Chapter 9

Summary and future work

9.1 Summary

In this thesis, we have studied several observational aspects of X-ray pulsars - especially the HMXBs taking advantage of the broadband characteristic of *Suzaku*. In the last chapter, we have studied the long term stability of pulse profiles of an isolated pulsar PSR B1509-58 using *RXTE*/PCA data. The summary of this thesis is as follows:

- In Chapter 3, it is noted that the variation of the cutoff energy with luminosity indicates that NS-HMXBs are divided into two branches. The branching does not seem to be based on the specific nature of the systems being a Be XRB or supergiant HMXB, nor on different beaming patterns characterizing their X-ray emission (as inferred from simultaneous study of their pulse profiles). For a subset of sources taken up, we find linear correlation between cyclotron line energy and the cutoff energy, confirming previous results obtained by *RXTE*

and *Ginga*. The *Suzaku* data revealed for the first time that this linear correlation is not unique, instead, three different branches could be identified. We also observe an anticorrelation between the spectral index and luminosity. Unlike previous works, we did not detect any anticorrelation between the X-ray luminosity and the equivalent width of Kα lines . Finally, we show that the equivalent width and the flux of the iron Kα line are smaller in SFXTs than in classical NS-HMXBs.

- In the first half of Chapter 4, we present updated mid-eclipse time for eclipsing X-ray binaries like Her X-1, Cen X-3, SMC X-1 and LMC X-4 using *Suzaku* data. We also plot the highest energies upto which pulsations could be detected for individual pulsars using *Suzaku*. Such an analysis opened up the diversity in the pulsation behaviour for different energies, even among the sources of the same class.

- In Chapter 5, we report results from analysis of two *Suzaku* observations of SWJ2000.6+3210 made at six months interval which reveal pulsations at $\sim 890s$ for both observations with a much weaker pulse fraction in the second observation. Previous reports on this pulsar had mentioned the spin period to be ~ 1056 s. After an extensive analysis we note pulsations ~ 890 s in the energy band of 0.3-10 keV of XIS for both observations and at high energies up to 40 keV for the second observation. No change in spectral parameters is detected between the observations. We have also analyzed several short observations of the source with *Swift*-XRT and detected only a few percent variation in flux

around a mean value of $3.5 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The results indicates that SWJ2000.6+3210 is a member of persistent Be X-ray binaries which have the same broad characteristics as this source and ruled out the previous classification of this source as a heavily absorbed X-ray binary.

- In Chapter 6, we present broadband pulsation and spectral characteristics of the accreting X-ray pulsar OAO 1657-415 with a 2.2 d long *Suzaku* observation covering its orbital phase range $\sim$ 0.12 - 0.34, with respect to the mid-eclipse. During this observation, the hardness ratio changed by a factor of more than 5, uncorrelated with the intensity variations. In two segments of the observation, lasting for $\sim$ 30-50 ks, the hardness ratio is very high. In these segments the spectrum shows a large absorption column density and correspondingly large equivalent widths of the iron fluorescence lines indicating that the neutron star was passing through clumpy wind. We found no conclusive evidence for the presence of a cyclotron line in the broad band X-ray spectrum with *Suzaku*.

- In Chapter 7, we presented the pulsation and spectral characteristics of the HMXB 4U 0114+65 for *Suzaku* observation covering the part of the orbit that included the previously known low intensity emission of the source (dip) and the egress from this state. This dip had been interpreted in previously published works as an X-ray eclipse. Notably, in this *Suzaku* observation, the count rate during the dip and outside the dip vary by a factor of only 2-4 at odds with the eclipses of other HMXBs, which are characterized by drops in intensity upto two orders of magnitude. The orbital intensity profile of 4U 0114+65 is characterized by a narrow dip in the *RXTE*-ASM light curve and a shallower one in the *Swift*-

BAT energy band different from eclipse ingress/egress of other HMXBs which show sharper ingress/egress in the hard X-rays (> 15 keV). Over the duration of the observation, the X-ray spectrum showed only a moderate absorption column density (N_H - 2-20 $\times$ 10^{22} atoms cm^{-2}) and a relatively low equivalent width of typically 30 eV & 12 eV of the iron K_α and K_β lines respectively; a soft excess below 2 keV is detected outside the dip. These characteristics do not match those typical of the X-ray spectra of HMXBs during eclipse which are characterized by an iron line with a large equivalent width ($\sim$ 1 keV). Both the XIS and PIN data showed clear pulsations during the dip, which was confirmed by using the entire archival data of the IBIS/ISGRI and JEM-X instruments onboard *INTEGRAL*. The results we presented in this chapter put into question the previous interpretation of the dip in the lightcurve of 4U 0114+65 as an X-ray eclipse.

- In Chapter 8, we used the Fourier decomposition technique to investigate the stability of the X-ray pulse profile of a young pulsar PSR B1509-58 by studying the relative amplitudes and the phase differences of its harmonic components with respect to the fundamental using data from the Rossi X-Ray Timing Explorer. The X-ray pulse profile of this source has been analysed for 15 years (1996-2011). The long term average amplitudes of the first, second and third harmonics (and their standard deviation for individual measurements) compared to the fundamental are 36.9 % (1.7 %), 13.4 % (1.9 %) and 9.4 % (1.8 %) respectively. Similarly, the phases of the three harmonics (and standard deviations) with respect to the fundamental are 0.36 (0.06), 1.5 (0.2), 2.5 (0.3)

radian respectively. We do not find any significant variation of the harmonic components of the pulse profile in comparison to the fundamental. Inspite of being a young and very energetic pulsar, the pulse profile of PSR B1509-58 seem to be stable. Therefore, profiles of other sources which are older and less energetic are quite likely to be stable. This is only the second such investigation after a study of the stability of the pulse profile of Crab [454].

9.2 Future works

With an extensive analysis of archived X-ray data obtained from *Suzaku*, we were able to probe into the details of the broadband X-ray spectral study of accreting XRBs as well as detailed timing studies of isolated pulsars could be carried out with *RXTE*. The techniques adopted here will be instrumental in carrying forward such analysis with new satellites like *ASTROSAT* launched last year. The time is now ripe for studying the accretion flow and magnetic field geometry through the study of pulse profiles and X-ray spectra of accretion powered pulsars. Some of the future studies that could be carried out with *ASTROSAT* are enumerated as follows:

- While some sources show an increase in the CRSF line value with luminosity, others are anti-correlated with luminosity. This has been explained by arguing that at different luminosities, different accretion geometries are at play [457]. With sufficiently long data, one could verify this theory. Another interesting aspect is that, with the increase in CRSF line energy, the width of line increases. This is only possible when the viewing angle with respect to the magnetic field is small. Given the large number of CRSF sources that we know, it comes as

a surprise that for all the sources, the viewing angle should be small. This brings us to a conclusion that perhaps, accretion has direct influence on the angle between the spin axis and magnetic field axis [6]. Another unexplored area is how accretion may influence the magnetic field in HMXBs. If we could study how CRSF line energy vary on longer timescales, it would give valuable information on the CRSF shape. This way with *ASTROSAT*, magnetic field distortions in HMXBs can be studied. (With the pseudo Lorentzian profile that we use for modelling spectral lines, distorted cyclotron line has been confirmed for only one HMXB- Cep X-4 so far).

- SFXTs are known to behave erratically, being suddenly luminous for a few hours and then going into quiescense. The exact mechanism for such a behaviour is not known. Besides the simplest theory ascribing clumpy wind nature around these objects, some authors put forward a theory stating that there could be magnetars in SFXTs and perhaps different kinds of mechanisms like magnetic gating and centrifugal barrier are at play [39]. If this were the case, SFXTs should have long spin period and extremely high magnetic fields of the order of 10^{14} G. Not many SFXTs have confirmed pulsations and for those where detected, the spin periods are not sufficiently long. Further, the evidence of cyclotron line in two SFXTs - IGRJ 17544-2619 and IGR J16393-4643 [299, 224] gives a moderate value for magnetic fields in SFXTs and have questioned the existence of magnetars in SFXTs. For *ASTROSAT*, the presence of SSM and LAXPC together will act as an added advantage since any transient activity detected by SSM can be conveniently followed up by LAXPC. Long exposures

for SFXTs during low X-ray flux will also shed much light on the study of SFXTs.

- Another interesting aspect would be to carry out a correlation study between the timing and high energy emission characteristics in both accreting and isolated pulsars. While the spin up/down for accreting pulsars have been easier to understand based on their accretion rate, for isolated pulsars, it is not so straightforward. It has been noticed that even for some isolated pulsars, when they spin slowly, they emit less (eg PSR B1931+24). Having an extremely large effective area, *ASTROSAT* will be very useful in monitoring the pulse profile evolution of short period pulsars (where *RXTE* had left off) which will give us useful clues about the evolution of pulse profiles and associated spectral changes for them. The Fourier decomposition of pulse profiles to check their stability are very useful in probing the usefuness of the pulsars in question for interplanetary spacecraft navigation. Besides these, in timing studies, the study of superorbital modulations is some HMXBs like Her X-1, SMC X-1, LMC X-4 and 4U0114+65 can also be linked to their simultaneous spectral characteristics giving us an overview of the environs of the neutron star. For some Be stars already significant correlation has been found in the timing and spectral properties using *RXTE*-ASM data [458].

- Be stars are known to show two types of outbursts - Type I, associated with periastron passage of compact object through the circumstellar disc of the companion star and Type II, which are uncorrelated to it's orbital phase. A simultaneous observation of X-ray emission from the compact objects as well as

observations of the companion star in other wavelengths by the use of the multi-wavelength instruments in *ASTROSAT* will provide a lot of useful information about the X-ray bursts. Be stars also show two different brances in hardness-intensity diagram, depending on whether the luminosity is below or above a certain value. This could mean two different modes of accretion coming into play [458]. Such studies can also be extended to supergiant systems with long and dedicated studies, perhaps using SSM.

- Another work that is in pipeline is to determine the mid-eclipse time of eclipsing XRBs using the technique described in Chapter 4. This will help us study the orbital evolution of eclipsing XRBs. Some progress has already been made in this regard using *RXTE*-PCA data. We intend to extend the same study with *ASTROSAT*.

- Lastly, it has been found that iron lines in particular are very weak for SFXTs compared to classical HMXBs. This has been associated with difference in interaction of compact objects and companion stars for these two groups. The spectra of SFXTs are also heavily absorbed. SXT onboard *ASTROSAT* will be very useful for study in the soft X-ray regime.