellite survey (Giacconi et al. 1972; Forman et al. 1978). Later searches through the Vela 5b database revealed that the source had already been observed by the satellite since 1969 (Whitlock et al. 1989). Precise positional determination by SAS-3, Ariel V and HEAO-1 satellites helped in identifying the companion star to be a heavily reddened Be-star, V635 Cas, with visual magnitude $V \approx 15.5$ (Comisky et al. 1978; Johnston et al. 1978, Johns et al 1978, Hutchings & Crampton 1981; Khopolov et al. 1981). The orbital parameters were determined by using the SAS 3 timing observations (Rappaport et al. 1978). Kelley et al. (1981) searched for apsidal motion in this source using the SAS-3 data for the 1978 outburst and early observations of *Uhuru* during the 1971 outburst and gave an upper limit on the apsidal motion ($\dot{\omega} \leq 2^0.1\, yr^{-1}$). Later observations of the source by Ariel-6, Ginga and BATSE-CGRO improved the orbital parameter estimates which can now be combined to obtain an improved measurement of the rate of apsidal motion. Before the BATSE and RXTE observations the system was known to display only type II activity. A series of type I outbursts were then detected by BATSE and RXTE (Bildsten et al. 1997, Negueruela et al. 1998). The BATSE observations were used to determine the times of periastron passage T_ω which were then used to obtain a more precise value for the orbital period ($P_{orb} \sim 24.317$ days). A consistent model for the source was formulated (Negueruela & Okazaki, 2001a; Negueruela & Okazaki, 2001b) which give a moderate value for the inclination angle of the system ($40^0 < i < 60^0$) and a high rotational velocity for the Be star ($v \sin i \sim 300\ kms^{-1}$) of mass $18 M_\odot$. The distance to the optical companion V635 Cas was determined to be ~ 7 kpc (Negueruela & Okazaki, 2001). Strong cyclotron resonance lines with main peak and harmonics are seen from this source which have given magnetic field strength of the neutron star as $B_{NS} \approx 1.5 \times 10^{12}\ G$ (Nakajima et al. 2006, Mihara et al. 2004, Santangelo et al. 1999, Lutovinov, Grebenev & Sunyaev 2000, Wheaton et al. 1979).

The source went into outburst in 1999 and 2004 and extensive observations were made with the RXTE. ASM light curves of the two outburst are shown in Figures 3.2 and 3.3. The light curves for spin period analysis are extracted from the standard-I mode data with a time resolution of 0.125 s. The photon arrival times are corrected to the barycentric times and the light curves are searched for pulsations. The pulse period at different orbital phases

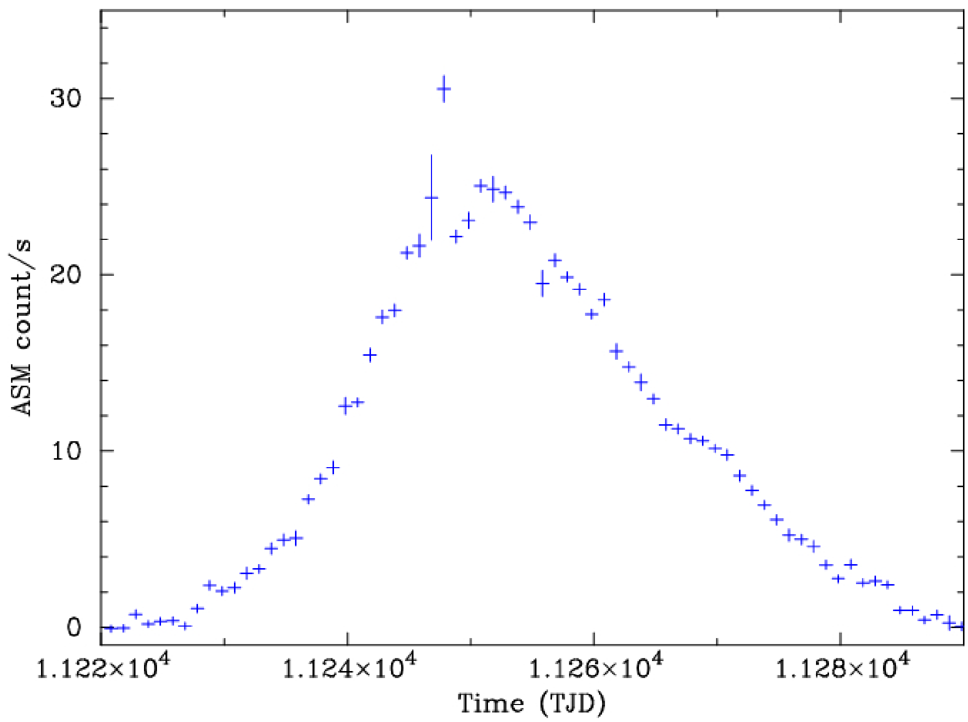

Figure 3.2 ASM light curve of the 1999 outburst of 4U0115+63

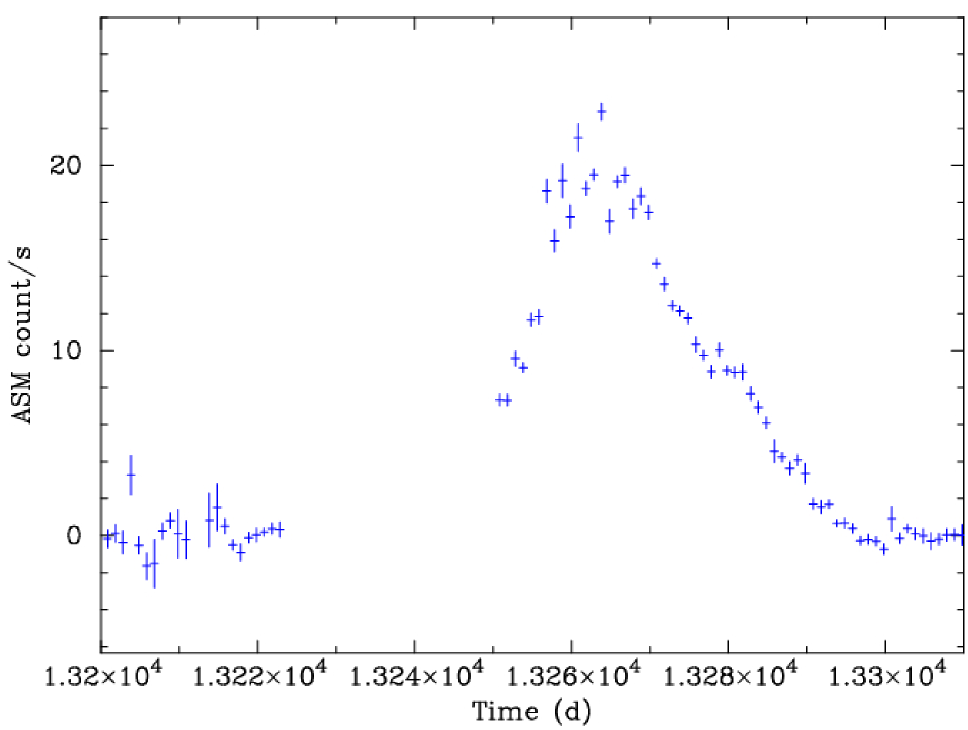

Figure 3.3 ASM light curve of the 2004 outburst of 4U0115+63

is determined by χ^2-maximisation using the task `efsearch` provided by FTOOLS. Error on the measured spin periods is calculated using the χ^2 versus spin period plot provided by `efsearch`. The points near the peak of this plot are fitted with a Gaussian. The error on the Gaussian center estimate is taken as the error on the spin period. Due to increased rate of mass accretion, the neutron star is spun up during the outburst. Hence the measured pulse period shows variation due to both the intrinsic rate of change of spin period and the Doppler effect due to the motion of the neutron star in the binary orbit. For the 1999 observations we obtained 73 spin period measurements spread over 48 days and during the 2004 observations there are 55 measurements spread over 45 days. The Doppler curve for the 1999 outburst is shown in the upper panel of Figure 3.4 and for the 2004 outburst is shown in the upper panel of Figure 3.5. Both these Doppler curves were fitted with equation 3.1 to determine the orbital elements. The following method was used to estimate error on the six free parameters measured. The parameter X whose error was to be estimated was held fixed at a particular value, and a fit to the spin period Doppler curve was done in the 5 parameter space to get the minimum χ^2. Then X was incremented by a small value and the fit repeated to get the next best χ^2. This gave a plot of χ^2 versus X, and 1σ error on X was then estimated as the change in X needed to change the minimum χ^2 value by 1.

The pulse profile of 4U 0115+63 shows evolution during both the 1999 and 2004 outburst. Figure 3.6 represents the pulse profile evolution during the 1999 outburst and Figure 3.7 for the 2004 outburst. The pulse profiles are generated using light curves with a time resolution 16 ms obtained from the event mode data of PCA. The light curves are folded with spin period obtained by using `efsearch`. Each pulse profile is an average of 100 consecutive pulses. The pulse profile is simple and has a single peak during the start of the outburst. As the outburst reaches the maximum flux the pulse profile also evolves and shows two peaks in the profile. The pulse profile again returns to a single peak profile in the tail of the outburst. This evolution of pulse profile restricts the accuracy with which the arrival time of the pulses can be measured. Therefore we have used only the spin period Doppler curve measurements to estimate the orbital parameters.

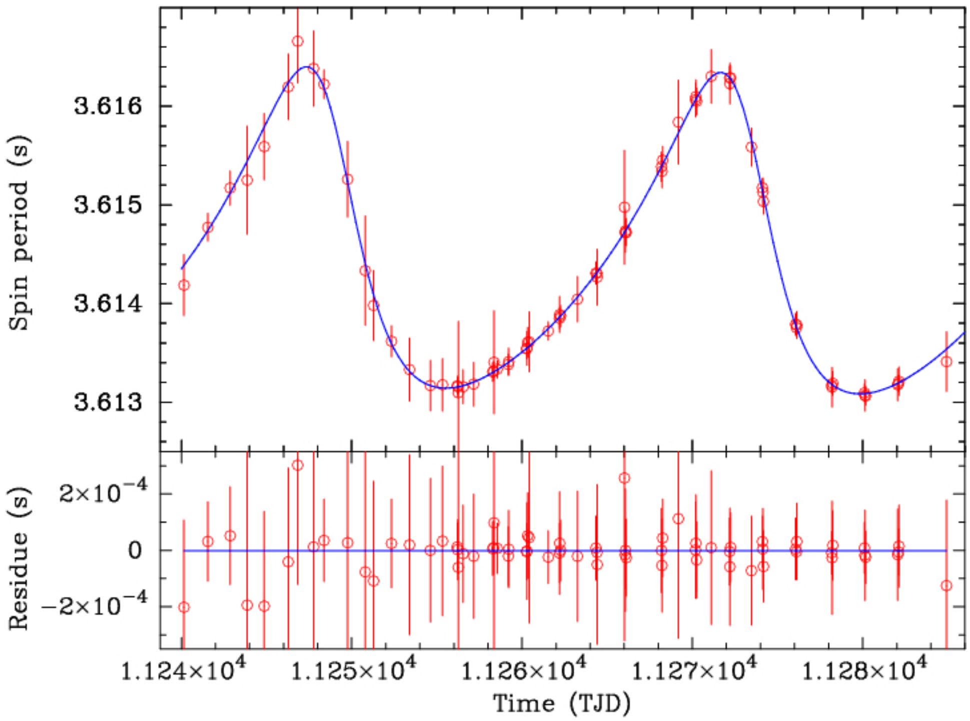

Figure 3.4 Spin period variations due to motion of neutron star in the binary orbit is shown for the observations of 1999

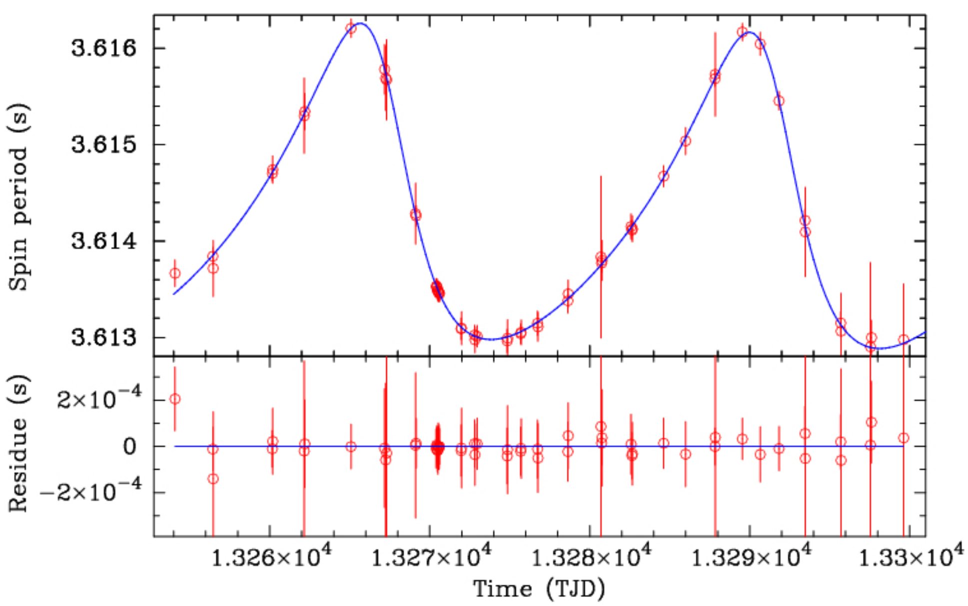

Figure 3.5 Spin period delay curve for the 2004 outburst of 4U0115+63

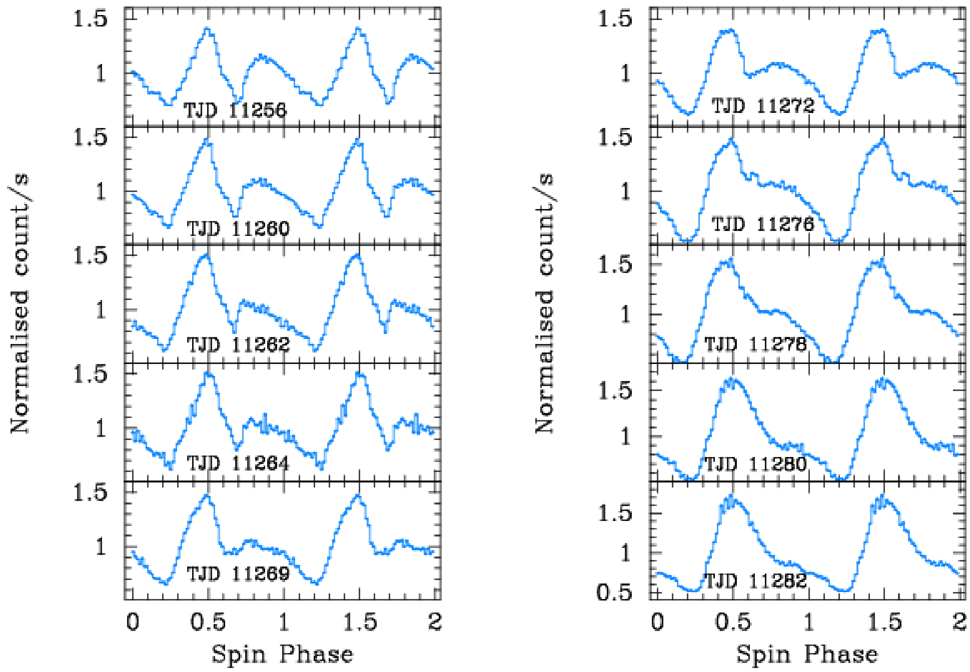

Figure 3.6 Pulse profile of 4U0115+63 at different orbital phases during the 1999 outburst

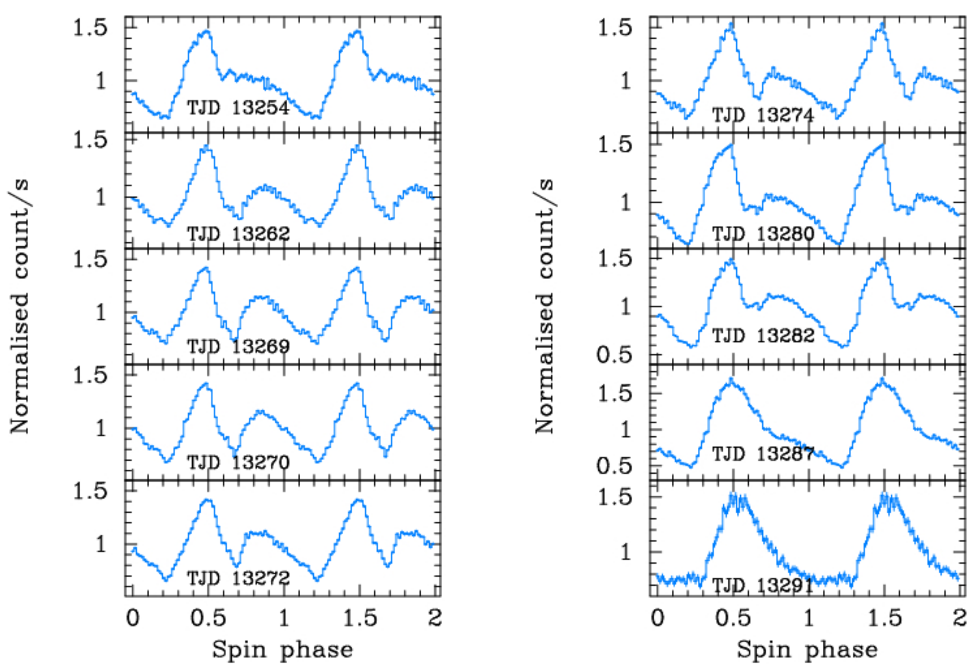

Figure 3.7 Pulse profile of 4U0115+63 at different orbital phases during the 2004 outbursts

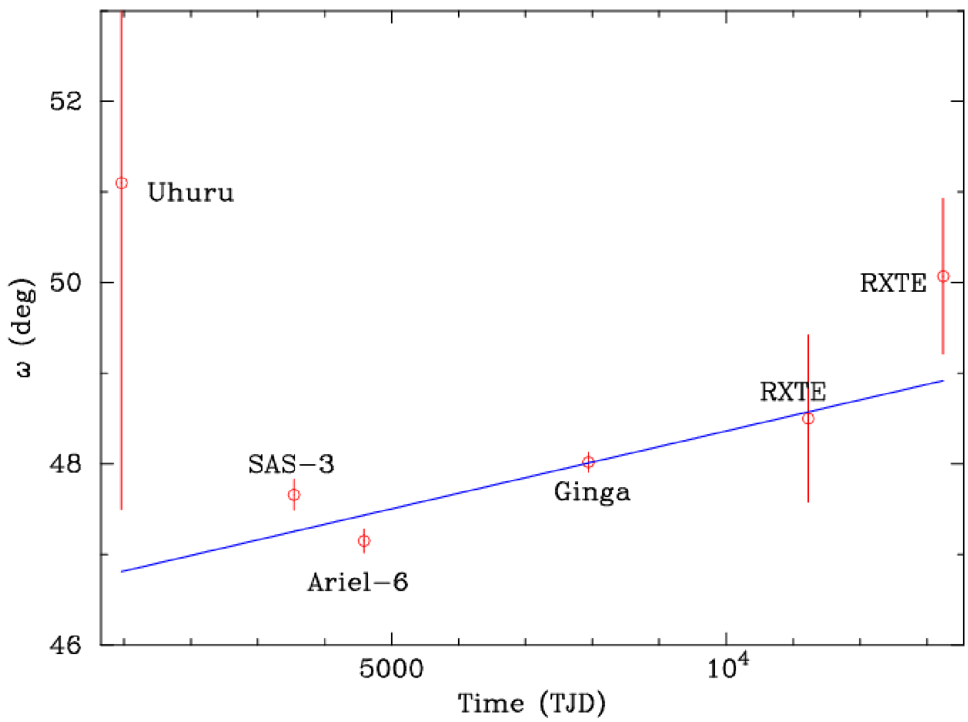

Figure 3.8 Figure shows the rate of change of ω of 4U 0115+63

Table 3.1 Orbital parameters of 4U0115+63

Parameter	Value	
	51240 MJD	53254 MJD
P_{spin} (s)	3.61447 ± 0.00002	3.61436 ± 0.00002
$\dot{P}_{spin}$ (s/day)	$(-2.5 \pm 0.6) \times 10^{-6}$	$(-3.81 \pm 0.55) \times 10^{-6}$
$a_x \sin i$ (lt-s)	140.69 ± 0.72	141.35 ± 0.78
ω (^{0})	48.5 ± 0.9	50.07 ± 0.85
e	0.342 ± 0.004	0.339 ± 0.005
T_ω (MJD)	51224.647 ± 0.051	53243.038 ± 0.051
$\dot{\omega}$ ($^o yr^{-1}$)	0.06 ± 0.01	
E_0 (MJD)	40962.851 ± 0.036	
P_{orb} (day)	24.3174 ± 0.0004	

The two new times of periastron passage that we derived from the 1999 and 2004 outburst were used along with previous measurements tabulated in Table 3.2 to look for orbital evolution in this system. But from the present observations we cannot find any evidence for orbital evolution. We derive an upper limit of $\frac{\dot{P}_{orb}}{P_{orb}}$ is $-1.12 \times 10^{-6}\ yr^{-1}$ for orbital evolution. The apsidal motion of the system is estimated using the values of ω tabulated in the Table 3.3. A straight line fit to these values gives $\dot{\omega} = 0^{o}.06 \pm 0^{o}.02\ yr^{-1}$. This is the first conclusive measurement of $\dot{\omega}$ and $\dot{P}_{orb}$ for a Be-/X-ray binary system. Using the value of $\dot{\omega}$ in the equation

$$\dot{\omega} = \frac{2\pi k}{P_{orb}}\left(\frac{R_c}{a}\right)^5 (15qf(e) + \Omega^2(1+q)g(e)) \quad (3.6)$$

where

$$f(e) = \left(1 + \frac{3}{2}e^2 + \frac{1}{8}e^4\right)(1-e^2)^{-5} \quad (3.7)$$

$$g(e) = (1-e^2)^{-2} \quad (3.8)$$

and q is the mass ratio of the neutron star mass to the companion star mass, R_c is the radius of the companion star, Ω is the ratio of rotational velocity of the companion star to the orbital angular velocity, e is the eccentricity of the orbit and P_{orb} is the binary orbital period (Kelley et al., 1981). We use the following values for the companion star (Negueruela & Okazaki 2001a): $q = 0.08$, $a = 86R_{\odot}$, $R_c = 8R_{\odot}$ and rotational velocity $v = 440$ km/s. The apsidal motion constant evaluated using the above formula is $k = 0.1$ which is higher than the apsidal motion constant generally quoted for an $18M_{\odot}$ star by theoretical stellar models (Jeffery, 1984).

Table 3.2 Epoch History for 4U0115+63

Orbit Number	Periastron time passage (TJD)	Satellite Name	References
0	963.080 ± 0.17	*Uhuru*	Kelley et al. 1981
106	3540.451 ± 0.006	SAS-3	Rappaport et al. 1978
287	7941.530 ± 0.006	*Ginga*	Tamura et al. 1992
304	8355.440 ± 0.07	CGRO	Bildsten et al. 1997
351	9498.1232 ± 0.0015	CGRO	Bildsten et al. 1997
374	10057.4015 ± 0.0032	CGRO	Bildsten et al. 1997
422	11224.6465 ± 0.051	RXTE	Present work
505	13243.038 ± 0.051	RXTE	Present work

Table 3.3 ω measurements for 4U0115+63

Epoch of measurement (TJD)	ω	Satellite Name	References
963.0800	$51^o.10 \pm 3^o.60$	*Uhuru*	Kelley et al. 1981
3540.4510	$47^o.66 \pm 0^o.17$	SAS-3	Rappaport et al. 1978
4585.700	$47^o.15 \pm 0^o.13$	Ariel-6	Ricketts et al. 1981
7941.530	$48^o.02 \pm 0^o.11$	*Ginga*	Tamura et al. 1992
11224.6465	$48^o.50 \pm 0^o.92$	RXTE	Present work
13243.0370	$50^o.07 \pm 1^o.86$	RXTE	Present work

3.4 V0332+53

V0332+53 is a Be-/X-ray binary transient which has been seen in outburst previously by other satellites. It was first observed by *Vela 5B* in 1973 during its type II outburst. This outburst was of a duration of nearly 100 days and reached a peak intensity of 1.6 Crabs (Terrell & Priedhorsky 1984). Ten years later in 1983 this source was again seen in outburst by the *Tenma* satellite. The flux level during this outburst was 10 times lower than that observed during the 1973 outburst (Tanaka et al., 1983). Observations with European Space Agency's X-ray observatory *EXOSAT* detected a subsequent outburst in 1983 and these observations also gave an accurate estimate of the location of this binary. This helped in identifying the optical/infrared counterpart to be a heavily reddened B-star (Brand et al. 1983; Argyle 1983; Kodaira 1983; Bernacca, Ijima and Stagni 1983; Honeycutt and Schlegel 1983). The optical identification suggests that this source is located at a distance of between 1.5 and 5 kpc. A total of 14 observations of V0332+53 were made by *EXOSAT* between 1983 November 20 and 1984 January 23 with each of the observations lasting upto 6 hr. Nine spin period measurements were made using this data which was used to conclude that the neutron star has a spin period of ~ 4.4 s and is in a binary orbit of period ~ 34.25 days, eccentricity ~ 0.31, $a_x \sin i \ \sim 48$ lt-sec and longitude of periastron $\omega \ \sim 313^o$. No intrinsic rate of change of spin period was considered. Reanalysis of the 1973 outburst by Whitlock (1984) revealed a pulsar period of 4.37 s and an orbital period of either 34.38 ± 0.02 or 34.07 ± 0.02 days. It was shown that the 1973 outburst was a type II outburst and the light curve of this outburst showed a residual periodicity when a Gaussian outburst trend was subtracted from the light curve. Since the 1973 outburst observation had poor statistics, phase connected pulse timing analysis was not possible. The time of periastron passage was found to be JD 2441870.00 ± 1.0 by assuming that the maximum X-ray flux corresponds to periastron. *Ginga* observed this source in type II outburst in 1989. Takeshima et al. (1994) reported a 0.05 Hz QPO from the 1989 outburst. A cyclotron absorption component observed at 28.5 keV suggested that the magnetic field could be as high as 2.5×10^{12} G on the neutron star surface (Makishima et al. 1990).

This source again went into outburst in November 2004. The outburst was followed using

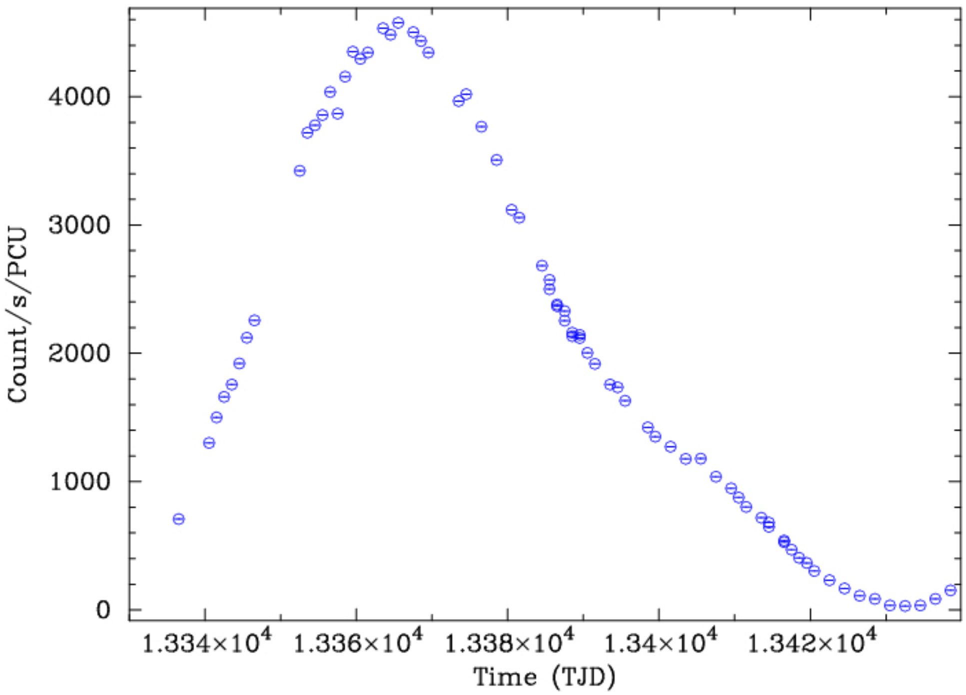

Figure 3.9 Light curve of the 2004 outburst of V0332+53

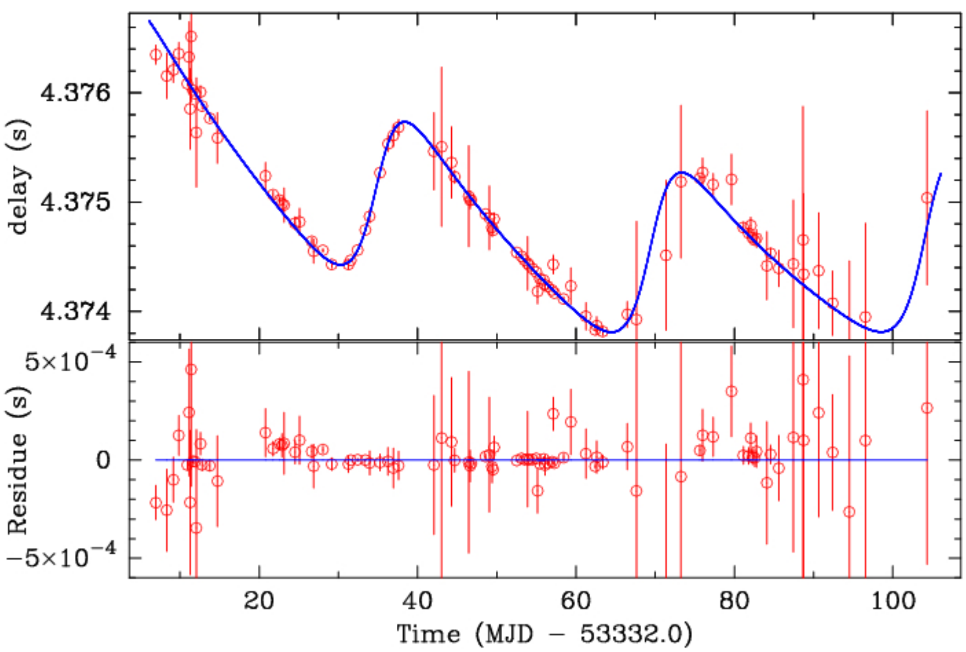

Figure 3.10 Spin period measurements for the 2004 outburst of V0332+53

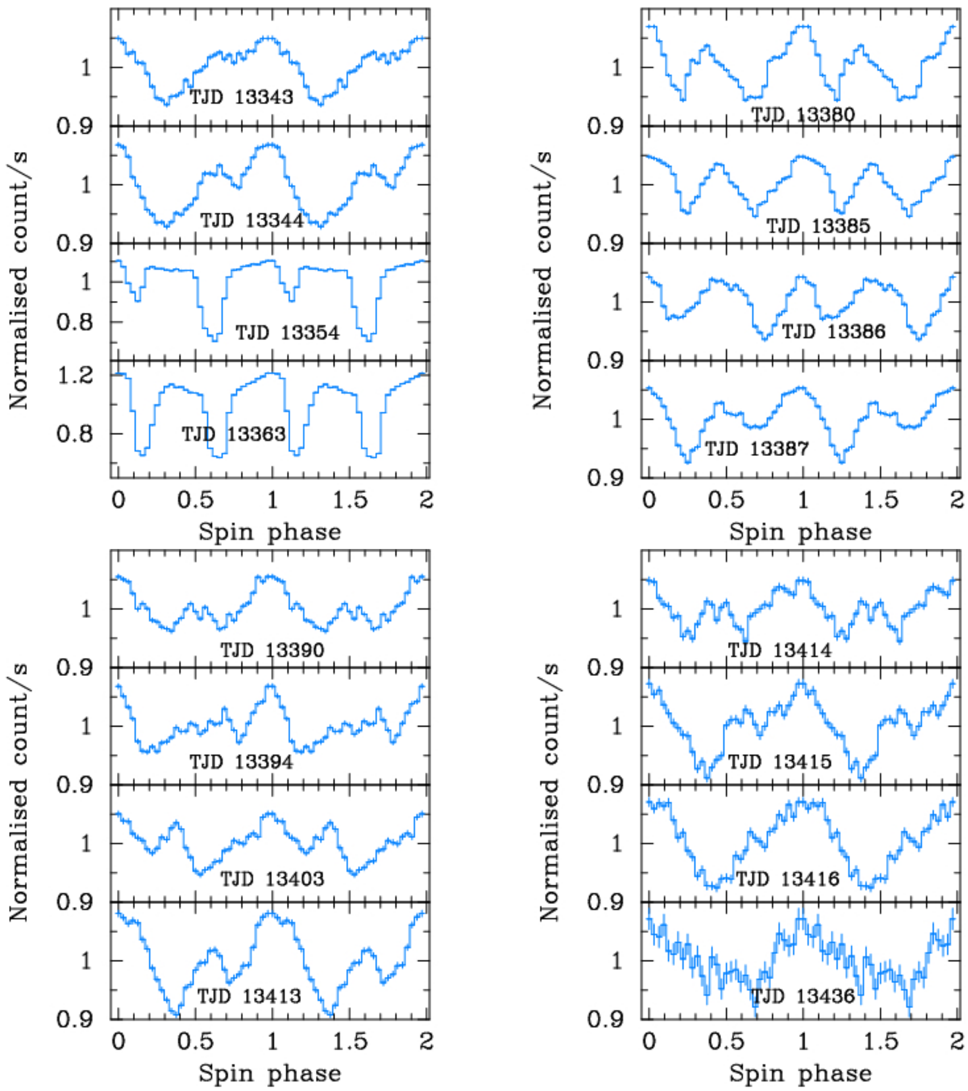

Figure 3.11 Pulse profile of V0332+53 at different orbital phases during the 2004 outburst

the RXTE PCA for almost 120 days from November 27, 2004 to March 27, 2005. It was also observed with the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) at hard X-rays. Three cyclotron lines were detected with INTEGRAL observation (Kreykenbohm et al. 2005) confirming the earlier report from RXTE (Coburn et al. 2002). Another QPO at 0.22 Hz was discovered with RXTE PCA observation to be riding on the spin frequency (Qu et al. 2005). Using part of RXTE PCA data and the INTEGRAL data, refined orbital parameters were obtained (Zhang et al. 2005). These authors had about 34 spin period measurements spread over nearly two binary orbits. They have considered only a spin down rate in fitting the spin period Doppler curve. We have used the entire 2.5 binary orbit data from RXTE PCA and have 93 spin period measurements which give an improved set of orbital parameters. From the full coverage of the outburst we see that the measured spin periods cannot be completely accounted for by just taking a spin period derivative and orbital modulation. An extra term for the rate of change of spin period derivative is needed to completely account for the observed spin period evolution. We obtain an improved measurement for the orbital period of 36.5 ± 0.28 which is almost 2 day greater than that reported by Zhang et al (2005) or Stella et al. (1985). The time of periastron passage we obtained from the complete data of the 2004 outburst is consistent with that obtained by Zhang et al. (2005) and Whitlock (1989) if we assume a $P_{orb} = 36.5d$. Below we describe our spin period analysis and results of the 2004 outburst.

3.4.1 Analysis and results

The 2004 outburst of V0332+53 was observed using the PCA and the data was recorded in event mode and/or binned mode along with the usual Standard-I and Standard-II mode. Since V0332+53 has a the spin period of $P_{spin} = 4.4\ s$, we used either the event mode or the binned mode data which provides better timing resolution than the Standard-I or Standard-II mode data. No spin period modulation is seen from light curves obtained from energy channels greater than 21 keV. We therefore created light curves of time resolution of 16 ms using photons collected in energy channels 1 keV - 21 keV. All the light curves were corrected to the solar system barycenter before further analysis. Spin period searches were done using the `efsearch` task of FTOOLS software package. Period searches were done using the full light curve of every pointed observation (No of pointed observations = 102). The χ^2 versus spin period plot obtained by `efsearch` was fitted with a Gaussian near the peak χ^2 values, the error in the Gaussian center was taken to be the error on the measured spin period. We measured a total of 93 spin periods spread over 2.5 binary orbits. The spin period Doppler curve obtained is shown in the top panel of Figure 3.10. We fitted the obtained spin period Doppler curve with equations 3.1 and 3.5. This results in a fit of 85 degrees of freedom. The errors on spin period measurement were multiplied by a constant factor so as to get a reduced χ^2 of 1. The error on the eight free parameters fitted was estimated with the same method as described for 4U 0115+63. The final parameters and the errors on them that we find are given in Table 3.4.1.

Pulse profiles were obtained by folding the light curve with the spin period obtained by `efsearch`. Figure 3.11a and 3.11b show some of the pulse profile obtained at different times and intensity of the outburst. The pulse profile has a single peak at the start of the outburst (TJD 13343). This single peak slowly starts to separate out into two peaks as the outburst progresses, the two peaks are fully separated when the outburst reaches the maximum flux. As the outburst starts to fade out the two peaks in the pulse profile start moving closer and the pulse profile again becomes single peaked in the tail of the outburst. This evolution of pulse profile is consistent with the picture that at high luminosity the emission from the polar caps is in a fan beam because of which the pulse profile is complicated whereas at low luminosity the emission from the polar caps is in a pencil beam and therefore the pulse profile is simple. But since the pulse profile is variable, the arrival time of pulses cannot be obtained accurately. Thus a pulse arrival time analysis subject to systematic error.

The orbital period we obtain is from the spin period Doppler curve. This value is 2.25 days greater than the value quoted by Stella et al. (1985) and 1.83 days greater than the value obtained by Zhang et al. (2005). The values obtained by Stella et al. (1985) was from very sparse orbital coverage. Also the $a_x \sin i$ obtained by Stella et al. (1985) is 1.7 times smaller than the value we obtain from 2004 outburst. Such a large change in $a_x sini$ cannot be accounted for by any orbital evolution or apsidal motion arguments. So we suspect that

Table 3.4 Orbital parameters of V0332+53

Parameter	Value
P_{spin} (s)^a	4.3763038 ± 0.0000002
$\dot{P}_{spin}$ (s/d)	$(-4.667 \pm 0.2) \times 10^{-5}$
$\ddot{P}_{spin}(s/d^2)$	$(5.414 \pm 0.092) \times 10^{-7}$
$P_{orb}(day)$	36.50 ± 0.29
$a_x \sin i$ (lt-s)	82.49 ± 0.94
ω (^{0})	283.49 ± 0.91
T_ω (MJD)	53330.584 ± 0.055
e	0.417 ± 0.007

a: P_{spin}at MJD 53332.0

the orbital element values determined by Stella at al. (1985) are incorrect. But Zhang et al. (2005) have used a subset of the 2004 outburst data and obtained an orbital period that is not consistent with the values obtained by us. We note that Whitlock (1989) have reanalysed the 1973 outburst of V0332+53 observed by *Vela 5b*. Assuming that the peak of the 1973 outburst was at periastron they find the time of periastron passage to be TJD 1869.5 ± 1.0. Using our value of orbital period we find that this is 314.002 orbital cycles before the T_ω we have measured. The T_ω measured independently by Zhang et al. (2005) is also consistent with the orbital period of 36.5 days. Therefore we conclude that the orbital period value quoted by Stella et al. is incorrect. Zhang et al. (2005) have not included a $\ddot{P}_{orb}$ term in fitting the observed spin period evolution which is very evident when the complete 2004 observations are used. This might be the reason for an inaccurate measurement of orbital period. This new set of accurate orbital element measurement can now be used to study the orbital evolution if any when the V0332+53 system goes into its next outburst in future.

3.5 2S1417-624

The X-ray source 2S 1417-624 was first detected using SAS-3 in 1978 (Apparao et al. 1980). This observation of the source revealed pulsations at a frequency of approximately 57 mHz (Kelly et al 1981) and the pulse frequency changed at the rate of $(3-6) \times 10^{-11} Hz/s$. Observations from Einstein X-ray observatory gave the position of the source which were then used for optical identification of the companion star. The companion was found to be a Be-

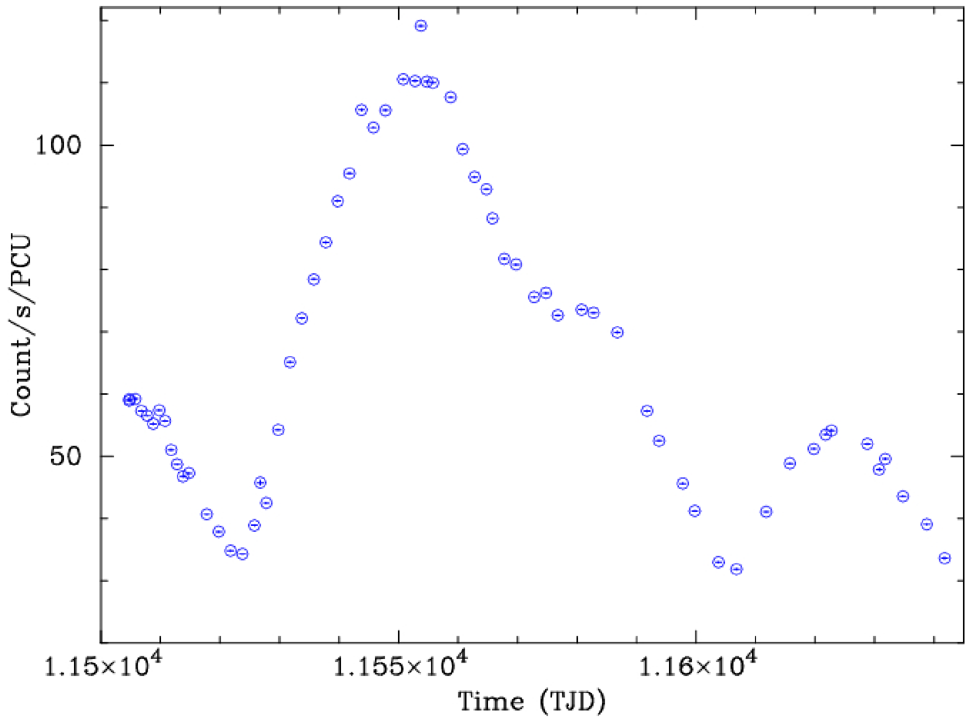

Figure 3.12   Light curve of the 1999 outburst of 2S1417-624

star at a distance of 1.4-11.1 kpc (Grindlay et al. 1984). The next outburst of 2S 1417-624 in 1994 was observed with BATSE on board Compton Gamma Ray Observatory (CGRO). The source was monitored using BATSE over 10 months in a series of six outbursts. The orbital parameters of the system were determined from these observations (Finger, Wilson and Chakrabarty 1996). It was noted that the variation in the observed spin period of the neutron star was due to both spin-up of the pulsar and the binary orbital motion of the pulsar about its companion. To separate these two effects, the authors modelled the spin-up rate as a function of the measured pulse flux, both of which are functions of mass accretion rate. They measured an orbital period $P_{orb} = 42.12 \pm 0.03$ days, $a_x \sin i = 188 \pm 2$ lt-s, eccentricity $e = 0.446 \pm 0.002$, $\omega = 300^o.3 \pm 0^o.6$ and time of periastron $T_\omega =$ TJD 9713.62 ± 0.05. They also measured the mass function $f(M) = 3.9 \pm 0.1 M_\odot$, which places a lower limit of $5.9 M_\odot$ on the mass of the companion star assuming that the neutron star mass is $1.4 M_\odot$. 2S 1417-624 again went into outburst in 1999 and was observed by RXTE-PCA. We present here the spin period analysis of this observation.

The 1999 outburst of 2S1417-624 was monitored using RXTE PCA for more than 200

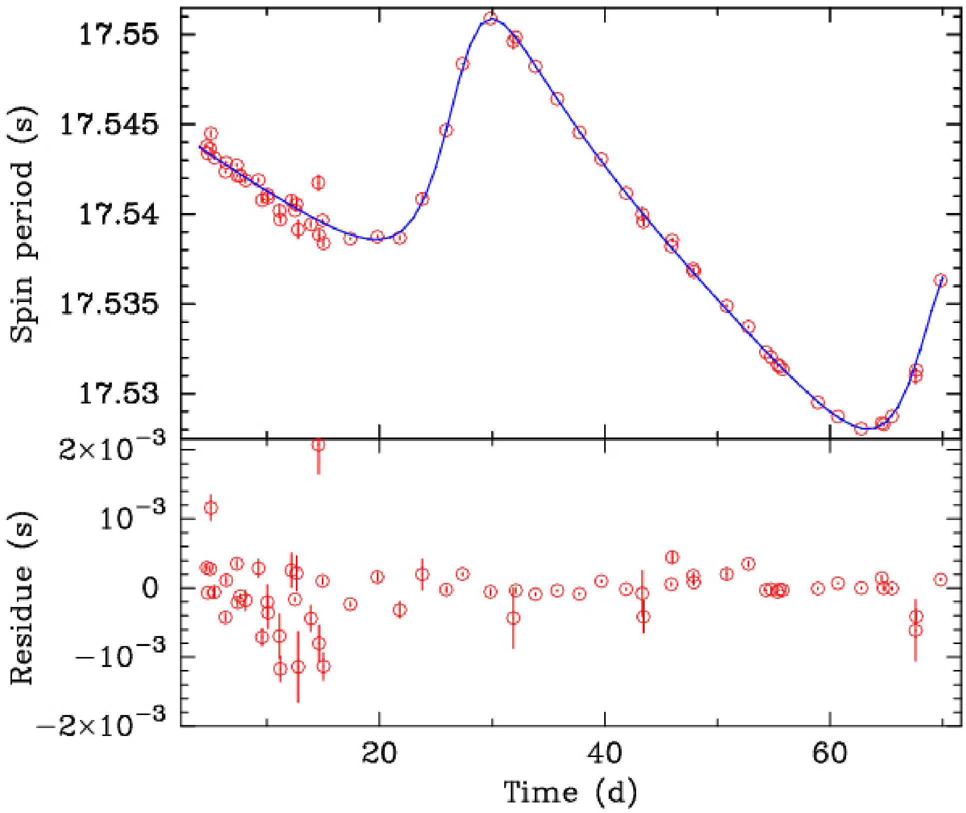

Figure 3.13 Spin period Doppler curve of 2S1417-624

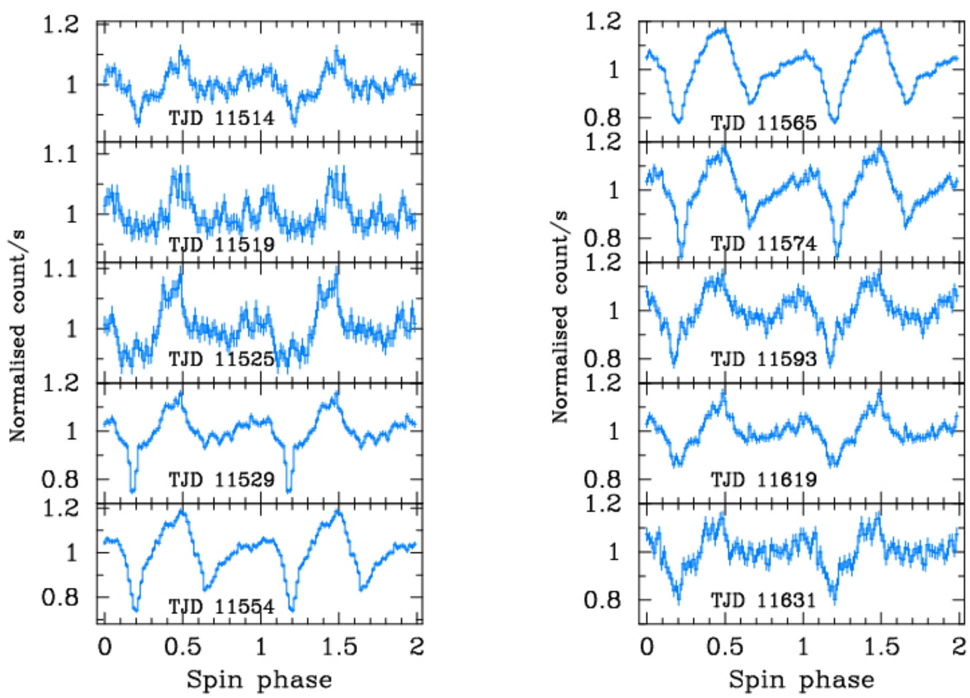

Figure 3.14 Pulse profile evolution of 2S1417-624

days. Figure 3.12 shows the light curve covering 200 days of observations. This light curve was obtained from the best sampled observation of the outburst. It was generated using Standard-II mode data with only photons collected by PCU-0 of the proportional counter array. A total of 211 pointed observations were made by RXTE-PCA during the outburst between TJD 10637 and TJD 11879. We have used only the pointed observations between TJD 11504 to TJD 11600 to get the spin period Doppler curve shown in Figure 3.13. These give 73 spin period measurements. The spin period measurements for time after TJD 11600 cannot be fitted using the simple model $P_{obs} = (P_{spin} + \dot{P}_{spin}t + \ddot{P}_{spin}t^2)\sqrt{\frac{1+v_r/c}{1-v_r/c}}$ and hence not used for orbital element estimation. At the end of the type II outbursts, when the X-ray flux is very small, the spin period evolution can be different, may even have a spin down due to propeller effect. The spin periods were measured using the task `efsearch` of FTOOLS. The χ^2 versus spin period plot generated by `efsearch` was used to measure the error on spin period. The points near the peak of this plot were fitted with a Gaussian and the error on the Gaussian center gave the error on the measured spin period. These errors had to be multiplied by a constant number to get a reduced χ^2 of 1 for the best fit model. The errors on the best fit orbital parameters were estimated using the same method as described in the 4U 0115+63 analysis section. The orbital parameters derived are given in Table 3.5.

Pulse profiles were obtained by folding the Standard-I light curves with the spin period derived from `efsearch`. The pulse profiles presented in Figure 3.14 are averaged over 100 consecutive pulses. The pulse profile shows evolution with progress of the outburst. There are two peaks in the pulse profile which almost merge forming a broad pulse profile at low count rates. As the source count rate increases the two peaks in the pulse profile become more evident and well defined. Due to this changing pulse profile we cannot have a unique pulse profile template for cross correlation which would give the arrival time delay of the pulses for timing analysis.

The orbital parameters we derived from the spin period analysis are in agreement with those derived by Finger et al. (1996) using the BATSE data of the 1994 outburst except for $a_x \sin i$ and ω. The value of $a_x \sin i$ is 19 lt-sec greater than the 1994 value. If we freeze the

Table 3.5 Orbital parameters of 2S 1417-624

Parameter	Values from 1999 outburst	Values from 1994 outburst[a]
P_{spin} (s)	17.544701 ± 0.000008	-
$\dot{P}_{spin}$ (s/d)	$(-3.46 \pm 0.56) \times 10^{-5}$	-
$\ddot{P}_{spin}(s/d^2)$	$(-3.42 \pm 0.47) \times 10^{-6}$	-
$a_x \sin i$ (lt-s)	207.05 ± 0.97	188 ± 2
ω (^{o})	298.85 ± 0.68	300.3 ± 0.6
T_ω (MJD)	51485.059 ± 0.057	49713.62 ± 0.05
e	0.4169 ± 0.0033	0.446 ± 0.002

a: Values reproduced from Finger, Wilson & Chakrabarty, 1996

value of $a_x \sin i$ to 188 lt-sec, the χ^2 value for the best fit is greater than the χ^2 value we get from the parameter set presented in Table 3.5. ω value we get is $1^o.45$ less than the 1994 outburst value. If this change in ω is due to apsidal motion then $\dot{\omega} = -0^o.29\ yr^{-1}$. Assuming a typical Be-star of mass $15M_\odot$, radius $10R_\odot$ and rotational velocity of 400 km/s, we get the apsidal motion constant of the companion star to be $k = -0.003$.

3.6 Conclusions

We have made measurement of the orbital elements of the three Be-/X-ray binaries using spin period measurement during their type II outbursts. Below we summarise the main results from our work.

1. 4U 0115+63 was seen in outburst in 1999 and 2004. Both these outbursts were observed using RXTE-PCA. The results obtained from the spin period analysis of this source are:

   (a) The pulse profile of the source shows similar evolution during both the 1999 and 2004 outburst. At the start and end of the outburst when the X-ray flux is low, the pulse profile is simple with only one prominent peak in the pulse profile. As the X-ray flux during the outburst increases, the pulse profile evolves into a more complex profile showing two well separated peaks during the times near the peak of the outburst. This evolution of pulse profile restricts the accuracy with which we can measure the arrival time of the pulses.

(b) Two new periastron passage measurements were obtained, one for the 1999 outburst and another for the 2004 outburst. Combining these two new measurements with the previous measurements, we find an improved measurement for the orbital period of the binary. No evidence was found for orbital evolution. We derive an upper limit of $\dot{P}_{orb}/P_{orb} \leq 1.1 \times 10^{-6}\ yr^{-1}$ for orbital evolution.

(c) Using the two new measurements of ω with the previous reported measurements, we derive the rate of apsidal motion in this system to be $\dot{\omega} = 0.06 \pm 0.01$. Using the values quoted by Negueruela 1997 for the companion star in the 4U 0115+63 system, we find the value of apsidal motion constant of the companion star $k = 0.1$. This value is slightly higher than that quoted in literature for an 18 $M_\odot$ Be-star.

2. V0332+53 was observed during the 2004 outburst using RXTE-PCA. Our spin period analysis have for the first time given the correct parameters of the binary orbit of this system.

   (a) The spin period of V0332+53 is changing during the outburst at the rate of -4.66×10^{-5} s/d, $\ddot{P}_{spin} \sim 5.414 \times 10^{-7}\ sd^{-2}$. The pulse profile also evolves with the outburst.

   (b) We derived the correct orbital period of this system $P_{orb} = 36.5 \pm 0.28$ d. The measured time of periastron is consistent with T_ω derived from the 1984 outburst of this source (Whitlock, 1989) if we assume the P_{orb} of 36.5 d.

   (c) The $a_x \sin i$ of this system is greater by a factor of 1.7 than the earlier reports from the sparse data available of the 1984 outburst.

   (d) The ω value we derive is 29^o greater than the previous measurement from the 1984 outburst. It is not clear Whether this is due to error in the older measurement or due to apsidal motion of the binary orbit. Apsidal motion in this system can now be searched for with future outburst.

3. 2S 1417-624 was observed in outburst in 1999 and was monitored using RXTE-PCA. We have used this data to derive the orbital parameters of this system.

(a) The spin period of this source shows evolution with the outburst. The spin period changes with $\dot{P}_{spin} \sim -3.46 \times 10^{-5}$ s/d and $\ddot{P}_{spin} \sim -3.42 \times 10^{-6}$ sd^{-2}. The pulse profile also shows evolution with the outburst.

(b) The $a_x \sin i$ we measure is larger than that measured during the 1994 outburst.

(c) The angle of periastron measured during the 1999 outburst is smaller than that measured during the 1994 outburst. If this change in ω is due to apsidal motion then the rate of apsidal motion of the 2S 1417-624 binary orbit is $\dot{\omega} \sim -0^{o}.29\ yr^{-1}$. This corresponds to the apsidal motion constant of -0.003 for a typical Be-star of mass $15M_{\odot}$, radius $10R_{\odot}$ and rotational velocity of 400 km/s.