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# Spectroscopic Studies of X-Ray Binary Pulsars

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**Abstract.** Several new features of X-ray binary pulsars are revealed from recent observations with ASCA, RXTE, BeppoSAX and other X-ray observatories. Among these, I will review in this paper some recent progress in spectroscopic studies of accreting X-ray pulsars in binary systems (XBPs). First, I will discuss soft excess features observed in the energy spectra of XBPs and propose that it is a common feature for various subclasses of XBPs. Next I will present some recent results of high resolution spectroscopy with ASCA and Chandra.

*Key words.* X-ray binaries, pulsars, spectra.

## 1. Introduction

Accreting X-ray pulsars in binary systems have a unique type of energy spectra among various classes of X-ray sources (White *et al*. 1983; Nagase 1989). X-ray spectra of supernova remnants, stellar coronae and clusters of galaxies show signature of thermal emission. X-ray spectra of black hole binaries and active galactic nuclei show a non-thermal power law spectra extended over wide energy range toward hard X-rays to $\gamma$-rays. In contrast to these X-ray sources, XBPs fundamentally show a power law spectra with photon indices 1–2 with high-energy turnover at relatively low energies of 10–30 keV. This spectral turnover is considered to be related to the strong magnetic field of the neutron star in XBPs.

Since most XBPs are located in the Galactic plane, their spectra are usually subjected to strong soft X-ray absorption. Massive wind-fed XBPs often exhibit a strong iron emission line at 6.4 keV and the intensity of this fluorescent line provides estimates of the column density of accreting matter surrounding the neutron star in the binary system.

Neutron stars in XBPs are relatively young and theoretically estimated to have a strong magnetic field of the strength $10^{12}$–$10^{13}$ G at the neutron star surface. In fact, the magnetic field of those neutron stars can be measured directly by detection of absorption features in X-ray spectra due to electron cyclotron resonant scattering feature (CRSF). The absorption feature appears at an energy of $E = 11.6B_{12}$ keV where $B_{12}$ is the magnetic field strength in units of $10^{12}$ G. Until late 1980s, this feature has been observed only from two pulsars, Her X-1 (Trümper *et al*. 1978), and 4U0115+63 (Wheaton *et al*. 1979). In early 1990s, the CRSF in the XBP spectrum has been systematically searched with large area proportional counters on board Ginga and detected from a dozen of XBPs (Mihara 1995; Makishima *et al*. 1999). The Ginga observations revealed that the surface magnetic field strengths of XBPs distribute over a narrow range of (1–4) $\times$ $10^{12}$ G as estimated from the CRSFs and the energy of CRSF is correlated with the turnover energy.

In addition to those features of XBP spectra, it was known that some low mass XBPs (LMXBPs), such as Her X-1 (McCray *et al*. 1982; Endo *et al*. 2000) and 4U1626−67 (Kii *et al*. 1986; Angelini *et al*. 1995), show a soft excess component at ∼ 1 keV in the spectra which can be fitted by an additional blackbody emission. Recent progress in observations with ASCA and BeppoSAX revealed that such soft-excess features are seen not only from LMXBPs but also from high mass XBPs (HMXBPs) and transient Be-star XBPs (BeXBPs) that constitute more than 70% among subclasses of XBPs. This soft excess feature in XBP spectra is discussed in the next section.

Spectroscopic studies with the CCD cameras on board ASCA revealed the existence of line-dominated component that is reprocessed by stellar wind surrounding the neutron star and has been highly photoionized due to irradiation by strong X-ray beam from the source. Strong emission lines due to radiative recombination followed by cascades are seen in the spectra of Vela X-1 (Nagase *et al*. 1994) and Cen X-3 (Ebisawa *et al*. 1996). The measurement of recombination lines from highly photoionized heavy elements provides a new tool to study densities, ionization structures, elemental abundances of these elements. Further detailed studies are expected to be carried out by observations with transmission gratings on board Chandra and reflection gratings on board XMM-Newton. Some early results with ASCA and Chandra will be presented in section 3.

## 2. Soft excess features in the spectra of XBPs

A soft-excess feature, a feature of excess intensities at energy below 1 keV in the spectrum over the extrapolation of a power low spectrum fitted to the higher energy, was first detected from a LMXBP, Her X-1 (McCray *et al*. 1982) and later from another LMXBP, 4U 1626−67 (Kii *et al*. 1986). The feature has been intensively investigated thereafter (e.g., Dal Fiume *et al*. 1998; Endo *et al*. 2000 for Her X-1 and Angelini *et al*. 1995; Orlandini *et al*. 1998 for 4U 1626–67). The excess over the power law component can be fitted by a blackbody emission of temperature ∼ 0.1 keV. Although it has been known that the pulses at low energies below 1 keV in Her X-1 show a broad sinusoidal shape, Endo *et al*. (2000) confirmed that this broad pulses at low energies correspond to the blackbody component. This fact supported the interpretation of the blackbody emission to be the result of reprocessing of the hard X-rays at the inner boundary of accretion disk (McCray *et al*. 1982).

Evidence of such a soft excess feature has also been reported from HMXBPs in the Magellanic clouds, LMC X-4 (Woo *et al*. 1996; La Barbera 2001) and SMC X-1 (Marshall *et al*. 1983, Wojdowski *et al*. 1998) owing to a small column density of soft X-ray absorption by intervening interstellar matter toward these directions. The soft component can also be fitted by a blackbody emission of temperatures ∼ 0.1 keV. Those soft excess features in spectra of LMC X-4 and SMC X-1 were also confirmed with the ASCA observations (Paul *et al*. 2001). The spectra observed with ASCA from SMC X-1 and LMC X-4 are basically fitted by a sum of a power law with a photon index $\Gamma = 0.8$–$0.9$ and a blackbody emission of a temperature $kT = 0.16$–$0.19$ keV and an iron fluorescent line at 6.4 keV, although the spectrum of LMC X-4 requires additional broad lines at ∼ 1 and ∼ 2 keV.

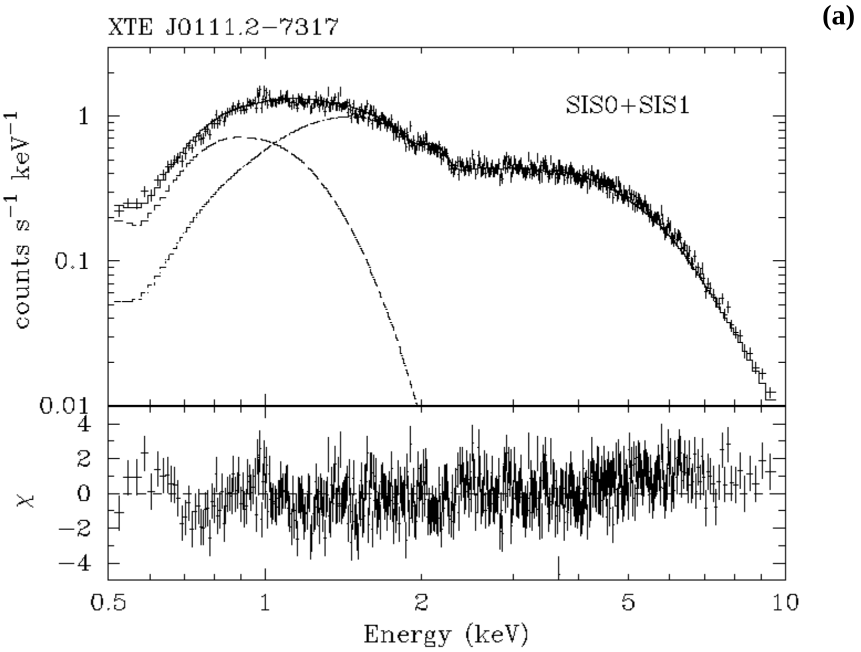
Such a clear soft excess feature, however, has not been reported from BeXBPs till the observations of pulsars in the Magellanic clouds with ASCA, because most of Galactic BeXBPs are subjected to a large soft X-ray absorption. Recently, clear examples of such a soft excess feature were obtained from ASCA observations of BeXBPs in SMC, such as RX J0059.2–7138 (Hughes 1994; Kohno *et al*. 2000) and XTE J0111.2–7317 (Yokogawa *et al*. 2000). The observed and unfolded energy spectra observed with ASCA from a BeXBP, XTE J0111.2−7317 is shown in Fig. 1 demonstrating clear existence of a soft excess component. A model of power law plus blackbody emission can fit the spectrum. The best fit parameters are given as $\Gamma = 0.8$, $kT = 0.15$ keV, and $N_{\rm H} = 2.7 \times 10^{21}$ cm$^{-2}$ for XTE J0111.2−7317 and these values are quite similar with those of SMC X-1 and LMC X-4 mentioned above. Thus, the spectral model that involves a power law and a soft blackbody emission, which is widely adopted to fit the soft-excess spectra observed from LMXBPs and HMXBPs, can be adopted also to the soft-excess feature seen in the spectra of some BeXBPs. This suggests that the emission mechanism and site of the soft component, which can be fitted by a blackbody model, should be common for all subclasses of accreting X-ray pulsars. It should be noted that the fraction of luminosity of the blackbody component is about 10% of the power law component for all the cases of Her X-1, SMC X-1, LMC X-4, and XTE J0111.2−7317.

However, the total X-ray luminosity of XTE J0111.2–7317 is as large as $\sim 2 \times 10^{38}$ erg s$^{-1}$, which is about the same as SMC X-1 and LMC X-4. If the soft excess emission is really blackbody emission from spherical body, the luminosity fraction of about one tenth of the total luminosity implies that the blackbody radii becomes about two order of magnitudes larger than the neutron star radius, assuming spherical emission at the distances of Magellanic clouds. Hence, it is an issue to be investigated further if the interpretation applied to Her X-1 (McCray *et al.* 1982; Endo *et al.* 2000), where the blackbody emission is considered to be the result of reprocessing of the hard X-rays at the inner boundary of accretion disk, is applicable to these XBPs in Magellanic clouds.

To further investigate this problem, Paul *et al.* (2002) performed a pulse-phase resolved spectral analysis of SMC X-1 data obtained with ASCA. The pulse phase dependences of the power-law flux, blackbody flux, and total flux are plotted in the right panel of Fig. 2 together with the energy dependent pulse profiles (left panel). Although statistically limited, the blackbody flux is modulated with a broad sinusoidal shape, as seen in the top of right panel of Fig. 2, contrary to the sharp double peak feature of power-law flux, which is just the same as the pulse profiles at high energies. A phase lag in modulation between the peaks of the blackbody component and that of the power law component is also seen in the figure. Interestingly, these situations are quite similar with those of Her X-1. This fact may give some hints to understand the soft-excess features commonly seen from LMXBPs, HMXBPs and BeXBPs, although some crucial consideration of the binary system geometry is required to explain the large luminosity of pulsating blackbody emission at the distances of Magellanic clouds.

Soft excess features are also observed from X-ray spectra of active galactic nuclei and black hole candidates, and they are considered to be the result of reprocessing by an accretion disk of the original X-ray emission. Hence it is interesting to investigate if the soft excess features observed from XBP spectra are related with the reprocessing by an accretion disk and share common mechanism with those X-ray sources. A merit of investigating soft excess feature using XBP spectra is that it allows us to search pulse modulation of the soft component.

Anomalous X-ray pulsars (AXPs) are also known to have a two component spectra, a steep power law and blackbody emission model (e.g., Mereghetti & Stella 1995).



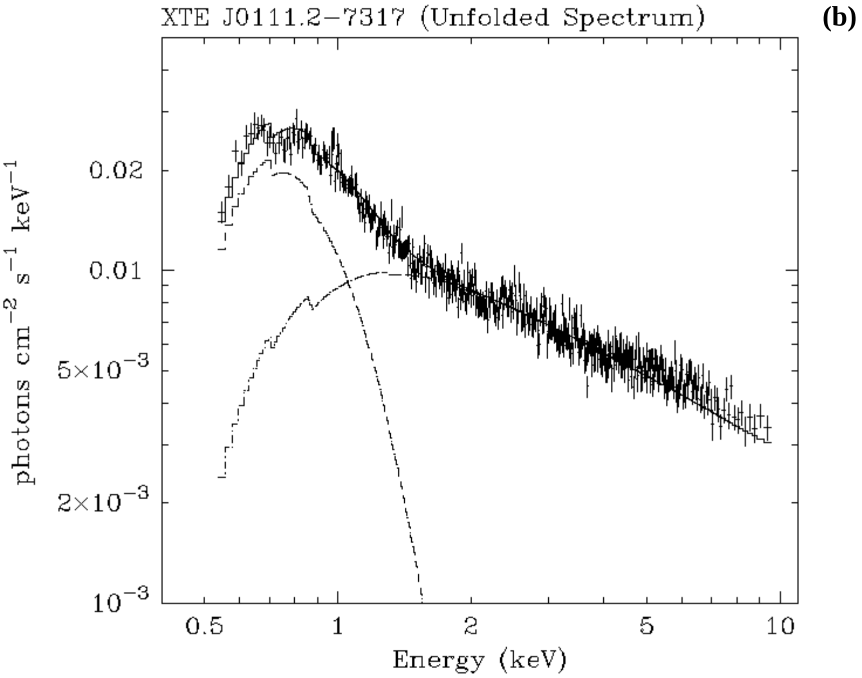


**Figure 1.** **(a)** Energy spectrum of XTE J0111.2–7317 observed with ASCA. The solid line indicates a summed best fit model, and the dotted and dashed lines represent the power law and blackbody components, respectively. **(b)** Unfolded incident spectrum of XTE J0111.2–7317.

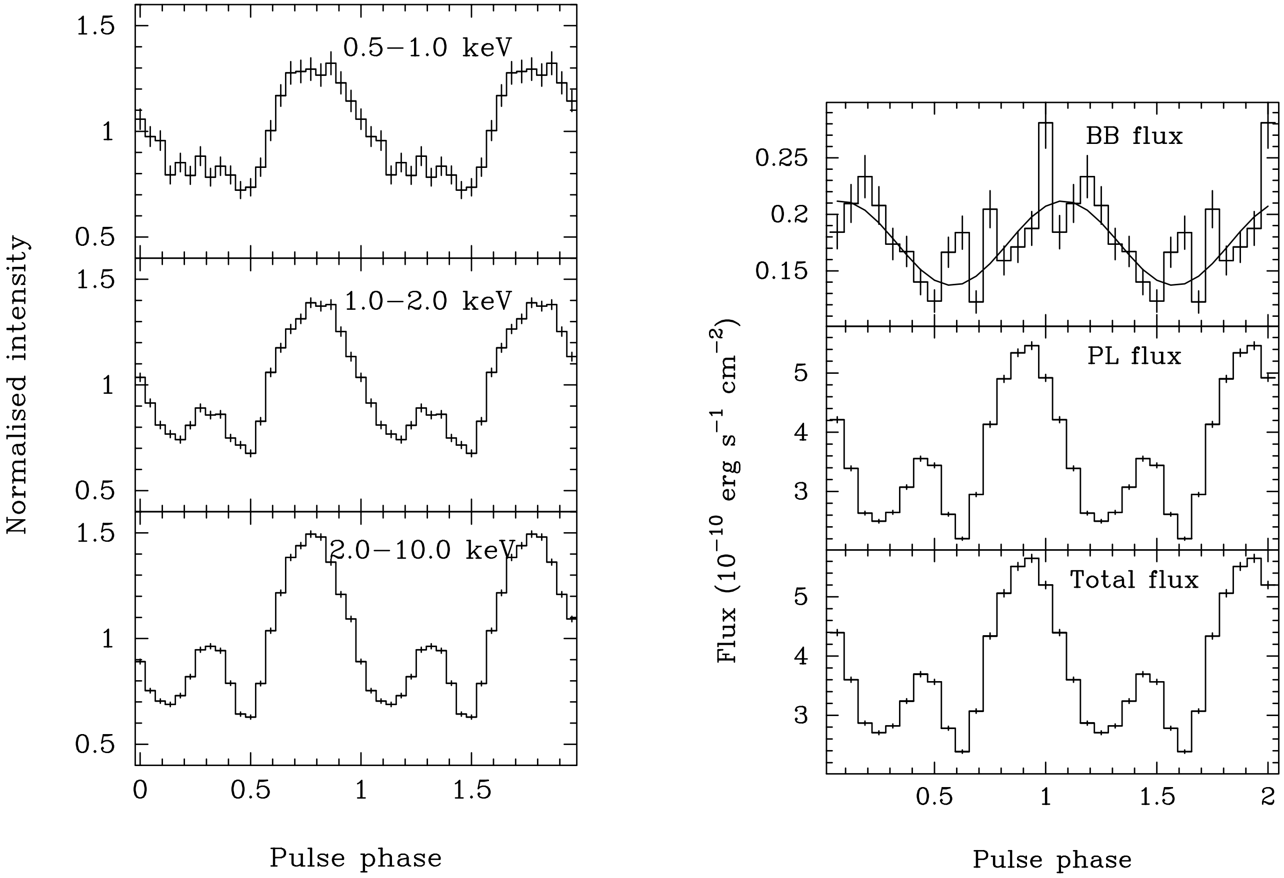


**Figure 2.** **Left panel**: Normalized pulse profiles of SMC X-1 in three energy bands observed with ASCA/GIS in 1993. **Right panel**: Modulation of the blackbody flux, power-law flux, and total flux in the 0.5–10 keV band of SMC X-1 obtained from pulse-phase resolved analysis of the ASCA/GIS spectrum.

However, the blackbody temperatures of AXPs are relatively high and the flux fraction of the blackbody emission to that of the power law component is significantly larger than that in the LMXBP, HMXBP, and BeXBP spectra. Thus the situation in AXPs is somehow different from the soft excess feature seen in other accreting X-ray pulsars. Recently AXPs are interpreted to be not in binary systems but consist of an isolated neutron star with extremely strong magnetic field (i.e., Magnetars) and X-ray emission is due to some different mechanisms (e.g., Thompson & Duncan 1996, Baring & Harding 1998).

## 3. High resolution spectroscopy of XBPs

Solid state imaging spectrometers (SIS, i.e., CCD cameras) on board ASCA had a good energy resolution, and it became possible to resolve K$\alpha$ emission lines of highly ionized (H-like or He-like) atoms of heavy elements, such as Mg, Si, S, Ar, Ca, and Fe, from those of neutral or low-ionization atoms. A few new discoveries were made in the field of accreting X-ray pulsars by utilizing the good resolution spectroscopy with the SIS.

A prominent emission line was detected at 1 keV in the spectrum of 4U 1626–67 and the line was identified as the K$\alpha$ line of He-like Ne (Angelini *et al*. 1995), giving an opportunity to study the nature of the companion star. Recombination lines of He-like and H-like ions of various heavy elements were detected in the spectra observed with ASCA from Vela X-1 (Nagase *et al*. 1994; Sako *et al*. 1999) and Cen X-3 (Ebisawa *et al*. 1996, Wojdowski *et al*. 2001) during their eclipse phase. These detections of recombination lines proved the existence of photoionized plasma spheres of stellar wind that were produced through the irradiation of stellar wind by the X-rays emitted from the neutron star. These observations made it possible to investigate in detail the photoionized structure of stellar wind surrounding the neutron star (Sako *et al*. 1999; Wojdowski *et al*. 2001).

Further detailed studies of plasma structure became possible with the high resolution grating spectrometers on board the recently launched X-ray astronomy observatories, Chandra and XMM-Newton. They have a power to resolve the triplet (resonance, intercombination, and forbidden) lines of He-like ions for various elements from oxygen to iron. Already, many early results of high resolution spectroscopy have been reported from observations of various X-ray sources including XBPs. An interesting example is the detection of blue and red shifted Doppler pair of lines from the LMXBP, 4U1626$-$67 with the Chandra/HETGS (Schulz *et al*. 2001). They resolved the O/Ne complex lines into blue shifted line of 1600–2600 km s$^{-1}$ and red shifted lines of 770–1900 km s$^{-1}$.

High resolution spectroscopy of Vela X-1 with Chandra/HETGS at three different orbital phases revealed dramatic changes of spectra with orbital phase (Sako *et al.* 2001). Spectra at orbital phases 0.0 and 0.5 are dominated by a lot of emission lines (about 50 lines), whereas the spectrum at orbital phase 0.25 consists primarily of continuum radiation with several weak resonant absorption lines. From comparison of spectra observed at orbital phases 0.0 and 0.5, bulk velocity fields of $\sim$ 500 km s$^{-1}$ are detected in the Ne X, Mg XII, and Si XIV K$\alpha$ lines. These observations provide crucial clues to understand the structure and dynamics of circumstellar matter in the binary system. Emission-line dominated spectra similar to Vela X-1 were also observed from SMC X-1 during eclipse and during the X-ray low state, contrary to the continuum dominated spectrum observed during X-ray high, non-eclipse phase (Vrtilek *et al.* 2001). Thus, it is promising that the high resolution observations with Chandra and XMM-Newton will open a new window to diagnose plasma structure and stellar wind dynamics in X-ray binary systems.

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