X-Ray Spectra of Neutron Stars vs. Black Holes

Yasuo Tanaka

[1] Max-Planck-Institut für Extraterrestrische Physik, D-85748 Garching, Germany
[2] Institute of Space and Astronautical Science, Sagamihara, Kanagawa-ken, Japan

Abstract. This paper gives an overview of the observed X-ray spectra of low-mass X-ray binaries containing a weakly-magnetized neutron star (NS-LMXRB) and those of X-ray binaries containing a black hole (BH-XRB). The X-ray spectra of these systems change with luminosity (the mass-accretion rate). At high X-ray luminosities ($L_X > 10^{37}$ erg s^{-1}), while soft thermal emission from the accretion disk dominates, there is a distinct difference in the X-ray spectrum between NS-LMXRBs and BH-XRBs. At a lower luminosity (typically $L_X \sim 10^{37}$ erg s^{-1}), both systems undergo transitions between a soft thermal state and a hard power-law state. The characteristics of these X-ray spectra are discussed.

1 Introduction

A wealth of observational results on X-ray binaries has become available from various X-ray astronomy satellites. Among them, luminous X-ray binaries are those containing either a neutron star (NS-XRB) or a black hole (BH-XRB). This paper gives a brief review of X-ray spectra of these systems. For NS-XRB, we deal here with those containing a weakly magnetized neutron star, for which the magnetic fields has little influence on the accretion flow. They are all low-mass X-ray binaries (NS-LMXRB).

In the following sections, it is shown that there is a distinct difference in the spectral shape between NS-LMXRB and BH-XRB when the luminosity is well above 10^{37} erg s^{-1}. Whereas, at lower luminosities, both systems undergo a radical change in the spectral shape, and the key features that distinguish these two systems go away. The important properties of the X-ray spectra of these systems are discussed. For previous reviews on the subject, see e.g. Tanaka & Lewin 1995; Tanaka & Shibazaki 1996.

In addition, some other related subjects of interest are also discussed.

2 X-Ray Spectrum at High Luminosities

NS-LMXRB at high luminosities ($> 10^{37}$ erg s^{-1}) show a common spectral shape, as shown in Fig. 1. It actually consists of two separate components: a soft component and a hard component. Each of the two components can be individually determined from the analysis of changes of the spectral shape with intensity (see Tanaka 1997).

ESO Symposia: Black Holes in Binaries, pp. 141–148, 2001.

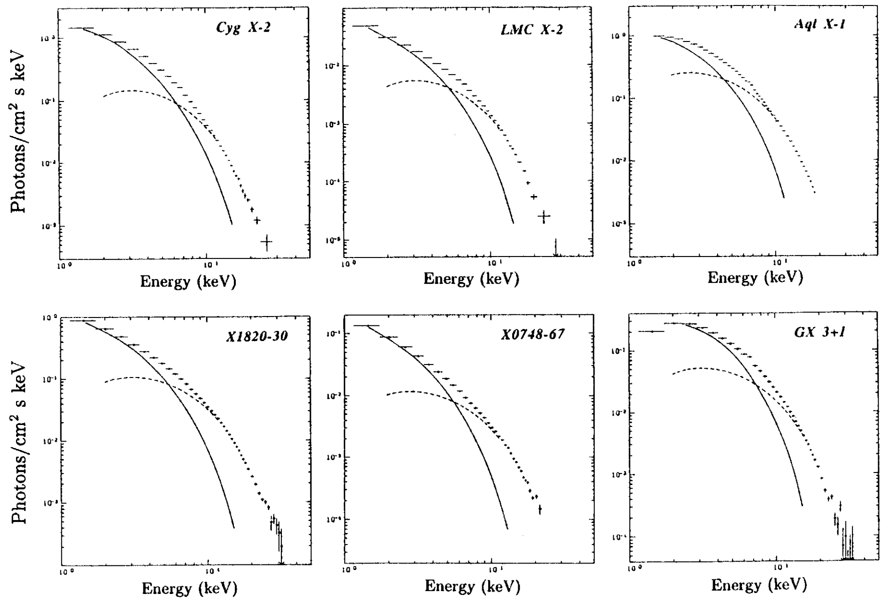

Fig. 1. X-ray photon spectra of NS-LMXRB at high luminosities, each consisting of a soft component (solid curve) and a blackbody component (dashed curve).

The soft component is well expressed by the multicolor blackbody disk model for an optically-thick accretion disk (Mitsuda et al. 1984) based on the standard Shakura-Sunyaev disk model (Shakura & Sunyaev 1973). This multicolor blackbody disc model includes only two free parameters, i.e. r_{in} and kT_{in}, where r_{in} is the innermost disk radius and kT_{in} is the color temperature at r_{in}. The excellent agreement with this model makes it certain that the soft component is the emission from an optically-thick accretion disc. The absence of emission lines that are expected for thin thermal plasma also supports that the disk is indeed optically thick. The observed color temperature kT_{in} is typically $1.4 - 1.5$ keV at $L_X \sim 10^{38}$ erg s^{-1} and goes down as luminosity decreases.

The hard component is best expressed by a modified blackbody spectrum (color temperature $kT_c \sim 2.3 - 2.5$ keV). This component is most probably the emission from the neutron star surface (or an optically-thick boundary layer) where the kinetic energy of accreting matter is eventually thermalized. The fact that this spectrum is very similar to that of X-ray bursts (thermonuclear flashes on the neutron star surface) also supports this interpretation. This blackbody component varies irregularly by as large as a factor of 5 (its maximum luminosity being comparable to the soft component) without changing the shape (see Tanaka 1997). The reason for this variation is unknown.

Table 1. Black-hole binaries established from the mass functions

Source name		Spectrum	Companion	$F(M)$ ($M_\odot$)	BH mass ($M_\odot$)
Cyg X-1	persistent	S+PL	O 9.7 Iab	0.241±0.013	~16 (>7)
LMC X-3	persistent	S+PL	B 3 V	2.3±0.3	>7
LMC X-1	persistent	S+PL	O 7–9 III	0.14±0.05	~6(?)
J0422+32	XNova Per	PL	M 2 V	1.21±0.06	>3.2
0620−003	XNova Mon	S+PL	K 5 V	3.18±0.16	>7.3
1124−684	XNova Mus	S+PL	K 0–4 V	3.1±0.4	~6
1543−475	XN '71,'83,'92	S+PL	A 2 V	0.22±0.02	2.7−7.5
J1655−40	XNova Sco	S+PL	F 3–6	3.24±0.09	7.02±0.22
1705−250	XNova Oph'77	S+PL	K ~3 V	4.0±0.8	~6
2000+251	XNova Vul	S+PL	early K	4.97±0.10	6−7.5
2023+338	XNova Cyg	PL	K 0 IV	6.26±0.31	8−15.5

S+PL: soft + power-law, PL: power law.

For references, see Tanaka & Shibazaki (1996) except for 1705−250 (Remillard et al. 1996) and 1543−475 (Orosz et al. 1998)

There appears to be a distinct difference in the X-ray spectrum between BH-XRB and NS-LMXRB when the X-ray luminosity is well above 10^{37} erg s^{-1}. So far, eleven X-ray binaries including two in the Large Magellanic Cloud have been shown to contain a compact object whose mass lower limit is greater than 3 $M_\odot$, as listed in Table 1. Hence, they are considered to be "reliable" black holes. Among these eleven sources, only three (Cyg X-1, LMC X-1 and LMC X-3) are persistent sources, and they are all high-mass systems. The other eight are all transient sources, and are all low-mass binaries. Of the eleven reliable BH-XRB (Table 1), nine show X-ray spectra of a common characteristic shape, as shown in Fig. 2. It consists of a soft thermal component and a hard power-law tail.

The soft component of BH-XRB is also well expressed by a multicolor blackbody disk model of the same functional form as that of NS-LMXRB, hence identified to be the emission from an optically-thick disk. The observed color temperature kT_{in} is typically $\sim$ 1.2 keV at $L_X \sim 10^{38}$ erg s^{-1}, significantly lower than that for NS-LMXRB of the same luminosity level.

On the other hand, a blackbody component that is always present in the spectra of luminous ($L_X > 10^{37}$ erg s^{-1}) NS-LMXRB is absent in the BH-XRB spectra. A fundamental difference between a neutron star and a black hole is the presence or absence of a solid surface. We consider the absence of a blackbody component to be a strong indication of an accreting black hole.

Furthermore, for a standard accretion disk model, kT_{in} scales as $\propto M_X^{-1/4}$ for a given accretion rate, where M_X is the compact object mass. That the observed kT_{in} for BH-XRB is significantly lower than that for NS-LMXRB, is consistent with a larger M_X. For a non- or slowly spinning black hole, r_{in}

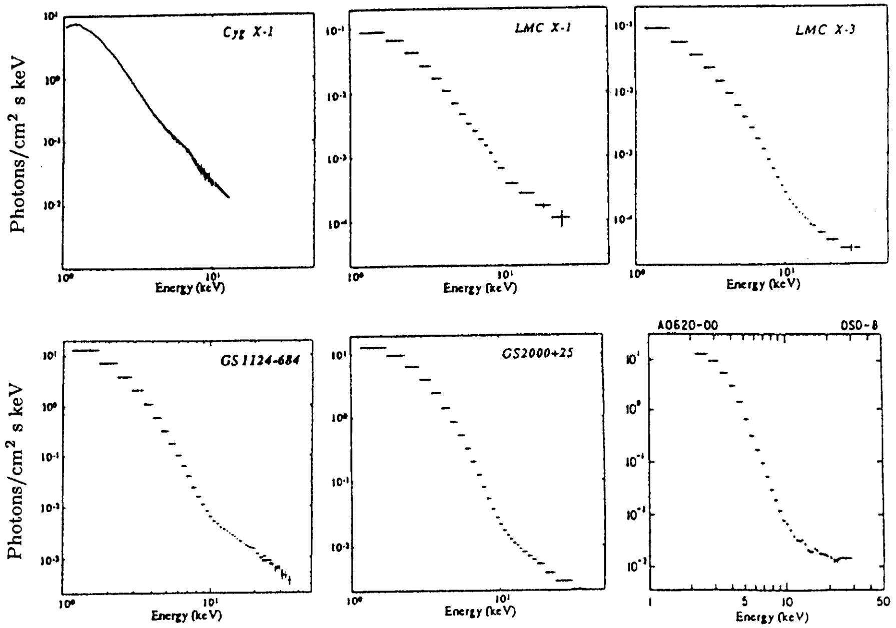

Fig. 2. X-ray photon spectra of reliable BH-XRB at high luminosities.

may represent three Schwarzschild radii, hence proportional to the compact object mass. If the source distance is known, r_{in} is obtained from the observed L_X and kT_{in} of the soft component. The estimated values of r_{in} for most BH-XRB turned out to be larger by a factor of 3 to 4 than those for NS-LMXRB, implying that the compact objects are more massive by this factor than a neutron star (see Tanaka & Lewin 1995; Tanaka 1997 for more detail). These results make it convincing that such a "soft + hard-tail" spectrum is a signature of an accreting black hole. Note that an estimate of the actual mass requires the consideration of general relativistic effects and a correction of the color temperature to the effective temperature (see e.g. Hanawa 1989; Ebisawa, Mitsuda & Hanawa 1991; Zhang, Cui & Chen 1997).

It is of interest that two systems GRO J1655–40 and GRS 1915+105 (black-hole candidate, see below), both superluminal jet sources, show significantly higher kT_{in} than other BH-XRB. Zhang, Cui & Chen (1997) suggest that the black holes in these systems rapidly spin in the same direction as the accretion disk. This could be related to the formation of relativistic jets.

In addition to these reliable BH-XRB, so far about fourteen more low-mass transients (including GRS 1915+105) are found to show the characteristic spectral shape (soft + power-law tail) when $L_X > 10^{37}$ erg s^{-1}. They are also believed to be BH-LMXRB. In fact, X-ray bursts (a definitive signature of an accreting neutron star) have never been detected in any of them.

The hard power-law tail that characterizes the BH-XRB spectrum extends well over 100 keV without a cut-off, sometimes observed up to ~ 1 MeV (e.g. Grove et al. 1998). The luminosity of the hard component relative to the soft component varies irregularly by an extremely large factor, from a comparable luminosity down to 1 ~ 2 orders of magnitude less (see Fig. 3a). The photon index of the hard tail remains fixed at 2.0 – 2.5 against these changes. The origin of the power-law tail is still unclear. It is generally considered to be produced by Comptonization of soft photons by high-energy electrons. Yet, how to accelerate electrons to such high energies and to maintain their energy against Compton cooling are serious problems. The fact that such a power-law tail is absent in the luminous NS-LMXRB might suggest that it is formed in the gap between the innermost stable orbit and the Schwarzschild radius. (In the case of a neutron star, the gap is presumably small.) Such a model has been proposed (see e.g. Laurent & Titarchuk 1999 and references therein), though it contains the above-mentioned problems as well.

It is to be remarked that among eleven reliable BH-XRB, GS 2023+338 and GRO J0422+32, are exceptions. Both sources showed an approximately single power-law spectrum even at high luminosities. The reason why they did not show the soft + hard-tail spectrum is still unknown.

3 X-Ray Spectrum at Lower Luminosities

Both NS-LMXRB and BH-XRB undergo a dramatic change in the spectral shape around a certain luminosity level between a soft thermal state (high state) as described in Section 3.1 and a hard state (low state) with an approximately single power-law form, as shown in Fig. 3. This transition between the two spectral states is considered to be a fundamental property of accretion disks regardless of whether the compact object is a neutron star or a black hole. The transition occurs at about $L_X \sim 10^{37}$ erg s^{-1} or a mass-accretion rate around 10^{17} g s^{-1}, but it might vary from source to source and even from one transition to another (see Tanaka & Shibazaki 1996, and references therein). Associated with the spectral change, the time variability also changes. As sources enter into the hard state, rapid large-amplitude intensity fluctuations (flickering) build up on all time scales down to milliseconds.

The power-law spectrum in the hard state is substantially harder than the power-law tail of BH-XRB in the soft state, and shows a high-energy cut-off. The observed photon indices in the hard state are in the range 1.7–1.9 for both BH-XRB and NS-LMXRB. Hence, once they go into the hard state, the distinction in spectral shape between these two systems is lost. The photon index in this state also remains remarkably constant against large luminosity changes. It is important to note that the power law emission in the hard state and that of the BH-XRB in the soft state are qualitatively different with respect to the presence or absence (at least up to the highest energy observed) of a cut-off and the variations with time.

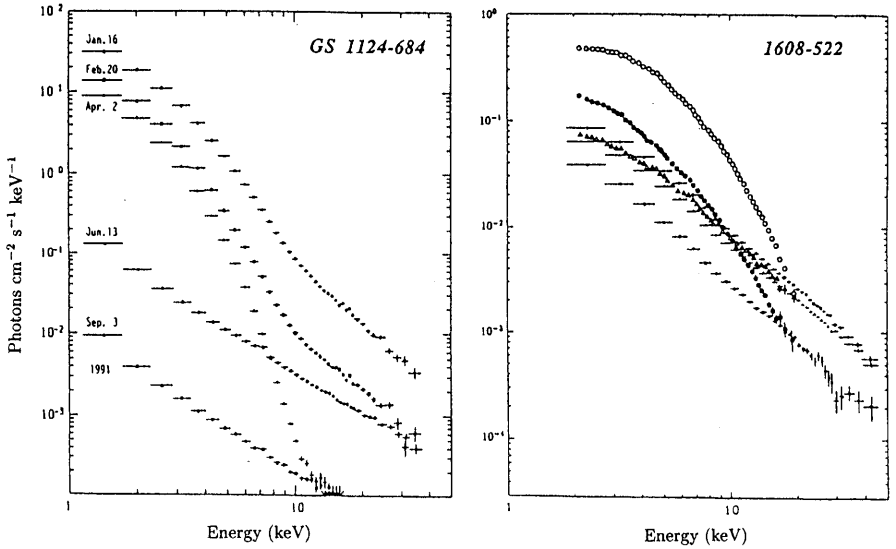

Fig. 3. Changes in the spectral shape with luminosity. (a) The spectra of the BH-LMXRB GS 1124-684, and (b) the spectra of the NS-LMXRB 4U 1608–522.

It is important to note that, despite a radical change in the spectral shape, the transition between the two spectral states does not cause a big jump in the total luminosity before and after transition (see e.g. Zhang et al. 1997 for the 1996 transition of Cyg X-1). Hence, it is not due to switching between a radiation-dominated accretion flow and an advection-dominated accretion flow (ADAF).

Transition from a soft state to a hard state has been considered as due to a change in the disk structure. There is evidence that a quick build-up of an optically-thin hot plasma occurs when a source goes into the hard state. For instance, when X 1608–522 was about to go into the hard state, the spectra of X-ray bursts (blackbody emission from the neutron star surface) also began to show a significant hard tail (Nakumura et al. 1989). Note that, for this effect, NS-LMXRB spectrum may mimic "soft + hard tail" near the critical mass-accretion rate. Therefore, it is important that the spectral distinction between BH-XRB and NS-LMXRB holds only when L_X is well above 10^{37} erg s^{-1}. The observed power-law spectra with a cut-off can be reproduced by thermal Comptonization of soft photons (e.g. Sunyaev & Titarchuk 1980). Yet, the mechanism of the transition and other striking properties (constancy of the photon index against large intensity changes, different photon-index values before and after transition, and flickering) remain to be explained.

It is worth noting that the properties of X-ray binaries in the hard state are strikingly similar to those of AGN, i.e. the same power-law index, and strong variations on time scales down to the shortest Keplerian periods. These similarities suggest that the basic process of accretion is essentially the same in both systems, despite huge differences in scale and power.

3.1 Reflection Component

When an optically-thick disk is illuminated with X-rays, part of the X-rays are reflected by Thomson scattering. This reflection component, predicted by Lightman & White (1988), was first discovered from AGN (Pounds et al. 1990). Since photoabsorption dominates Thomson scattering at low energies, the reflected component is characterized by a hard continuum, much harder than the incident spectrum, and a K-absorption edge of iron accompanied by a fluorescent emission line. In particular, the iron lines from Seyfert galaxies are found to be relativistically broadened as described by Fabian et al. (1989), which provides clear evidence for the general relativistic effect unique to the close vicinity of a massive black hole (see e.g. Tanaka et al. 1995).

Since the reflection component provides a useful diagnostic tool of an accretion disk, it has been studied also for X-ray binaries, in particular Cyg X-1. The ASCA spectrum (the best spectral resolution so far available) of Cyg X-1 in the hard state shows a weak narrow line and a shallow K-edge of iron

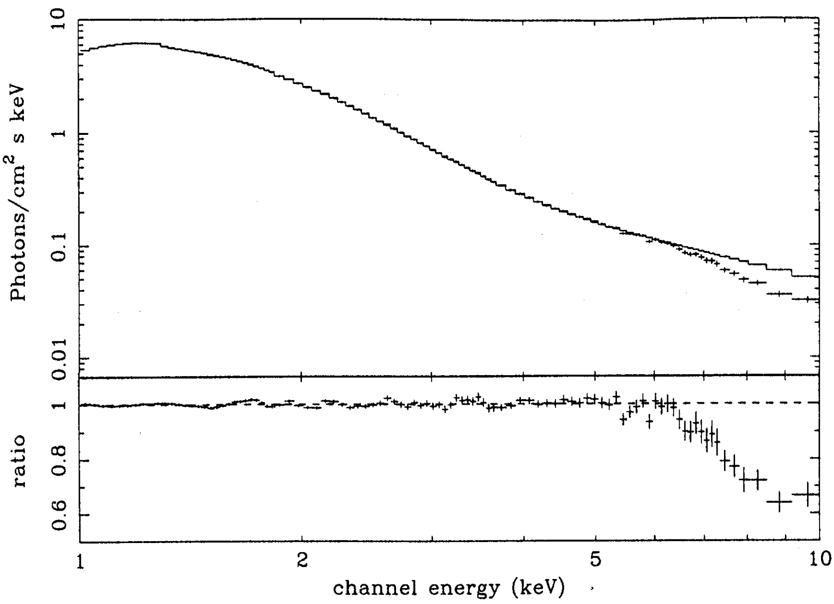

Fig. 4. Cyg X-1 spectrum in the soft state (upper panel) observed with ASCA SIS, and the ratio to the best-fit model determined below 6 keV (lower panel).

(Ebisawa et al. 1996; Done & Życki 1999), indicating a relatively minor contribution of the reflection component. In the soft state, the effect of reflection appears significantly different. As shown in Fig. 4, intensity decreases substantially above 7 keV due to iron K-absorption, but the structure is quite broad (smeared edge). On the other hand, the fluorescence line that must be emitted is hardly visible.

The situation in X-ray binaries seems to be more complicated than in Seyfert galaxies. Because of an orders of magnitude smaller size scale, the effect of photoionization, particularly at high luminosities, becomes much more important. Ross, Fabian & Young (1999) demonstrated a pronounced dependence of the line intensity and relative contribution of the reflected component on the ionization degree of the disk. The line profile and the edge structure are degraded by Compton broadening and also relativistic blurring (if near the black hole). Thus, detailed investigation of the properties of reflection will lead to understanding of the fundamental questions on the disk structures in the two states and where and how the illuminating X-rays are generated.

References

1. Done, C., Życki, P.T., 1999, MNRAS, 305, 457
2. Ebisawa, K., Mitsuda, K., Hanawa, T., 1991, ApJ, 367, 213
3. Ebisawa, K., Ueda, Y., Inoue, H., Tanaka, Y., White, N.E., 1996, ApJ, 467, 419
4. Fabian, A.C., Rees, M.J., Stella, L., White, N.E., 1989, MNRAS, 238, 729
5. Grove, J.E. et al., 1998, ApJ, 500, 899
6. Hanawa, T., 1989, ApJ, 341, 948
7. Laurent, P., Titarchuk, L., 1999, ApJ, 511, 289
8. Lightman, A.P., White, T.R., 1988, ApJ, 335, 57
9. Mitsuda, K. et al., 1984, PASJ, 36, 741
10. Nakamura, N. et al., 1989, PASJ, 41, 617
11. Orosz, J.A., Jain, R.K., Baylin, C.D., McClintock, J.E., Remillard, R.A., 1998, ApJ, 499, 375
12. Pounds, K.A., Nandra, K., Stewart, G.C., George, I.M., Fabian, A.C., 1990, Nature, 344, 132
13. Remillard, R.A., Orosz, J.A., McClintock, J.E., Baylin, C.D., 1996, ApJ, 459, 226
14. Ross, R.R., Fabian, A.C., Young, A.J., 1999, MNRAS, 306, 461
15. Shakura, N.I., Sunyaev, R.A., 1973, A&A, 24, 337
16. Sunyaev, R.A., Titarchuk, L.G., 1980, A&A, 86, 121
17. Tanaka, Y., Lewin, W.H.G., 1995, in Cambridge Astrophys. Ser. Vol. 26, X-Ray Binaries, eds. W.H.G. Lewin, J. van Paradijs & E.P.J. van den Heuvel (Cambridge: Cambridge Univ. Press), 126
18. Tanaka, Y., Shibazaki, N., 1996, ARA&A, 34, 607
19. Tanaka, Y., 1997, in LNP Vol. 487, Accretion Disks - New Aspects (Berlin: Springer Verlag) 1
20. Tanaka, Y. et al., 1995, Nature, 375, 659
21. Zhang, S.N., Cui, W., Chen, W., 1997, ApJ, 482, L155
22. Zhang, S.N. et al., 1997, ApJ, 477, L95