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Observation of Black Holes in X-ray Binaries

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Abstract. Recent results of X-ray observations of Galactic X-ray binaries containing black holes are reviewed. So far, eleven X-ray binaries are confirmed to contain a black hole based on the mass determined from the optical mass functions. Study of these X-ray binaries shows that accreting black holes exhibit a characteristic X-ray spectrum that is distinct from that of accreting neutron stars. In total, about two dozen X-ray binaries show this characteristic spectrum and are believed to contain a black hole. Most of them are low-mass X-ray binaries and are transients. The statistics indicate the presence of several hundred or more black holes in quiescent X-ray binaries in our galaxy. The observed properties of accreting black holes are discussed, and other, related subjects are also presented.

1. Introduction

A wealth of observational results on X-ray binaries has been available from various X-ray astronomy satellites. As a result, the presence of black holes in some galactic X-ray binaries has become beyond doubt.

The most convincing evidence for black holes comes from mass estimations based on the optically-determined mass functions of certain X-ray binaries. According to the current theory, a neutron star more massive than $3M_\odot$ cannot exist stably and will collapse into a black hole. Therefore, a compact object with mass exceeding $3M_\odot$ is believed to be a black hole. As shown in Section 2, eleven X-ray binaries are currently known to contain compact objects with mass lower limits greater than $3M_\odot$; hence, they are "reliable" black holes.

In order to find other black-hole signatures, we examine X-ray properties of these binaries containing "reliable" black holes. It is shown in Section 3 that, at high luminosities, there is a distinct difference in the shape of X-ray spectra between binaries containing a black hole (BH-XRB) and those containing a neutron star (NS-XRB). Based on various discussions in Section 3, the distinct spectral shape that most of the reliable BH-XRB commonly exhibit is considered to be a convincing signature of accreting black holes.

Relativistic effects that are expected from the unique environment of black holes have not been found, as yet. Relativistic jets have been suspected to be a

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signature of black holes. However, as discussed in Section 4, it is still thought to be inconclusive.

In addition, some other, related subjects of interest are also discussed in this paper. For the previous reviews on these subjects, see Tanaka & Lewin (1995) and Tanaka & Shibazaki (1996).

2. Mass Functions: Mass Lower Limit of Compact Objects

So far, eleven X-ray binaries, including two in the Large Magellanic Cloud, have been shown to contain compact objects with mass lower limits greater than $3M_\odot$, as listed in Table 1. 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 that underwent X-ray nova outbursts and are all low-mass binaries.

Table 1. Black-hole binaries established from the mass functions. For references, see Tanaka & Shibazaki (1996), except for 1705–250 (Remillard et al. 1996) and 1543–475 (Orosz et al. 1998).

Source name		Spectrum	Companion	$F(M)$ ($M_\odot$)	BH mass ($M_\odot$)
Cyg X-1	persistent	US+PL	O 9.7 Iab	0.241±0.013	~16 (>7)
LMC X-3	persistent	US+PL	B 3 V	2.3±0.3	>7
LMC X-1	persistent	US+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	US+PL	K 5 V	3.18±0.16	>7.3
1124−684	XNova Mus	US+PL	K 0−4 V	3.1±0.4	~6
1543−475	XN '71,'83,'92	US+PL	A 2 V	0.22±0.02	2.7−7.5
J1655−40	XNova Sco	US+PL	F 3−6	3.24±0.09	7.02±0.22
1705−250	XNova Oph'77	US+PL	K ~3 V	4.0±0.8	~6
2000+251	XNova Vul	US+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

US+PL: ultrasoft + power-law, PL: power law.

3. Energy Spectrum

3.1. X-ray Spectrum at High Luminosities

A distinct difference in the X-ray spectrum appears between BH-XRB and NS-LMXRB when the X-ray luminosity L_X is high, typically $L_X > 10^{37}$ erg s^{-1}.

Of eleven reliable BH-XRB (Table 1), nine show X-ray spectra of a common characteristic shape, as shown in Figure 1. It consists of a soft thermal component and a hard power-law tail.

The soft component is well expressed by the multicolor-blackbody disk model describing the emission from an optically-thick accretion disk (Mitsuda et al. 1984) in the framework of the standard Shakura-Sunyaev disk model (Shakura & Sunyaev 1973). This multicolor-blackbody disk model includes only two free

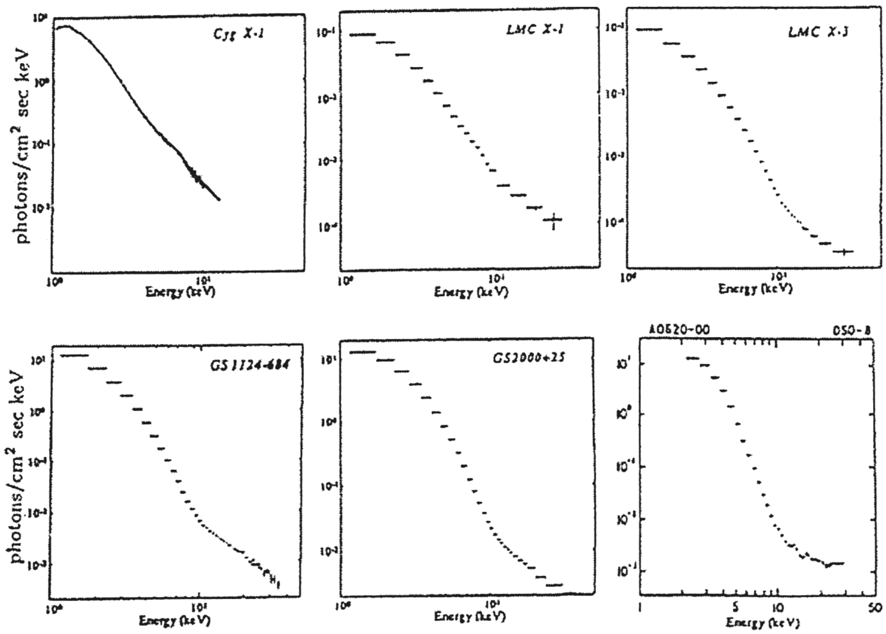

Figure 1. X-ray photon spectra of reliable BH-XRB at high luminosities.

parameters, i.e., $S(E) = S(r_{in}, T_{in}; E)$, where r_{in} is the innermost disk radius and T_{in} is the color temperature at r_{in}. The excellent agreement of the soft component of the observed spectrum with this model makes it certain that the soft component is the emission from an optically-thick accretion disk. The ASCA observations of several luminous LMXRB support the idea that the disk is indeed optically thick because of the absence of emission lines (except for a very weak iron line). The observed color temperature T_{in} is typically ~ 1.2 keV for $L_X \sim 10^{38}$ erg s^{-1}and decreases as luminosity decreases.

On the other hand, the X-ray spectra of NS-XRB at high luminosities are distinctly different from those of BH-XRB. Since neutron stars with high magnetic fields manifest themselves as pulsars, we deal here with X-ray binaries containing a weakly magnetized neutron star, which are all low-mass X-ray binaries (NS-LMXRB). NS-LMXRB at high luminosities ($> 10^{37}$ erg s^{-1}) show a common spectral shape, as shown in Figure 2. It looks like a thermal bremsstrahlung spectrum. However, a detailed study shows that it consists of two separate components: a soft component and a hard component, as shown in Figure 2. Each of the two components can be determined by analyzing changes of the spectral shape with intensity (see Tanaka 1997).

The soft component of NS-LMXRB is also expressed by a multicolor-blackbody spectrum of the same functional form as that of BH-XRB and, hence,

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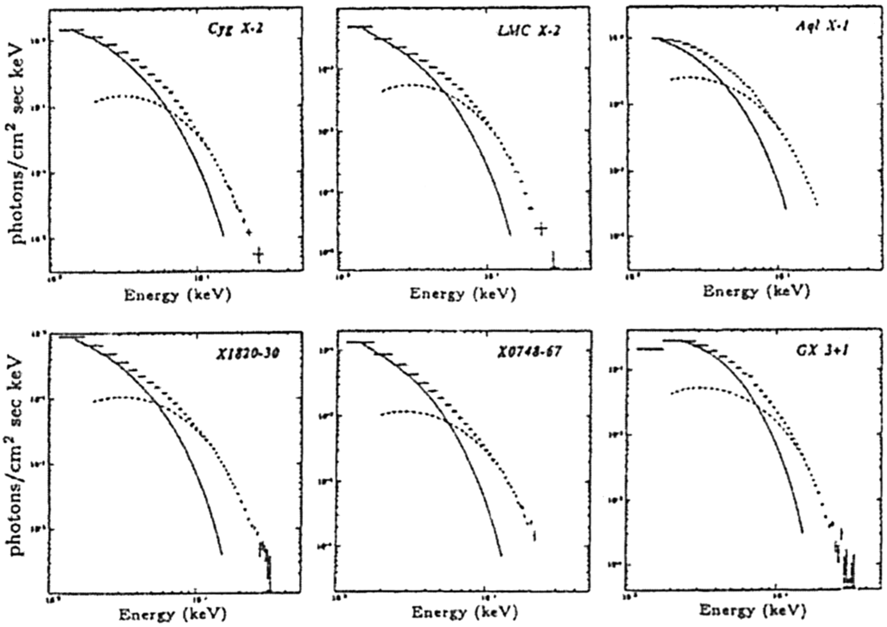

Figure 2. X-ray photon spectra of NS-LMXRB at high luminosities, each consisting of a soft component (solid curve) and a blackbody component (dashed curve).

identified as the emission from an optically-thick accretion disk. The observed color temperature T_{in} is typically 1.4–1.5 keV for $L_X \sim 10^{38}$ erg s^{-1}, significantly higher than that for the BH-XRB of the same luminosity level.

The hard component is best expressed by a modified blackbody spectrum of a single temperature (a color temperature kT ~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 flash on the neutron star surface) also supports this interpretation.

A fundamental difference between a neutron star and a black hole is the presence or absence of a solid surface. NS-LMXRB at high luminosities always show the blackbody component expected from a solid surface, whereas such a blackbody component is absent in the BH-XRB spectra. We consider the absence of a blackbody component to be a strong indication for an accreting black hole.

In addition, for a standard accretion-disk model, the temperature of the innermost accretion disk, T_{in}, scales as $\propto M_X^{-1/4}$ for a given accretion rate, where M_X is the compact object's mass. In fact, the observed kT_{in} for BH-XRB is significantly lower than that for NS-LMXRB. If the source distance is known, one can estimate r_{in} from the observed L_X and kT_{in} of the soft component. The quantity r_{in} is proportional to the compact object's mass. The estimated values of r_{in} for BH-XRB turn out to be larger by a factor of 3 to 4 than those for NS-LMXRB, implying that the compact objects are much more massive than a neutron star (see Tanaka & Lewin 1995; Tanaka 1997 for more detail). Note that derivation of the actual mass requires corrections for the general-relativistic effects and conversion of the color temperature to the effective temperature (see, e.g., Hanawa 1989; Ebisawa, Mitsuda, & Hanawa 1991; Zhang, Cui, & Chen 1997a). These results make it convincing that such a "soft + hard-tail" spectrum is a signature of an accreting black hole.

In addition to the eleven reliable BH-XRB listed in Table 1, about fourteen more low-mass transients are so far known to have the same characteristic spectral shape (soft + power-law tail). 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 from any of them.

The hard power-law tail that characterizes the BH-XRB spectrum extends well beyond 100 keV without a cutoff, sometimes observed up to ~ 1 MeV (e.g., see Grove et al. 1998). The luminosity of the hard component relative to the soft component varies irregularly with time by an extremely large factor, from a comparable luminosity down to $1 \sim 2$ orders of magnitude less (see, e.g., Figure 3a), whereas the photon index of the hard tail remains fixed at 2.0–2.5 against luminosity 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 is far from being understood. In particular, how to accelerate electrons to such high energies and maintain their energy against Compton cooling is a serious problem. The fact that such a power-law tail is absent in the luminous NS-LMXRB suggests that the site of formation is in the gap between the last stable orbit and the Schwarzschild radius. (For the case of a neutron star, the gap is presumably small.) Such a model has been proposed. See, for example, Laurent & Titarchuk (1999) and references therein. Yet, the source of high-energy electrons also remains a problem.

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.

3.2. X-ray Spectrum at Lower Luminosities and Spectral State Transitions

BH-XRB undergo a dramatic change in the spectral shape around a certain luminosity level between a soft thermal state (high state) and a hard power-law state (low state). NS-LMXRB also exhibit a similar change. Therefore, this transition between the two spectral states is considered to be a fundamental property of an accretion disk regardless of whether the compact object is a black hole or a neutron star.

As the luminosity decreases below a certain level, the spectrum changes from the shape described in Section 3.1 into an approximately single power-law

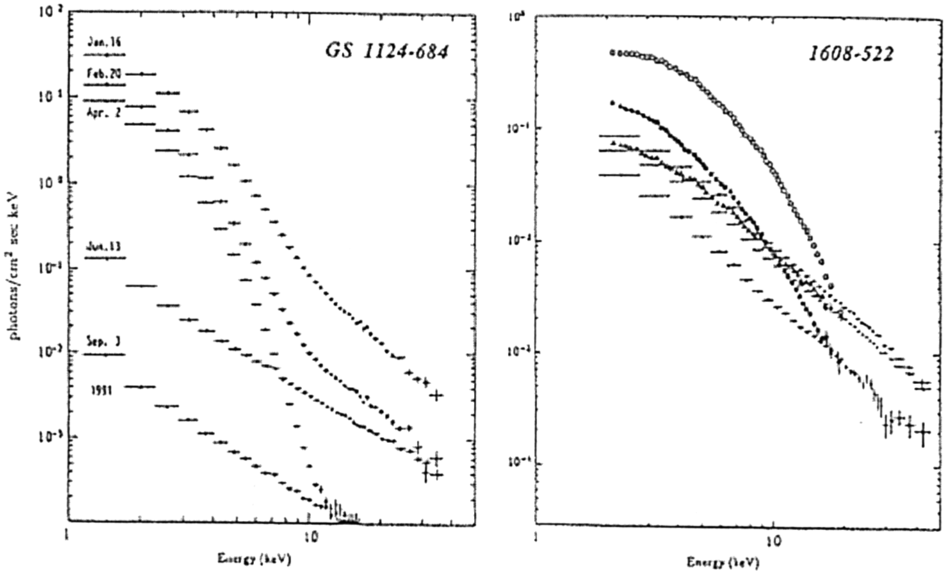

Figure 3. Changes in the spectral shape with luminosity. (a) The spectra of the BH-LMXRB GS 1124–684, and (b) the spectra of the NS-LMXRB 4U 1608–522.

form, and vice versa, as shown in Figure 3. Not only a spectral change, it is accompanied by a remarkable change in time variability. As sources enter into the hard state, fast, large-amplitude intensity fluctuations (flickering) build up in all time scales down to ms.

The power-law spectrum in the hard state is substantially harder than the power-law tail of BH-XRB in the soft (high-luminosity) state and shows a high-energy cutoff. 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, there is no distinction in spectral shape between these two systems. 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 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 cutoff and the time variabilities, suggesting a different mechanism.

The available data indicate that the transition occurs across a luminosity level $L_X \sim 10^{37}$ erg s^{-1}or a mass accretion rate around 10^{17} g s^{-1}, but this value might vary from source to source and even from one transition to another (see Tanaka & Shibazaki 1996 and references therein). It is important to note that, despite a drastic change in the spectral shape, the transition between the two spectral states does not seem to cause a big jump in the total luminosity before and after the transition (see, e.g., Zhang et al. 1997b 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 sudden build-up of an optically-thin, hot plasma occurs when a source goes into the hard state (see Tanaka 1997). The observed power-law spectra with a cutoff can be reproduced by thermal Comptonization of soft photons (e.g., see Sunyaev & Titarchuk 1980). Yet, the mechanism of the transition and other striking properties (constancy of the photon index against large intensity changes and for the particular photon-index values before and after transition) 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 in the following points:

1. AGN commonly show power-law spectra with the photon indices distributed within a fairly small range around 1.7, very similar to the values for X-ray binaries in the hard state.

2. The photon index remains constant against large changes in luminosity in both systems.

3. Both systems exhibit high time-variabilities on various 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 the scale and power.

3.3. Reflection Component

When X-rays from the inner part of the disk illuminate surrounding, cool (neutral or partially ionized) material, presumably the accretion disk, some of the X-rays are reflected by Thomson scattering. This reflection component, predicted by Lightman & White (1988), was first discovered from AGN by 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. (The effects of elements other than iron are usually insignificant.) In particular, the iron lines from Seyfert galaxies are found to be relativistically broadened, as given by Fabian et al. (1989), providing unique evidence for a general-relativistic effect near a massive black hole (see, e.g., Tanaka et al. 1995).

Since the reflection component provides a useful diagnostic tool of an accretion disk, this has been studied also for X-ray binaries, Cyg X-1 in particular. 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 (Ebisawa et al. 1996; Done & Życki 1999), indicating a relatively minor contribution by the reflection component. Presence of a relativistically broadened line is not evident. In the soft state, the Cyg X-1 spectrum appears somewhat different. As shown in Figure 4, intensity decreases significantly above 7 keV due to iron K-absorption, but it is quite broad (smeared edge). On the other hand, no accompanying fluorescent line is visible.

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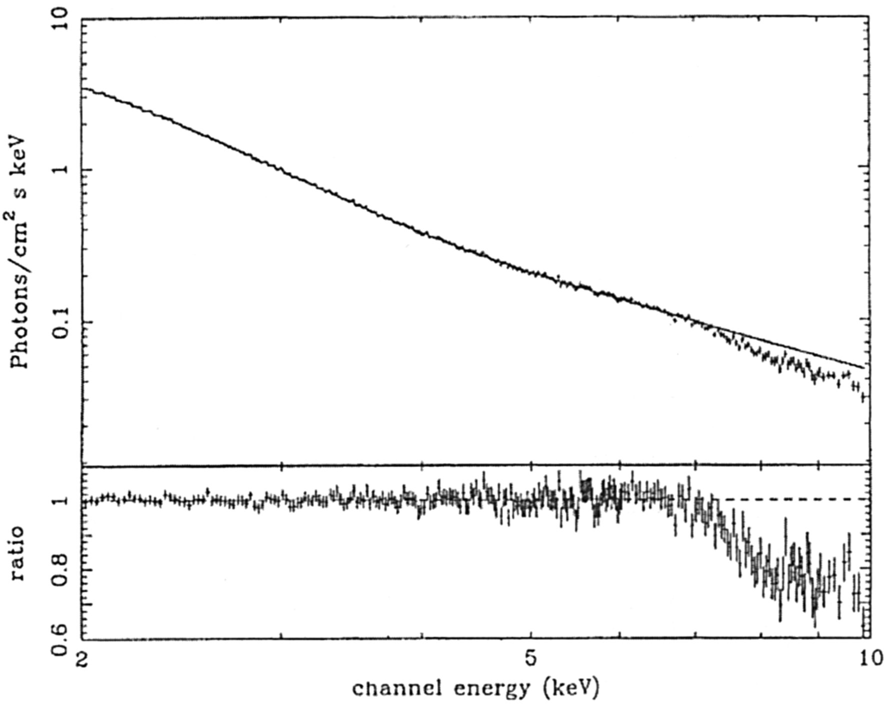

Figure 4. X-ray spectrum of Cyg X-1 in the soft state (upper panel) observed with ASCA/GIS, and the ratio to the best-fit model determined below 6 keV (lower panel).

The situation in X-ray binaries seems to be more complicated than in Seyfert galaxies. Because of an orders-of-magnitude-smaller scale size, the effect of photoionization becomes much more important, particularly at high luminosities. 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 emission-line profile and the edge structure will also be degraded by Compton broadening in addition to relativistic blurring (for emission near the black hole). A more fundamental question on which these reflection features depend is how the disk is illuminated, i.e., whether the X-ray sources are located above the accretion disk or whether a hot plasma covering the disk Comptonizes the disk photons to produce X-rays. Further investigations are required.

4. Relativistic Jets

The sources that show relativistic jets in our Galaxy are listed in Table 2, taken from a recent review by Mirabel & Rodriguez (1999). For references, see Mirabel & Rodriguez (1999). In particular, three BH-XRB, GRS 1915+105, GRO J1655-

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40, and XTE J1748-288, showed superluminal radio jets with an intrinsic velocity exceeding $0.9c$ during transient outbursts.

Table 2. Sources of Relativistic Jets in the Galaxy [(1)].

Source	Compact object	V_{app}[(2)]	V_{int}[(3)]	Θ[(4)]
GRS 1915+105	black hole	$1.2c$–$1.7c$	$0.92c$–$0.98c$	66°–70°
GRO J1655-40	black hole	$1.1c$	$0.92c$	72°–85°
XTE J1748-288	black hole	$1.3c$	$> 0.9c$	
SS 433	neutron star ?	$0.26c$	$0.26c$	79°
Cyg X-3	neutron star ?	$\sim 0.3c$	$\sim 0.3c$	$> 70°$
CI Cam	neutron star ?	$\sim 0.15c$	$\sim 0.15c$	$> 70°$
Sco X-1	neutron star	$\sim 0.5c$		
Cir X-1	neutron star	$\geq 0.1c$	$\geq 0.1c$	$> 70°$
1E 1740.7-294	black hole [(*)]			
GRS 1758-258	black hole [(*)]			

[(1)] Sources reported as of December 1998.
[(2)] V_{app} is the apparent speed of the highest velocity component of the ejecta.
[(3)] V_{int} is the intrinsic velocity of the ejecta.
[(4)] Θ is the angle between the direction of motion of the ejecta with the line of sight.

[(*)] Note by the present author: Other than the radio jets, no firm evidence for a black hole as yet (see text).

Other than those listed in Table 1, radio outbursts were detected in association with the transient X-ray outbursts of several other BH- and NS-XRB (see Hjellming & Han 1995). From the observed characteristics, Hjellming & Rupen (1995) suggest that these radio outbursts may have been relativistic jets, as well. These facts indicate that relativistic jets alone are no evidence for a black hole, although there could be possible systematic differences in the speed and power of jets between BH- and NS-XRB. 1E 1740.7-294 and GRS 1758-258 are shown to be associated with well-collimated radio structures, most probably relativistic jets. These sources are sometimes suspected to be BH-XRB (see Table 1). However, they show X-ray spectra of a single power-law form typical of low-luminosity XRB (see Section 3.2), and no firm evidence for being a black hole has yet been obtained.

Relativistic mass ejection seems to occur when sudden accretion into the inner disk takes place regardless of the kind of the compact object. Harmon et al. (1995) showed that the radio jets from GRO J1655–40 were emitted shortly following hard X-ray bursts. From simultaneous X-ray, infrared, and radio observations of GRS 1915+105, Mirabel et al. (1998) concluded that the ejection of relativistic plasma occurs during an episode when the inner accretion disk is replenished (according to the interpretation of spectral changes by Belloni et al. 1997a, 1997b).

5. Population of Black-Hole Binaries

In the past years, many soft X-ray transient outbursts (X-ray novae) have been detected, and most of them have later turned out to be BH-LMXRB. The average rate of detection of outbursts is $\sim 2\,\mathrm{y}^{-1}$ in the last several years. There must be many more BH-LMXRB in our Galaxy that are currently in a quiescent state but that will eventually undergo an outburst. Based on the current statistics, the total number of them has been estimated (see Tanaka & Shibazaki 1996; Romani 1998). The large unknowns are the average recurrence time of outburst of BH-LMXRB and their galactic distribution. However, modest estimations show that at least least several hundred, and probably more than one thousand, BH-LMXRB are present in the whole Galaxy. This implies that the population of BH-LMXRB is no smaller, and is possibly larger, than that of NS-LMXRB. These results may provide important clues to the problem of formation and evolution of BH-LMXRB.

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