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X-RAY NOVAE

Y. Tanaka

Max-Planck Institut für Extraterrestrische Physik, D-85748 Garching, Germany and Institute of Space and Astronautical Science, Yoshinodai, Sagamihara, Kanagawa 229, Japan

N. Shibazaki

Department of Physics, Rikkyo University, Nishi-Ikebukuro, Toshima-ku, Tokyo 171, Japan

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1. INTRODUCTION

In our galaxy there exist about 200 X-ray binaries containing a neutron star or a black hole (van Paradijs 1995). About one third of them are not persistently visible and are detected as transient sources. The transient sources are divided into two different classes: one belonging to the high-mass X-ray binaries (HMXBs) and the other belonging to the low-mass X-ray binaries (LMXBs). The HMXBs are systems with an O or B star companion, while the LMXBs have primarily K or M dwarf companions.

Most of the HMXB transients are Be-binary pulsars. They exhibit outbursts with regular intervals that are considered to be periodic encounters of a neutron star in an eccentric orbit with a stellar wind zone around an early-type star. Because their X-ray spectra are significantly harder than those of LMXBs, they are called "hard X-ray transients."

LMXB transients are characterized by episodic X-ray outbursts. During an outburst, they show a soft X-ray spectrum that is characteristic of the persistent luminous LMXBs and do not exhibit regular pulsations. These are generally called "soft X-ray transients," or "X-ray novae." X-ray outbursts are accompanied by optical outbursts. The optical outbursts are considered to be due

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to reprocessing of the X rays in the accretion disk, which indicates that the companion has a low intrinsic luminosity and thus a low mass. Since the X-ray and optical properties of the soft X-ray transients during outbursts are so similar to those of the persistent LMXBs, the soft X-ray transients are most likely the same class of object, i.e. a close binary system composed of a Roche-lobe-filling low-mass star and either a weakly magnetized neutron star or a black hole. Soft X-ray transients belong to this class of object. Many soft X-ray transients exhibit recurrent outbursts with intervals ranging from several months to tens of years. Perhaps all of them are recurrent.

Because all LMXBs are variable, the distinction of X-ray novae from persistent sources undergoing a large intensity increase is sometimes ambiguous. We employ the following criteria for X-ray novae for the convenience of this review:

1. The X-ray flux increases by more than two orders of magnitude within several days.

   In reality, the pre-outburst flux levels were often below the detection limit of the instruments. In the light of the recent results, a more appropriate criterion would be an increase of X-ray intensity from below 10^{33} erg s^{-1} to well above 10^{37} erg s^{-1} in the range 1–10 keV, whenever a distance estimate is available. Hereafter, the quoted X-ray luminosity values are those in the 1–10 keV range, unless otherwise mentioned. Because of the uncertainties in the distance of many of these objects, the estimated luminosities may be uncertain by a factor of 2 or sometimes even more.

2. The flux declines on time scales of several tens of days to more than one hundred days, and it eventually returns to the pre-outburst level.

   The light curves are various: Some show a rather monotonic decline, but in many cases the light curves are complex. In some cases, the sources are “turned on” and remain persistently visible for a year or longer after an outburst.

3. In recurrent transients, the duration of an outburst is shorter than the “quiescent” (pre- or post-outburst) period: The duty ratio over a long time span is smaller than unity.

4. There is no fixed periodicity of recurrence.

An outburst of X-ray novae is caused by a sudden dramatic increase of mass accretion onto the compact object. During an outburst, the optical counterpart also brightens significantly (> 5 mag) with a spectrum characteristic of an X-ray illuminated disk. Radio outbursts are often observed during X-ray outbursts. In some cases, relativistic jets such as seen from active galactic nuclei are found, though these are much smaller in scale and power. This evidence shows that an eruptive mass ejection occurs as a result of sudden mass accretion.

In this review, we first summarize the observed results of X-ray novae in Section 2. Following the classification of X-ray novae in Section 2.1, the properties of X-ray outbursts and the optical counterparts are briefly described in Section 2.2, and the associated radio outbursts are outlined in Section 2.3.

The long quiescent period of X-ray novae also allows detailed optical measurements of the secondary star. This is not feasible for persistent sources in which the optical flux is dominated by that from the accretion disk. Optical photometry and spectroscopy allow measurements of the type of the secondary star, the orbital parameters, and in favorable cases the mass functions (see Section 2.2).

The remarkable increase of sensitivity obtained with focusing X-ray telescopes has enabled detailed X-ray studies of these systems in the quiescent state to be made, especially using *ROSAT* and *ASCA.* The results of these observations are summarized in Section 2.4. X-ray emission during the quiescent period provides diagnostic information on the condition of lowest-rate mass accretion to the compact objects, which is crucial for understanding the outburst mechanism. In addition, because the accretion rate in X-ray novae varies over several orders of magnitude, these objects are extremely useful for studying the physics of mass accretion and the relationship of the X-ray properties to the mass accretion rate.

In Section 3, the following major questions are discussed in the light of the recent observational results:

1. What conditions make LMXBs persistent or transient?

2. What are the mechanisms of X-ray nova outbursts?

3. How many still "sleeping" LMXBs are there in the Galaxy?

The first question is addressed in Section 3.1, based on various observed characteristics of X-ray novae. The optical observations during quiescence also give an essential clue to the understanding of this problem. The mass accretion during the quiescent period is a new subject as discussed in Section 3.2, and has an important relation to the outburst mechanism.

The mechanisms of X-ray nova outbursts are discussed in Section 3.3. It is often noted that X-ray novae are similar to dwarf novae in several respects (e.g. van Paradijs & Verbunt 1984, Priedhorsky & Holt 1987). Mechanisms of X-ray novae outbursts have so far been discussed primarily based on two different kinds of models that were originally proposed to explain dwarf novae outbursts: disk instability models and mass transfer instability models.

From the current statistics of X-ray novae, we infer that still many more LMXBs await discovery, in particular those containing a black hole, which are in quiescence at present. We estimate the total number of them in Section 3.4. This issue relates to the problems of the origin of LMXB systems and of their birth rate.

For previous reviews related to X-ray novae, see White et al (1984), Priedhorsky & Holt (1987), Cowley (1992), van Paradijs & McClintock (1995), and Tanaka & Lewin (1995). For a general review of the properties of X-ray binaries, see e.g. White et al (1995).

2. OBSERVATIONAL RESULTS

2.1 *Classification of Soft X-Ray Transients*

In the recent catalog of X-ray binaries by van Paradijs (1995), which contains 124 LMXBs, 41 are categorized as transient sources and the remaining 83 as persistent sources. About 30 transients show a maximum flux greater than 100 μJy in 2–10 keV, which is roughly equal to $\sim$0.1 the Crab Nebula intensity (the Crab Nebula is sometimes used for a flux standard: The Crab Nebula intensity = 1 Crab). These transients are listed in Table 1 along with more recently discovered transients observed by the *Compton Gamma-Ray Observatory* (*CGRO*) and *GRANAT*. Note, however, that Table 1 includes those for which sufficient outburst data are not available. Some of them are simply new detections of previously uncatalogued sources and may not fulfill the criteria for X-ray novae given in Section 1. Of these 33 bright transients, 18 belong to the class of black-hole LMXBs, i.e. LMXBs for which the compact object is a black hole. Remarkably, all the black-hole LMXBs currently known are transient sources. The three known persistent black-hole X-ray binaries are all high-mass systems; two are in the Large Magellanic Cloud (LMC X-1, LMC X-3), leaving only one (Cyg X-1) in our own galaxy. In contrast, amongst the LMXBs of which the compact object is a neutron star (neutron-star LMXBs), only 1/7 are transients. Although the above classification is not entirely secure, this contrast is robust and quite striking.

We briefly summarize below how LMXBs are classified into black-hole binaries and neutron-star binaries.

2.1.1 X-RAY BURST: A FIRM SIGNATURE OF A NEUTRON-STAR LMXB Matter accumulated on the surface of a neutron star in a LMXB undergoes a thermonuclear flash under certain conditions and generates an X-ray burst. To be exact, there are two distinctly different types of X-ray burst [designated Type I and Type II by Hoffman et al (1978)]. Type I burst are the ones due to thermonuclear flashes and exhibit gradual softening of the blackbody spectrum (cooling) during the burst decay, whereas Type II bursts are those caused by spasmodic accretion and do not show cooling with time. Thus, if a Type I burst is found from a source, it is an unequivocal signature that the compact object is a neutron star. Since Type II bursts are observed only from 1730–335 (see Section 2.2.1) and possibly Cir X-1, we hereafter call Type I bursts simply X-ray bursts.

Burst sources comprise a large fraction ($\sim 40\%$) of LMXBs, but not all the neutron-star LMXBs are known to produce X-ray bursts. This fraction is uncertain because bursts are not always frequent and some bursts could have been missed. Also, very luminous ($\sim 10^{38}$ erg s^{-1}) neutron-star LMXBs do not produce bursts. Among X-ray novae, X-ray bursts have been seen from about ten sources (see Table 1). They are definitely neutron-star LMXBs. For details of X-ray bursts, see e.g. a recent review by Lewin et al (1995).

2.1.2 MASS FUNCTION A precise optical measurement of the radial velocity curve of the secondary star provides a determination of the mass function, which, in turn, gives an absolute minimum mass of the compact primary. A more accurate estimate of the mass of the primary can be obtained with additional information on the secondary mass and the orbital inclination.

According to the current theory, a neutron star more massive than 3 $M_\odot$ cannot be stable and will collapse into a black hole. Therefore, a lower limit to the mass exceeding 3 $M_\odot$ has been considered to be reliable evidence for a black hole. The relativistic effects that are unique to black holes have not been confirmed as yet.

So far nine sources including three high-mass systems are known to have a compact primary with a mass $> 3\ M_\odot$. They are listed in Table 2. All six low-mass systems are X-ray novae.

2.1.3 X-RAY SPECTRUM X-ray emission is powered by mass accretion. If the compact object of a LMXB is a neutron star, X rays are considered to be emitted from two regions: an accretion disk and an optically thick neutron star envelope. As shown in Figure 1*a*, the observed spectra of luminous ($\geq 10^{37}$ erg s^{-1}) neutron-star LMXBs consist of two components, a blackbody component, which is most probably the emission from the neutron star envelope (an optically thick boundary layer), and a softer component, most probably from the accretion disk (Mitsuda et al 1984, White et al 1988). These two components can be separately determined observationally. The soft component is represented by a multicolored blackbody spectrum expected from an optically thick accretion disk (Mitsuda et al 1984, Tanaka 1992b). The characteristic temperature of the soft component is ~ 1.5 keV (color temperature) when the X-ray luminosity L_X is $\sim 10^{38}$ erg s^{-1} and decreases as luminosity goes down. However, the above properties hold for $L_X < 10^{37}$ erg s^{-1}. At $L_X < 10^{37}$ erg s^{-1}, the X-ray

Table 1 List of X-ray novae

a. Black-hole LMXBs

Source[a] name	Outburst year	Spectrum[b]	Distance (kpc)	Optical[c] counterpart	Companion type	Orbital period (hour)	Ref.[d]
J0422+32 N Per	'92	PL	2	V518 Per	M0–5, M2V	5.09	1
0620–003 N Mon	'17, '75	U+PL	0.9	V616 Mon	K5V	7.75	1
1009–45 N Vel	'93	U+PL		[5]			4
1124–684 N Mus	'91	U+PL	3		K0–4V	10.4	1
1354–645 N	'67(?), '87	U+PL		BW Cir			2,3
1524–617 N	'74	U+PL	4.4 [6]	KY TrA			2,3
1543–475 N	'71, '83, '92	U+PL	4		A2V		2,3
1630–472 RN	(∼ 600d)	U+PL					2,3
J1655–40 N Sco	'94	U+PL	3.2		F3–6	62.7	1
1659–487 RN (GX339–4)	(∼ 460d)	U+PL	4?	V821 Ara		14.83	2,3
1705–250 N Oph	'77	U+PL		V2107 Oph			2,3
1716–249 N Oph (J1719–24)	'93	PL		[8]			7
1730–312 N	'94	U+PL					9
1741–322 N	'77	U+PL					2,3
1846+031 N	'85	U+PL					2,3
1915+105 N Aq1	'92	U+PL	12.5	IR star			1
2000+251 N Vul	'88	U+PL	2	QZ Vul	early K	8.26	1
2023+338 N Cyg	'38, '56, '79(?),'89	PL	3.5	V404 Cyg	K0IV	155.4	1

[a]N: Nova outburst, RN: Recurrent nova outbursts (recurrent period).
[b]PL: Power law, U+PL: Ultrasoft + power law.
[c]IR: infrared star.
[d]References:
1. see Section 2, and references therein
2. van Paradijs 1995, and references therein
3. Tanaka & Lewin 1995, and references therein
4. Lapshov et al 1993, 1994; Sunyaev et al 1994
5. Della Valle & Benetti 1993
6. Barret et al 1995
7. Ballet et al 1993; Harmon et al 1993; Sunyaev et al 1994
8. Della Valle et al 1993; Della Valle et al 1994
9. Borozdin et al 1995

spectral characteristics of the sources change and the spectra become power law in form (see Section 2.1.4).

In contrast, nearly 20 sources commonly show a spectral shape characterized by a soft component and a hard power-law tail as shown in Figure 1*b*, which is distinctly different from the spectra of neutron-star LMXBs. The blackbody component seen in the neutron-star LMXBs is conspicuously absent. The soft components of these sources are also represented by a multicolored blackbody spectrum, from an optically thick accretion disk but they have a significantly lower characteristic temperature ($\leq$ 1.2 keV) than those observed from luminous neutron-star LMXBs and hence the spectra are called "ultrasoft." The

b. Neutron-star LMXBs

Source[a] name	Outburst year	Remark[b]	Distance (kpc)	Optical[c] counterpart	Companion type	Orbital period (hour)	Ref.[d]
0748–676		B		UY Vol		3.82	2,3
1455–314 N (Cen X-4)	’69,’79	B	1.2	V822 Cen	K5–7	15.10	1
1516–569 RN (Cir X-1)		B	9	BR Cir		398	2,3
1608–522 RN		B	3.6	IR			1
1658–298		B		V2134 Oph		7.11	2,3
1730–335 RN (Rapid Burster)		B	10	in Lil 1			1
1730–220 N	’72						2
1731–260		B					2
1735–28							2
1742–289		B(?)			K dwarf?		2
1744–361		LM or HM?					2
1745–203				in NGC 6440			2
1803–245		LM or HM?					2
1908+005 RN (Aq1 X-1)		B	2.5	V1333 Aql	G8–K0V	19.0	1
1947+300		LM or HM?					4

[a]N: Nova outburst, RN: Recurrent nova outbursts
[b]B: Burster, LM or HM?: Uncertain whether it is a low-mass system or a high-mass system.
[c]IR: infrared star.
[d]References: 1. see Section 2, and references therein
2. van Paradijs 1995, and references therein
3. White, Nagase & Parmar 1995, and references therein
4. Borozdin et al 1990

power-law component changes its intensity irregularly and is unrelated to the intensity of the soft component. The photon index remains essentially constant at around ~ 2.5 during the intensity changes (Tanaka 1992b).

White et al (1984) first suggested that this ultrasoft spectrum is a possible black-hole signature. In fact, seven of the nine reliable black-hole sources with large mass lower limits (Table 2) show this characteristic spectral shape (see Figure 2 of Tanaka 1994 and Section 2.2.2 below). The absence of a blackbody component is consistent with the compact object being a black hole, since no solid surface is present in a black hole. Also, X-ray bursts have never been observed from these sources at any luminosity level. The characteristic temperature is expected to be lower for an accretion disk around a black hole, since it scales as $M^{-1/2}$ for a given accretion rate with the mass M of the compact

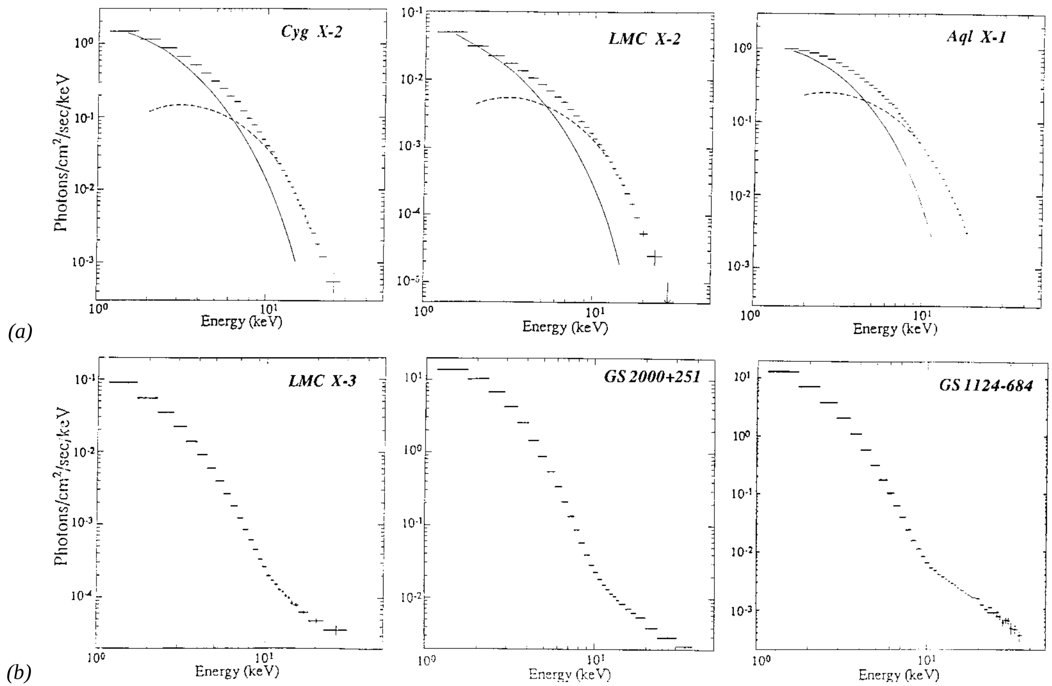


Figure 1 Examples of the energy spectra of X-ray binaries at high luminosities ($L_X > 10^{37}$ erg s^{-1}). (*a*) The spectra of the neutron-star LMXBs, which are composed of a soft component expected from an optically thick accretion disk (*solid curve*) and a blackbody component from the neutron star envelope (*dashed curve*) (Tanaka 1994). Cyg X-2 and LMC X-2 are persistent sources, whereas Aql X-1 is a transient source. (*b*) The spectra of the black-hole binaries (Tanaka 1994) established with the mass lower limit of the compact object exceeding 3 $M_\odot$ (see text). The spectra are dominated by an ultrasoft component expected from the accretion disk (softer than the corresponding soft component in the neutron-star LMXBs) and are accompanied by a hard tail. LMC X-3 is a persistent HMXB, whereas GS 2000+251 and GS/GRS 1124−684 are low-mass transients.

Table 2 Black-hole binaries established from the mass functions

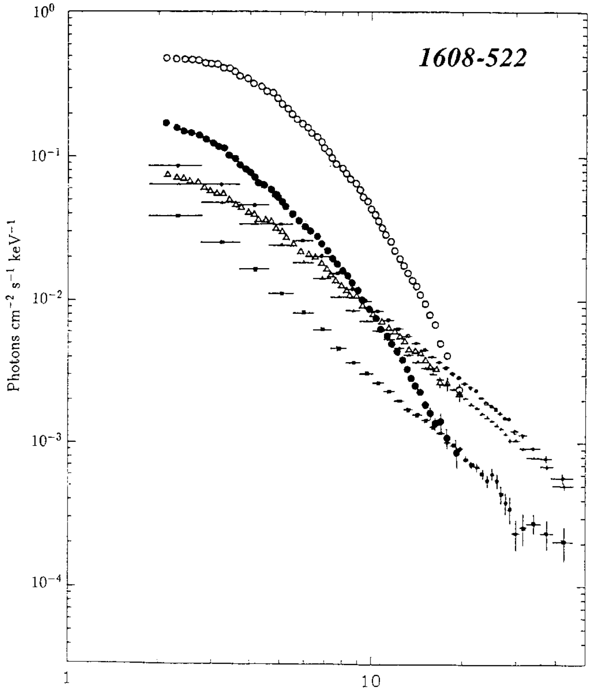
Source name		Spectrum[a]	Companion[b]	$F(M)$ ($M_\odot$)	BH mass ($M_\odot$)	Ref.[c]
Cyg X-1	persistent	US+PL	HM O 9.7 Iab	0.241 ± 0.013	$\sim 16 (> 7)$	1
LMC X-3	persistent	US+PL	HM B 3 V	2.3 ± 0.3	> 7	2
LMC X-1	persistent	US+PL	HM O 7–9 III	0.14 ± 0.06	~ 6(?)	3
J0422+32	Nova Per	PL	LM M 2 V	1.21 ± 0.06	> 3.2	4
0620−003	Nova Mon	US+PL	LM K 5V	3.18 ± 0.16	> 7.3	5
1124−684	Nova Mus	US+OL	LM K 0–4 V	3.1 ± 0.4	~ 6	6
J1655−40	Nova Sco	US+PL	LM F 3–6	3.16 ± 0.15	4–5.4	7
2000+251	Nova Vul	US+PL	LM early K	4.97 ± 0.10	6–7.5	8
2023+338	Nova Cyg	PL	LM K 0 IV	6.26 ± 0.31	8–15.5	9

[a]US+PL: ultrasoft + power-law, PL: power law.
[b]HM: high-mass system, LM: low-mass system.
[c]References:
1. Gies & Bolton 1982
2. Cowley et al 1983
3. Hutchings et al 1987
4. Filippenko et al 1995a
5. McClintock & Remillard 1986
6. McClintock, Bailyn & Remaillard 1992
7. Bailyn et al 1995b
8. Filippenko et al 1995b
9. Casares et al 1992

object (Mitsuda et al 1984). For these reasons, an ultrasoft spectrum plus a hard power-law tail can be considered as a probable signature of a black-hole binary. For more discussion, see Tanaka & Lewin (1995).

2.1.4 SOFT-HARD TRANSITION: NO BLACK-HOLE SIGNATURE Two of the nine reliable black-hole binaries, GS 2023+338 and GRO J0422+32, showed an approximate single power-law spectrum at all luminosity levels observed (with no ultrasoft component; see Section 2.2.2), indicating the presence of black-hole binaries of another spectral type.

For some time, a hard power-law spectrum associated with flickering (rapid intensity fluctuations) or soft-hard (high-low) transitions such as that seen in Cyg X-1 has been considered to be a possible black-hole signature. However, this is not the case. Studies of X-ray novae clearly show that, regardless of whether the compact object is a neutron star or a black hole, the X-ray spectrum changes from a soft state at high luminosities (as described above) to a hard power-law state with a photon index of 1.5–2.0 at low luminosities (see White et al 1995; Tanaka 1989, 1994; Tanaka & Lewin 1995). Transitions between these two spectral states have been observed from several X-ray novae as they undergo luminosity changes; e.g. Aql X-1 and 1608−522 (neutron-star systems) and GS/GRS 1124−684 and GX 339–4 (black-hole systems), as shown

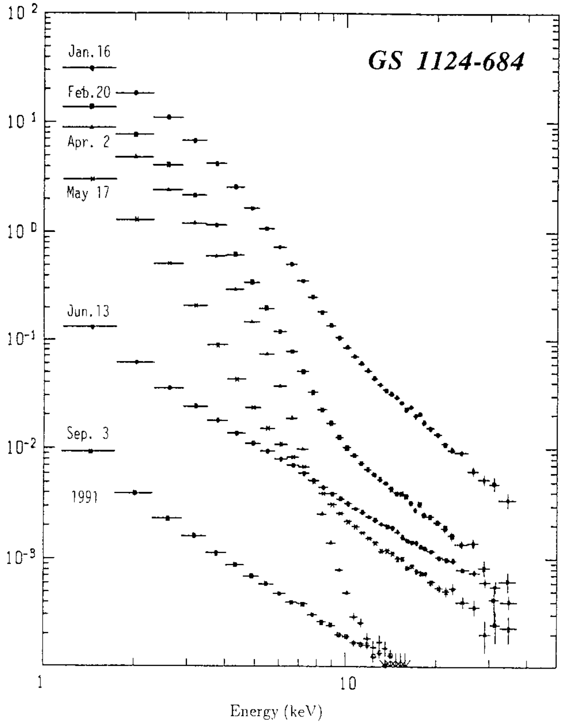


(a)

Figure 2 Changes in the shape of X-ray spectrum with luminosity. (*a*) The spectra of the neutron-star LMXB 1068−522 (Mitsuda et al 1989, Yoshida et al 1993). (*b*) The spectra of the black-hole LMXB GS/GRS 1124−684 (Ebisawa et al 1994), in which the *Ginga* observation dates are indicated. These spectra have been corrected for the detector response (Tanaka 1992b, 1994).

in Figure 2. Note that the power-law photon index of the black-hole systems becomes smaller (harder) when the ultrasoft component disappears (Tanaka 1992a). This transition seems to occur around $L_X \sim 10^{37}$ erg s^{-1} or lower. The change in the spectrum is most probably due to an accretion-dependent change in the structure of the accretion disks in these sources. Flickering (rapid intensity fluctuations on various time scales down to $\ll 1$ s) is also one of the common properties in the power-law state at low luminosities (Yoshida et al 1993). The power law extends to 100 keV and beyond, and is most probably formed by Comptonization of soft photons (see White et al 1995, Nakamura et al 1989).

Thus, a power-law spectrum alone is insufficient to classify a source. Since all neutron-star LMXBs observed show soft thermal spectra when L_X is well



(b)

Figure 2 (*Continued*)

above 10^{37} erg s^{-1}, we may consider a source to be a black-hole binary only if it shows a single power-law spectrum when $L_X \gg 10^{37}$ erg s^{-1}. However, this classification is less secure than cases where the spectrum consists of an ultrasoft component and a power-law tail.

2.2 *Outbursts*

2.2.1 NEUTRON-STAR X-RAY NOVAE We summarize the characterisitics of X-ray nova outbursts of the systems in which the compact object is known to be a neutron star (neutron-star X-ray novae). Our discussion is based primarily on the results of the detailed studies of Cen X-4, Aql X-1, 1608−522, and 1730−335. All of these have been studied at various phases of activity over a wide range of luminosity.

Cen X-4 Two outbursts of Cen X-4 have been observed—the first in July 1969 (Evans et al 1970) and the second in May 1979 (Kaluzienski et al 1980). In the 1969 outburst, the X-ray intensity reached a maximum of $\sim 10^{38}$ erg s^{-1}

(for $d = 1.2$ kpc) in a few days followed by a decline that became steeper after about two months. The second outburst was smaller: a peak flux of $\sim 1/5$ of the first and a duration of about a month. The light curve of the second outburst showed a complex multipeaked structure for about 10 days, followed by a relatively smooth decay. The X-ray spectrum was typical of a luminous neutron-star LMXB (Kitamura et al 1971, Matsuoka et al 1980). An X-ray burst was detected during the decay of the 1979 outburst (Matsuoka et al 1980). The total energy emitted during an outburst was $\sim 3 \times 10^{44}$ erg for the 1969 outburst and $\sim 3 \times 10^{43}$ erg for the 1979 outburst (van Paradijs & Verbunt 1984).

The optical counterpart (V822 Cen), which had brightened from $V = 18.3$ to $V = 12.8$, was discovered by Canizares et al (1980). It was identified as a late K5–7V star (van Paradijs et al 1980, Cowley et al 1988, Chevalier et al 1989, McClintock & Remillard 1990) with a binary period of 15.1 h (Chevalier et al 1989). The mass function of 0.20 $M_{\odot}$ was obtained by McClintock & Remillard (1990). Liller (1979) noted the absence of earlier optical outbursts brighter than 16 mag since 1900. The distance is estimated to be ~ 1.2 kpc (Matsuoka et al 1980, Chevalier et al 1989).

A radio outburst was also observed (Hjellming et al 1988; see Section 2.3.).

Aql X-1 Aql X-1 undergoes major outbursts roughly once a year (Kaluzienski et al 1977a, Priedhorsky & Holt 1987). Minor outbursts (subflares) are also seen between major outbursts. The rise time is typically ~ 5 days. The light curve is complex and is often multi-peaked; it decays with a typical *e*-folding time of a month (though it is not an exponential decay). For the large outbursts in June 1978 (Charles et al 1980) and March 1987 (Kitamoto et al 1993), the peak luminosity was $\sim 2 \times 10^{37}$ erg s^{-1} (for $d = 2.5$ kpc). The total energy per outburst varied from 1 to 5 $\times 10^{43}$ erg (van Paradijs & Verbunt 1984). X-ray bursts were also detected (Koyama et al 1981, Czerny et al 1987).

The X-ray spectrum is typical of a luminous neutron-star LMXB (a soft component plus a blackbody component) during outburst, but it was a single power law when $L_X \sim 10^{35}$ erg s^{-1} (Czerny et al 1987, Tanaka 1994). There is an indication in the result of Czerny et al (1987) that this spectral change occurred around 4×10^{36} erg s^{-1}.

Priedhorsky & Terrel (1984) reported an underlying recurrence periodicity of 122–125 days based on 10 years of *Vela 5B* data from 1969, although only some cycles showed an outburst. However, the data of a longer span exclude the 125-day periodicity (Kitamoto et al 1993). Although the occurrence of outbursts appears quasiperiodic, there is no underlying clock in the system.

A positive correlation between the peak intensity (also the total energy emitted in an outburst) and the time since the preceding outburst was first pointed out by White et al (1984) (at 99.7% confidence; Priedhorsky & Holt 1987). This correlation was confirmed with increased samples including smaller outbursts (Kitamoto et al 1993). Although the scatter of data points is large, the data are consistent with a linear relation, suggesting that it releases in one outburst all the potential energy accumulated since the last. This result favors a disk instability model (see Section 3.3.1).

The optical counterpart (V1333 Aql) was discovered by Thorstensen et al (1978). The spectrum during X-ray quiescence was of a main-sequence G7-K3 star, near K0V. In a large outburst in June 1978, it brightened from $V \sim 19$ in quiescence to 14.8 (Charles et al 1980). Chevalier & Ilovaisky (1991) discovered a probable binary period of 18.97 h. The distance was estimated to be between 1.7 and 4.0 kpc by Thorstensen et al (1978) and 1–2 kpc by Margon et al (1978). The peak luminosities of X-ray bursts (Koyama et al 1981, Czerny et al 1987) set an upper limit of ~ 4 kpc. The most probable distance is ~ 2.5 kpc (Thorstensen et al 1978).

A radio outburst was observed in an X-ray outburst (Hjellming et al 1990; see Section 2.3).

1608−522 Many outbursts of 1608−522 have been observed (see e.g. Lochner & Roussel-Dupré 1994 and references therein). During major outbursts, the peak luminosity goes up to $\sim 4 \times 10^{37}$ erg s^{-1} (for $d = 3.6$ kpc) (e.g. Nakamura et al 1989). The light curves of the outbursts are various (see Lochner & Roussel-Dupré 1994). In several outbursts, the X-ray intensity rose in a few days followed by a decay with an *e*-folding time of ~ 10 days, but some outbursts lasted for more than 100 days (see Figure 1 of White et al 1984). Some outbursts showed a slow rise (> 10 days). Outbursts occur randomly with intervals ranging from several months to years. The total energy per outburst varies in the range 10^{43}–10^{44} erg. No significant correlation between the outburst energy and the waiting time was observed (Lochner & Roussel-Dupré 1994).

1608−522 is exceptional in the following aspects: 1. It occasionally remains persistent. According to the *Vela 5B* 10-year history, the source stayed on at the $\sim 2 \times 10^{36}$ erg s^{-1} level for more than four years from around September 1971 through early 1976 (Lochner & Roussel-Dupré 1994). It was probably on between April 1983 and June 1984 as well (Nakamura et al 1989). 2. Some outbursts occurred even when the source was persistently on (see figures in Lochner & Roussel-Dupré 1994).

The evolution of the X-ray spectrum was studied throughout the decay of an outburst (Mitsuda et al 1989). As the luminosity decreased to 10^{37} erg s^{-1}, the thermal spectrum quickly hardened and became a single power-law for lower luminosities (Mitsuda et al 1989, Yoshida et al 1993), as shown in Figure 2*a*. 1608−522 is a well-known burster, generating frequent X-ray bursts (see Lewin et al 1995 and references therein). The distance was estimated to be 3.6 kpc from the bursts that show a luminosity saturation presumably at the Eddington limit (Nakamura et al 1989).

The optical counterpart was identified by Grindlay & Liller (1978) with a reddened, low-mass star that brightened by more than 2 I-magnitudes during a flare in July 1977. No further details of this star are known.

1730−335: The Rapid Burster 1730−335, discovered by Lewin et al (Lewin 1976), is a unique transient source that exhibits a train of rapidly repetitive bursts when active, hence it has been called the Rapid Burster. These bursts are due to spasmodic mass accretion (Type II bursts). The Rapid Burster also produces bursts due to thermonuclear flashes (Type I bursts) (Hoffman et al 1978). The source is located in a globular cluster (Liller 1977) at a distance of $\sim$10 kpc. Recurrences of activity at a rate of once to twice a year have been observed, but sometimes no activity was detected for a few years. An active period (outburst) lasts about a month. The time-averaged luminosity and the total energy emitted vary from one active period to another. The total energy emitted in one outburst is rougly in the range (0.3–1) $\times 10^{44}$ erg.

The X-ray spectrum is best described with a blackbody, unlike the spectra of other neutron star LMXBs. For more details, see Lewin et al (1995) and references therein.

2.2.2 BLACK-HOLE X-RAY NOVAE In this section, we deal with X-ray nova outbursts of the systems in which the compact object is a black hole. Both reliable cases with mass lower limits $> 3\ M_\odot$ and probable ones based on the spectral characteristics are included.

The X-ray light curve of the outburst is different from source to source. However, the outbursts of four X-ray novae, A 0620−003, GS 2000+251, GS/GRS 1124−684, and GRO J0422+32, exhibit striking similarities: a fast rise followed by a relatively smooth exponential decay with similar time constants and the presence of a secondary increase. Some of these light curves are shown in Figure 3.

Other black-hole X-ray novae display much more complex light curves: multiple peaks and/or irregular decay (see White et al 1984, Harmon et al 1994). Also, there are at least two sources that show an unusually slow rise: $\sim$ a month for GX 339-4 and $\sim$ 3 months for GRS 1915+105 (Harmon et al 1994).

Brief summaries of individual outbursts that are relatively well studied are given below.

0620−003 (Nova Mon 1975) The outburst of A 0620−003 was detected on August 3, 1975, with *Ariel V* (Elvis et al 1975). After a small precursory peak, the X-ray luminosity reached a maximum of 1.3×10^{38} erg s^{-1} (for $d = 0.9$ kpc).

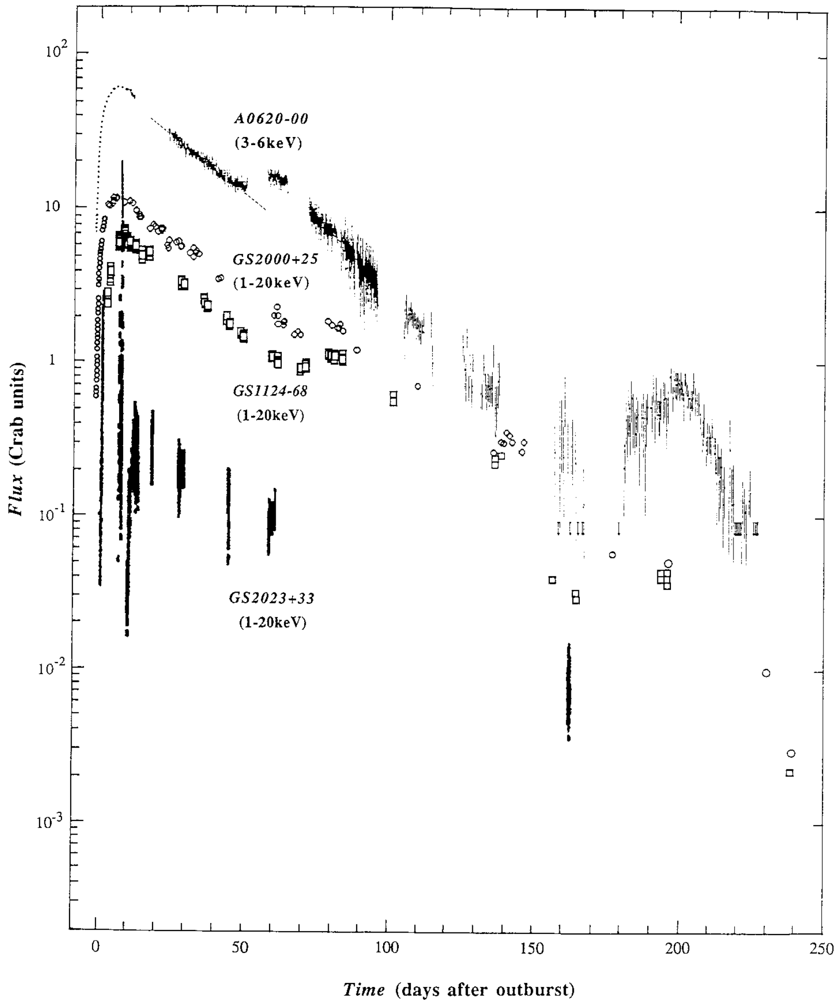


Figure 3 X-ray light curves of four bright black-hole X-ray novae. The observed X-ray fluxes are shown in units of the Crab Nebula intensity in the energy band separately indicated for each source. The dotted curve for A 0620−003 is from Elvis et al (1975), and the dots with vertical error bars are from Kaluzienski et al (1977b). The GS 2000+251 data (*open circles*) are from Tsunemi et al (1989) and Takizawa (1991). The GS 2023+338 data (*thick vertical bars*, which indicate actual large flux excursions) are from Tanaka (1992a). The GS/GRS 1124−684 data (*open squares*) are from Kitamoto et al (1992) and Ebisawa et al (1994).

The time to rise from 10% to 90% of the peak flux was ~ 4 days. As seen in Figure 3, the decay of the count rate (3–6 keV) was approximately exponential, with a decay constant $\tau \sim 24$ days (Kaluzienski et al 1977b). (Note that count rate decreases faster than the bolometric luminosity because of progressive softening of the spectrum; see below.) About ~ 50 days after onset, the flux increased again and reached a secondary peak (a factor of ~ 2 higher than the extrapolation of the initial decay) around 60 days; it then decreased at about the same time constant as before, and a third broad maximum was observed around 200 days (Kaluzienski et al 1977b). The count rate then declined steeply. The total energy emitted in the outburst is estimated to be $\sim 4 \times 10^{44}$ erg.

The X-ray spectrum was approximately a power law (with a photon index of ~ 1.6) in the first few days until the flux (2–18 keV) rose to $\sim 1/10$ the maximum; it then changed to an ultrasoft spectrum accompanied by a hard tail (Ricketts et al 1975). The spectrum steadily softened through the decay until at least 80 days after the outburst peak (Matilsky et al 1976).

The optical counterpart (V616 Mon) brightened to $V \sim 12$ (Boley et al 1976) from $V \sim 18.3$ in quiescence (Murdin et al 1980). The spectrum is characteristic of a K5V dwarf (Oke 1977, Whelan et al 1976, Murdin et al 1980), and its orbital period is 7.75 h (McClintock et al 1983). The distance is estimated to be ~ 0.9 kpc (Oke 1977). McClintock & Remillard (1986) determined the mass function to be $3.18 \pm 0.16\ M_\odot$ and estimated the mass of the compact object as $> 7.3\ M_\odot$. The optical record shows that a previous outburst occurred in 1917 (Eachus et al 1976).

A bright radio outburst was observed following the X-ray outburst (Davis et al 1975, Owen et al 1976, Hjellming et al 1988; see Section 2.3).

2000+251 (Nova Vul 1988) An outburst of GS 2000+251 was detected on April 23, 1988, with *Ginga* (sensitive in the range 1–40 keV) (Makino 1988, Tsunemi et al 1989). The flux increased from 10% to 90% of maximum in ~ 3 days and reached a maximum luminosity of $\sim 1.5 \times 10^{38}$ erg s^{-1} (for $d = 2$ kpc). The count rate decayed exponentially with $\tau \sim 30$ days (see the light curve in Figure 3). However, the decay of the bolometric luminosity was slower, with $\tau \sim 40$ days, due to steady softening (see below). A secondary peak with an increase of ~ 50% appeared around 80 days after the onset; this was followed by a decay with the same τ. Although there is no obvious tertiary increase, a flattening of decay is noted around 200 days, followed by a much steeper decay than before. The total energy emitted in the outburst was $\sim 5 \times 10^{44}$ erg.

The X-ray spectrum was ultrasoft, having a hard power-law tail with a photon index varying in the range 2.1–2.5 (Tanaka 1989). The ultrasoft component steadily softened during decay. The power-law component changed its flux widely and was irregularly independent of the ultrasoft flux (Tanaka 1989). This power-law component extended to ~ 300 keV (Sunyaev et al 1988; Döbereiner et al 1989, 1994). After 230 days, the spectrum became a single power law with a photon index of ~ 1.7. This spectral change occurred at an exceptionally low luminosity level of the order 10^{35} erg s^{-1}.

The optical counterpart was identified with a star (QZ Vul) that brightened to $V \sim 16.4$ from a reddened $R = 21$ mag state in quiescence (Charles et al 1988, Okamura & Noguchi 1988, Wagner et al 1988, Tsunemi et al 1989). This is likely to be an early K dwarf at a distance of 2–3 kpc, with a probable orbital period of 8.26 h (Callanan & Charles 1991; Chevalier & Ilovaisky 1990, 1993). Recently, Filippenko et al (1995b) determined the mass function to be $4.97 \pm 0.10\ M_{\odot}$, with a plausible mass of the compact object between 5.9 and 7.5 $M_{\odot}$.

Radio emission was detected in the observation during the decay (Hjellming et al 1988; see Section 2.3).

2023+338 (Nova Cyg 1989) GS 2023+338 was discovered on May 21, 1989, with *Ginga* (Makino 1989, Kitamoto et al 1989). The outburst of this source was unlike those of any other X-ray nova. The X-ray activities during the first 10 days and at later times were qualitatively different.

At first the flux increased from 0.1 Crab (the Crab Nebula Flux) to 4 Crab (1–6 keV) within a day and then declined quickly in a few days. Nine days later on May 30, a dramatic outburst occurred (see Figure 3.6 of Tanaka & Lewin 1995). The flux rose to a maximum of ~ 21 Crab and then showed repeated rapid changes between this level and a minimum of ~ 0.1 Crab for ~ 3 h. The luminosity at the maximum was very high, $\sim 2 \times 10^{39}$ erg s^{-1} in 1–40 keV (for $d = 3.5$ kpc), and the luminosity seems to saturate at this level, which is possibly the Eddington limit (Tanaka 1989).

In the first 10 days, not only the flux fluctuated by more than two orders of magnitude, but the spectrum also changed dramatically from time to time (Tanaka 1989, in't Zand et al 1992; see Figure 3.7 of Tanaka & Lewin 1995). Although the spectral features are complex, the main cause of spectral changes (consequently resulting in flux changes) was the occurrence of large changes in absorption. The absorption column on the line of sight fluctuated rapidly and sometimes exceeded 10^{24} H atoms cm^{-2}, suggesting that the outer accretion disk was suddenly flooded by a large amount of cool matter. From time to time, the source became essentially free from low-energy absorption. The intrinsic (unabsorbed) spectrum was approximately a single power law with a photon index of ~ 1.5 (Tanaka 1989). An ultrasoft component was never present. The power-law component was detectable up to ~ 300 keV and showed a high-energy cutoff (an exponential steepening of the slope) (Aref'ev et al 1989, Sunyaev et al 1991, Döbereiner et al 1994). There is a clear indication that the cutoff shifts to lower energies as the luminosity increases, probably due to Compton cooling (Inoue 1994).

After the first 10 days, the violent changes ceased and an approximately exponential decay started from a level of ~ 0.5 Crab with $\tau \sim 40$ days (see the light curve in Figure 3). The spectrum was a single power law with a photon index of ~ 1.7. Absorption was much reduced and changed little. At about the same time, strong flickering started and continued throughout the decay. The total energy emitted in the outburst was roughly 6×10^{43} erg.

The optical counterpart was identified with V404 Cyg (Hurst & Mobberley 1989, Marsden 1989, Wagner et al 1989). Previous outbursts were recorded optically in 1938 (Wachmann 1948), 1956, and possibly 1979 (Richter 1989). V404 Cyg brightened to $V \sim 11.6$ near X-ray maximum (Buie & Bond 1989, Wagner et al 1991, Leibowitz et al 1991). The increase in brightness was ~ 7.5 mag in *V.* The secondary star is either a K0 IV star or a stripped giant (Wagner et al 1992a, King 1993) and is probably a subgiant (Casares et al 1993). Distance estimates are 2–3 kpc (Charles et al 1989, Casares et al 1991, Gotthelf et al 1992), > 3 kpc (Han & Hjellming 1990), and ~ 3.5 kpc (Wagner et al 1992a). Casares et al (1992) obtained an orbital period of 6.47 days and a mass function of $6.26 \pm 0.31\ M_\odot$, which is the largest among known black-hole systems. The probable mass of the compact primary is in the range 8–15.5 $M_\odot$ (Casares et al 1992), with a firm lower limit of 7 $M_\odot$ (Casares et al 1993).

A strong radio outburst was also observed (Hjellming et al 1989; Han & Hjellming 1992a, see Section 2.3).

1124−684 (Nova Mus 1991) An outburst of GS/GRS 1124−684 was detected on January 8, 1991, with *Ginga* (Makino 1991, Kitamoto et al 1992) and independently with the *GRANAT WATCH* (sensitive in the range 8–60 keV) (Lund & Brandt 1991, Brandt et al 1992). With a rise time from 10 to 90% of the peak in 4–5 days, it reached a maximum of $\sim 2.5 \times 10^{38}$ erg s^{-1} (for $d = 3$ kpc). The count rate (1–20 keV) decayed exponentially with $\tau \sim 30$ days (see the light curve in Figure 3), while the decay of the bolometric luminosity was slower with $\tau \sim 40$ days (Ebisawa et al 1994). A secondary increase by a factor of ~ 2 occurred with a rise time of ~ 10 days and peaked around 80 days after the onset. The following decay was slightly slower than before. A tertiary peak was observed around 200 days, after which the flux decreased rapidly. These characteristics of the X-ray light curve are very similar to those observed in A 0620–003. The total energy emitted in the outburst was $\sim 10^{45}$ erg.

The X-ray spectrum was hard in the first few days, dominated by a power law (Brandt et al 1992, Ebisawa et al 1994). It then became ultrasoft with a hard power-law tail (Figure 2*b*) and remained so until mid-May (Ebisawa et al 1994). The soft component steadily softened during decay. The power-law component with a photon index of 2.5–2.7 extended to ~ 500 keV (Goldwurm et al 1992, Sunyaev et al 1992). The flux of the power-law component varied widely and was independent of the ultrasoft flux (see Figure 2*b*), which is similar to the case of GS 2000+251. After mid-June, the spectrum was a single power law with a photon index of ~ 1.6, distinctly harder than before (Ebisawa et al 1994). Flickering started at the same time. This change occurred when the luminosity had decreased to $(1 \sim 2) \times 10^{37}$ erg s^{-1}. A transient 480-keV line was observed during the outburst with the *GRANAT SIGMA*; this was interpreted as an electron-positron annihilation line (Goldwurm et al 1992, Sunyaev et al 1992).

The optical counterpart was identified with a star that brightened to $V \sim 13.5$ (Della Valle et al 1991) from $V \sim 20.4$ in quiescence. This star is of spectral type K0–4 and has an orbital period of 10.4 h (Remillard et al 1992). McClintock et al (1992) determined the mass function to be $3.1 \pm 0.4\ M_{\odot}$ and estimated the minimum mass of the primary to be $3.75 \pm 0.43\ M_{\odot}$. The optical spectrum in quiescence is strikingly similar to that of V616 Mon (A 0620–003) (Remillard et al 1992). The distance is estimated to be between 1 and 5 kpc—probably ~ 3 kpc (West 1991).

A strong radio outburst was observed during the X-ray outburst (Kesteven & Turtle 1991; see Section 2.3).

J0422+32 (Nova Per 1992) The outburst of GRO J0422+32 was discovered by the *CGRO BATSE* instrument (which is sensitive in the range 20–300 keV) on August 5, 1992 (Paciesas et al 1992). The X-ray spectrum is a power law with a photon index of ~ 1.5, extending from 2 keV to 500 keV, modified by an exponential cutoff with a characteristic energy around 100 keV (Sunyaev et al 1993, Döbereiner et al 1994, Harmon et al 1994). The source was detected up to 2 MeV during the outburst peak (van Dijk et al 1995). The conspicuous absence of an ultrasoft component is similar to the case in GS 2023+338 (Sunyaev et al 1993). The peak luminosity is estimated to be $\sim 3 \times 10^{37}$ erg s^{-1} in 2–300 keV (for $d = 2$ kpc) by extrapolation of the *Mir-Kvant* result to the outburst peak (Sunyaev et al 1993).

J0422+32 reached its maximum flux in 6 days (Harmon et al 1994) (the rise time from 10% to 90% of the peak was ~ 4 days). The decay was approximately exponential with $\tau \sim 40$ days (Harmon et al 1994) to 44 days (Vikhlinin et al 1995). These values are similar to those of the decay in bolometric luminosity for both GS 2000+251 and GS/GRS 1124−684 (~ 40 days), and probably also for A 0620−003 if the gradual softening during decay is taken into account. A distinct secondary increase began at ~ 125 days and peaked at ~ 140 days after the onset of the primary outburst; this was followed by a decay with the same τ as before (Harmon et al 1994). The secondary peak flux was ~ 3 times that extrapolated from the primary decay. The decay apparently steepened after ~ 230 days, which is similar to the last decay phase of A 0620−003, GS 2000+251, and GS/GRS 1124−684. However, a tertiary peak such as observed in A 0620−003 and GS/GRS 1124−684 did not occur. The total energy emitted in the outburst is estimated to be $\sim 1.2 \times 10^{44}$ erg.

The optical counterpart (V518 Per) is an M star; M0–5 (Martin et al 1995), ∼ M0V (Chevalier et al 1995, Orosz et al 1995) or M2V (Filippenko et al 1995a). It brightened by ∼ 7 mag to $V \sim 13.2$ (Castro-Tirado et al 1992a, 1993; Wagner et al 1992b). No previous outburst was found from the search of optical archive data (Shao 1992). The distance to the source is >1 kpc (Callanan et al 1995) and probably ∼ 2 kpc (Chevalier et al 1995). A periodicity is found from photometry and spectroscopy at 5.09 h, which is probably the binary period (Kato et al 1993, Chevalier et al 1995, Orosz et al 1995, Callanan et al 1995, Casares et al 1995). The mass function was determined to be $0.9 \pm 0.4\ M_\odot$ by Oroz et al (1995) and more recently $1.21 \pm 0.06\ M_\odot$ by Filippenko et al (1995a). Although this does not preclude the possibility of the compact object being a neutron star, its mass may exceed 3 $M_\odot$ depending on the secondary mass and the inclination angle (Orosz et al 1995). In fact, Filippenko et al (1995a) estimate the mass of the primary to be $3.57 \pm 0.34\ M_\odot$ for a normal M2 secondary.

The initial optical outburst lasted about 250 days. Two smaller optical outbursts occurred later (5.5 mag in V) (see Chevalier & Ilovaisky 1995, Callanan et al 1995, and references therein). Separations of the major optical outbursts (including the one coincident with the secondary X-ray increase) from the initial one are found to be integer multiples of ∼ 120 days (Chevalier & Ilovaisky 1995), suggesting echos (delayed mass transfer triggered by X-ray illumination) (Augusteijn et al 1993). Note, however, that the third X-ray/optical increase was missing.

Radio emission was also detected (Han & Hjellming 1992b).

1915+105 (Nova Aql 1992) GRS 1915+105 was discovered by the *GRANAT WATCH* (Castro-Tirado et al 1992b, 1994) in August 1992. The source had begun to be visible in May 1992 with the *CGRO BATSE* (Harmon et al 1994). The rise was unusually slow at ∼ 3 months. At a distance of 12.5 kpc (Mirabel & Rodriguez 1994), the peak luminosity was close to 10^{39} erg s^{-1} (Sazanov et al 1994). Multiple flaring events, each lasting 10–20 days, were observed over two years, with recurrent periods of several months and a peak flux of ∼ 1 Crab in 8–20 keV (Sazanov et al 1994). The hard X-ray light curve observed with the *CGRO BATSE* also shows violent flaring activity (Harmon et al 1994). The source still remains active as of August 1995.

The spectrum of 1915+105 is ultrasoft and is accompanied by a power-law tail. An intense ultrasoft component was observed with *Mir-Kvant*

(Alexandrovich et al 1994a) and also with *ASCA* (T Kotani 1994, private communication). The power-law component extends to $\sim$ 230 keV with a photon index of ~ 2.5 (Sazanov et al 1994) and shows an exponential cutoff above several tens of keV (Harmon et al 1994).

Mirabel et al (1994) found a variable star in the near infrared at the position of the radio source. The reddening ($A_V \sim 30$ mag) and the absorption column of $\sim 5 \times 10^{22}$ H atoms cm^{-2} obtained with *ROSAT* (Greiner et al 1994) suggest a distance > 8 kpc. Mirabel & Rodriguez (1994) estimate that $d = 12.5 \pm 1.5$ kpc.

Radio jets revealing superluminal motion were also discovered by Mirabel & Rodriguez (1994): See Section 2.3.

J1655−40 (Nova Sco 1994) GRO J1655−40 was discovered in outburst on July 27, 1994, with the *CGRO BATSE* (20–300 keV) (Zhang et al 1994). The hard X-ray light curve is complex, showing four outbursts in the first five months (Harmon et al 1995). Each outburst is characterized by a fast rise (typically ~ 1 day) and an abrupt fall. The source is still bright as of August 1995 with repeating episodic hard X-ray outbursts.

The spectrum consists of an ultrasoft component and a power-law component. The ultrasoft component was observed with *Mir-Kvant* in September 1994 and February 1995; flux values differed by a factor of ~ 3 (Alexandrovich et al 1994b, 1995). The recent *ASCA* observation in the range 0.5–10 keV in August 1995 also revealed an intense ultrasoft component with a luminosity of $\sim 4 \times 10^{37}$ erg s^{-1} (for $d = 3$ kpc) accompanied by a power law (Y Ueda et al 1995, private communication). However, the long-term behavior of the ultrasoft component is not known. The power-law component is highly variable in intensity and extends to at least 600 keV, with a slope varying between 2.5 and 3.1 (Harmon et al 1995). The maximum luminosity of outburst is probably as high as 10^{38} erg s^{-1} in the range 1–300 keV.

The optical counterpart was discovered by Bailyn et al (1995a). The observation on August 10, 1994, yielded $V = 14.4$ mag. It had brightened by 3 mag. The estimated distance is around 3 kpc (McKay & Kesteven 1994, Tingay et al 1995, Bailyn et al 1995a, Greiner et al 1995). Hjellming & Rupen (1995) obtained $d = 3.2 \pm 0.2$ kpc from an analysis of the radio jets. The recent spectroscopic observation shows that the secondary star is an F3–6 star with a binary period of 62.7 h and that the mass function is $3.16 \pm 0.15\ M_\odot$ (Bailyn et al 1995b). Photometric observations show primary and secondary eclipses, indicating a large inclination of the system (see Bailyn et al 1995b). The radio-jet axis is at an inclination angle of 85° to the line of sight (Hjellming & Rupen 1995). Given such a large system inclination, the primary mass will be between 4.0 and 5.4 $M_\odot$ for a secondary mass between 0.4 and 1.5 $M_\odot$ (Bailyn et al 1995b).

Radio jets showing superluminal motion were also discovered (Tingay et al 1995, Hjellming & Rupen 1995; see Section 2.3).

2.3 *Radio Outbursts*

Radio outbursts associated with the X-ray outbursts were discovered from Cen X-4, Aql X-1, A 0620−003, GS 2000+251, GS 2023+338, GS/GRS 1124−684 (see references in Sections 2.1 and 2.2), and more recently from GRS 1915+105 and GRO J1655−40 (see below). Most probably, every X-ray outburst is accompanied by a radio outburst. In particular, relativistic radio jets showing superluminal motion have been resolved from the last two sources, as described below.

The radio outbursts in X-ray novae are interpreted to be ejections of "synchrotron bubbles" that contain relativistic electrons and magnetic fields. Sudden commencement of a large mass inflow in an accretion disk would cause a dynamical event that produces an outward-moving shock in which relativistic electrons are accelerated (Dickel et al 1989). A spherically expanding synchrotron bubble model fits the observed multiwavelength radio data well (Hjellming & Han 1995). This model may also apply for the individual plasma bubbles ejected in radio jets.

Hjellming & Rupen (1995) note that the observed characteristics of the radio flares in GRO J1655−40 (see below) are similar to those in A 0620−003, GS 2000+251, GS 2023+338, GS/GRS 1124−684, Cen X-4, and Aql X-1; they suggest that these may have been collimated jet events as well.

For a review, see Hjellming & Han (1995) and references therein.

1915+105 Following the detection of strong radio outbursts (Rodriguez & Mirabel 1993, Gerard et al 1994), Mirabel & Rodriguez (1994) discovered superluminal motion of a pair of radio blobs associated with GRS 1915+105. This is the first Galactic superluminal source. The standard model of relativistic jets yields a velocity of the radio blobs of $(0.92 \pm 0.08)c$ for an estimated distance of 12.5 ± 1.5 kpc (Mirabel & Rodriguez 1994). Mirabel & Rodriguez (1994) noted that the large kinetic energy of the radio blobs would require a minimum rate of 10^{41} erg s^{-1} to accelerate the twin ejecta—much larger than the maximum X-ray luminosity of the source ($\sim 10^{39}$ erg s^{-1}; Sazanov et al 1994). This enormous energy generation rate, far exceeding the Eddington limit, cannot be explained in terms of accretion energy. One possibility is that the ejecta are electron-positron plasmas. Further study is required.

J1655−40 A strong radio outburst was detected during the decline of the initial X-ray outburst (Campbell-Wilson & Hunstead 1994). Radio outbursts were observed following each X-ray outburst (Hjellming & Rupen 1995, Harmon et al 1995).

Tingay et al (1995) discovered superluminal motion. The detailed structure of the jets was resolved by Hjellming & Rupen (1995). They show that the jets move at $(0.92 \pm 0.02)c$ almost perpendicular to the line of sight ($i \cong 85^\circ$). Backward extrapolation of the motion of the subcomponents shows that ejection of radio-emitting plasma occurred several days to two weeks after the onset of each hard X-ray outburst (Hjellming & Rupen 1995). Tingay et al (1995) suggest that the formation and ejection of the radio component was suppressed while the inner accretion disk is radiation-pressure dominant and geometrically thick. Note, however, that any relationship between the radio outbursts and the soft X-ray component of the source (Section 2.2.2) is not known because no soft X-ray (< 10 keV) data around the radio events are available.

2.4 *Properties During Quiescence*

Owing to a dramatic increase in sensitivity in recent years, X rays from several X-ray novae in the quiescent state have been positively detected at luminosity levels from below 10^{31} to 10^{33} erg s^{-1}. The results of X-ray observations of X-ray novae in quiescence, along with the 3σ upper limits, are listed in Table 3. Several individual sources are briefly described below: three neutron-star LMXBs (Cen X-4, Aql X-1, and 1068–522) and two black-hole LMXBs (A 0620–003 and GS 2023+338). As we discuss in Section 3, the X-ray and optical properties of X-ray novae in quiescence are important not only for understanding mass accretion at extremely low rates but also for clarifying the mechanism of X-ray nova outbursts.

Cen X-4 Van Paradijs et al (1987) detected X rays from Cen X-4 with the *Einstein Observatory* and *EXOSAT* at $(4–8)\times10^{32}$ erg s^{-1} in 0.5–4.5 keV (for $d = 1.2$ kpc). This was the first X-ray detection of X-ray novae in quiesence. The source was recently detected with *ASCA* at a luminosity of $\sim 2.4 \times 10^{32}$ erg s^{-1} in 0.5–10 keV (Asai et al 1995). The spectrum is very soft, but is accompanied by a significant hard tail with a photon index of ~ 1.9. If the soft component is fitted with a blackbody spectrum, the temperature kT is approximately 0.2 keV and the emitting area is ~ 10 km^2.

Aql X-1 Aql X-1 was observed with *ROSAT* five times at various luminosity levels from $\sim 4 \times 10^{36}$ erg s^{-1} down to 4.4×10^{32} erg s^{-1} (for $d = 2.5$ kpc) in 0.4–2.4 keV (Verbunt et al 1994). When $L_X \geq 10^{35}$ erg s^{-1}, the spectrum is consistent with a hard power law (Czerny et al 1987, Tanaka 1994). However, it changes to a very soft spectrum when $L_X < 10^{33}$ erg s^{-1}. The best-fit blackbody temperature is $kT \cong 0.3$ keV, which gives an emitting area of ~ 1 km^2 (Verbunt et al 1994).

Table 3 X-ray luminosity and spectrum during quiescence

Source name	Class[a]	Observed range (keV)	Luminosity[b] (10^{32} erg/s)	kT (for b.b.) (keV)	Ref.[c]
Cen X-4	ns	0.5–4.5	4–8		1
		0.5–10	2.4	0.2	2
				+ hard tail (2–10 keV)	
Aql X-1	ns	0.2–2.4	4.4	0.3	3
1608–522	ns	0.5–10	6	0.3	2
0620–003	bh	0.2–2.4	0.06	0.16	4
2023+338	bh	0.2–2.4	80	0.2	3,5
2000+251	bh	0.2–2.4	< 0.1		2
		0.5–10	< 0.3 (Crab)		6
			< 0.1 (b.b)		
1124–684	bh	0.5–10	< 0.1 (Crab)		6
GX339–4	bh	0.5–10	< 0.3 (Crab)		6
			< 0.1 (b.b.)		
1705–250	bh	0.2–2.4	< 5 ($d = 3$ kps assumed)		3

[a]ns: neutron-star LMXB, bh: black-hole LMXB.
[b]b.b.: for a blackbody spectrum, Crab: for a Crob-like spectrum.
[c]References:
1. van Paradijs et al 1987
2. Asai et al 1995
3. Verbunt et al 1994
4. McClintock et al 1995
5. Wagner et al 1994
6. ASCA result, unpublished

1608−522 1608−522 was detected with *ASCA* at a luminosity of $\sim 6 \times 10^{32}$ erg s^{-1} (for $d = 3.6$ kpc) in 0.5–10 keV (Asai et al 1995). The spectrum is very soft: For a blackbody fit, $kT \cong 0.3$ keV, and the emitting area is ~ 10 km^2. No hard tail such as seen in Cen X-4 is present.

0620−003 McClintock et al (1995) detected A 0620−003 with *ROSAT* at a luminosity of 6×10^{30} erg s^{-1} (for $d = 0.9$ kpc): the lowest positive detection among X-ray novae in quiescence. A previous upper limit for A 0620–003 was 10^{32} erg s^{-1} (Long et al 1981). The observed spectrum was markedly soft: If fitted with a blackbody, $kT \cong 0.16$ keV, and the emitting area is ~ 1 km^2. Although a K dwarf can emit X rays in excess of 10^{30} erg s^{-1} (Verbunt 1995), most of the observed X rays are considered to come from the accretion disk. If the accretion disk is optically thick, the mass transfer rate to the black hole is extraordinarily small: $\dot{M} \sim 2 \times 10^{-15}\ M_\odot$ y^{-1} or $\sim 10^{11}$ g s^{-1} (McClintock et al 1995).

2023+338 Mineshige et al (1992) reported detection of GS 2023+338 with *Ginga* at a luminosity of $\sim 3 \times 10^{34}$ erg s^{-1} (for $d = 3.5$ kpc) in 1.2–10 keV after the source had returned to its quiescent optical brightness. More recently, Verbunt et al (1994) (see also Verbunt 1995) detected the source in the *ROSAT All-Sky Survey*. The count rate corresponds to a luminosity of $\sim 8 \times 10^{33}$ erg s^{-1} in the 0.4–2.4 keV band, if $N_H = 1.5 \times 10^{22}$ cm^{-2} (Wagner et al 1994). Wagner et al (1994) also detected the source with *ROSAT* at about the same luminosity. The intensity showed marked variations: a factor of ~ 2 variability in ~ 0.5 h and a factor of ~ 10 decrease over an interval of < 0.5 day. The minimum luminosity observed ($\sim 8 \times 10^{33}$ erg s^{-1}) corresponds to a mass accretion rate into the black hole of $\sim 10^{14}$ g s^{-1} for an optically thick disk. The spectrum was very soft: The best-fit blackbody temperature is $kT \cong 0.21$ keV.

The above results show that the X-ray spectra commonly become very soft when L_X goes down below 10^{34} erg s^{-1}, in contrast to the hard power-law (photon index of 1.5–2.0) spectra when $L_X = 10^{35} - 10^{37}$ erg s^{-1}. If the spectrum is fitted with a blackbody, the blackbody temperature kT is around $0.2 \sim 0.3$ keV. Whether this spectral change is a sudden transition or gradual is as yet unclear. Note, however, that the spectral shape in quiescence has not been too well constrained: A blackbody spectrum, a thin thermal (bremsstrahlung) spectrum, and a steep power law are equally acceptable for all cases. It is important to note that there is no characteristic difference in the X-ray spectrum in quiescence between the neutron-star systems and the black-hole systems (see the discussion in Section 3.2).

3. DISCUSSION

3.1 *Persistent vs Transient*

As mentioned in Section 2.1, there are many LMXBs that are persistently visible, whereas a number of LMXBs are not persistent and undergo transient outbursts. What causes this distinct difference?

Table 4 lists the estimates of time-averaged luminosity between outbursts: the total energy emitted in an outburst divided by the interval from the last. In those cases where no record of the previous outburst is available, the estimates are only qualitative. Interestingly, the time-averaged luminosities are all in the range from 10^{35} to 10^{36} erg s^{-1}. Two sources with short (~ 1 y) recurrence periods, 1608−522 and 1730−335, are on the high side of the range. This translates into a range of mass accretion rates of 10^{15}–10^{16} g s^{-1} (for a conversion factor $L_X/\dot{M} \sim 10^{20}$ erg g^{-1}), which appears to be lower than that for the persistent LMXBs (although this needs confirmation). From this, White et al (1984) suggested that mass accretion becomes unstable below a critical rate around 3×10^{16} g s^{-1}.

Indeed, the observed facts (Section 2) seem to indicate that stable mass accretion onto the compact objects cannot be maintained below an accretion rate

Table 4 Time-averaged luminosity of outbursts

Source name	Outburst year (or recur. period)	Total energy (10^{44} erg/s)	Interval[a] (year)	Ave. luminosity (10^{35} erg/s)	Ave. accretion rate (10^{15} g/s)	Ref.[b]
Cen X-4	1969	3	70*	1.4	0.7	
	1979	0.3	10	1	0.5	2
Aql X-1	∼1yr	0.1–0.5		3	1.5	2
1608–522	0.5–3yr	0.1–1		16–40	8–20	3
1730–335	0.5–3yr	0.3–1	1*	10∼30	5∼15	1
0620-003	1917					
	1975	4	58	2	2	2
200+251	1988	5	50*	3	3	1
2023+338	1956,1979?	0.6	if 10	2	2	1
	1989		if 33	0.6	0.6	
1124–684	1991	10	50*	7	7	1
J0422+32	1992	1.2	50*	0.8	0.8	1

[a]*: assumed interval.
[b]References: 1. see Section 2, and references therein
2. White et al 1984
3. Lochner & Rousel-Dupre 1994.

of around 10^{16} g s^{-1}. Four black-hole LMXBs, A 0620–003, GS 2000+251, GS/GRS 1124−684, and GRO J0422+32, that display similar exponential decays all show an abrupt steep fall in the last phase of the decay (see Figure 3). This steepening begins at around similar luminosity levels for all of them: $\sim 0.5 \times 10^{36}$ erg s^{-1} for GRO J0422+32, $\sim 2 \times 10^{36}$ erg s^{-1} for GS/GRS 1124–684, and $\sim 10^{36}$ erg s^{-1} for A 0620–003 and GS 2000+251. The light curve of the 1969 outburst of Cen X-4 also shows a steepening (Evans et al 1970), but at a somewhat higher luminosity ($\sim 4 \times 10^{36}$ erg s^{-1}). Another neutron-star LMXB, 1608–522, sometimes stays on persistently at a level of $\sim 2 \times 10^{36}$ erg s^{-1}, but it gets turned off below this luminosity. These results can be interpreted to show that the accretion flow into the inner part of the disk is choked below a luminosity of $\sim 10^{36}$ erg s^{-1}, or for an accretion rate $\dot{M} < 10^{16}$ g s^{-1}, and the source can no longer remain persistently X-ray luminous (see discussions in the next section).

On the other hand, the optical observations invariably show that mass transfer from the secondary star continues even during the quiescent periods of X-ray novae. The optical spectrum during quiescence clearly reveals the presence of emission from the accretion disk characterized by a blue continuum and the hydrogen Balmer emission lines (van Paradijs et al 1980), contributing $\sim 30\%$ in the V-band for Cen X-4 (Chevalier et al 1989) to 30–60% for GRO J0422+32 (Filippenko et al 1995a) and $\sim 55\%$ for A 0620–003 (McClintock et al 1995). The optical disk luminosities of these sources are $\sim 10^{32}$ erg s^{-1}. The continued mass transfer during quiescence supports the idea that the secondary star fills its Roche lobe. At such low X-ray luminosities as observed in quiescence, optical emission due to reprocessing of X rays is implausible. The optical emission may come from either the outer accretion disk heated by viscous dissipation or a hot spot in the stream-disk collision region (McClintock et al 1995).

From the optical disk luminosity of A 0620–003, McClintock et al (1995) estimate the mass transfer rate onto the outer disk $\dot{M}_{\rm d}$ to be $\sim 6 \times 10^{15}$ gs^{-1}, employing the empirical relations derived for dwarf novae. This rate is only slightly lower than the critical value inferred above for the stable accretion onto the compact object. Similar $\dot{M}_{\rm d}$ values in quiescence are inferred from the optical luminosity for Cen X-4 and GRO J1655−40 (see above) and for other X-ray novae in quiescence that show similar optical emission from the disk. Remarkably, this optically inferred mass transfer rate is the same order of magnitude as the long-term average of $\dot{M}$ (see Table 4). This is consistent with the idea that a large fraction of the transferred matter is stored in the disk during a quiescent interval. The potential energy of the accumulated matter can account for the total energy of a next outburst; this lends support to a disk instability for outbursts (see Section 3.3).

Conversion of the observed X-ray luminosity to the mass accretion rate depends on the assumption of the disk structure. If the inner accretion disk is optically thick, all the gravitational energy released is radiated away. In this case, the estimated values of $\dot{M}$ through the inner disk during quiescence range from 10^{11} (for A 0620+003; McClintock et al 1995) to 10^{13} g s^{-1} or even less, which are orders of magnitude smaller than the optically inferred rates $\dot{M}$d onto the outer disk. This would imply that very little of the transferred mass goes onto the compact object and provides strong evidence for steady mass accumulation in the disk during quiescence. However, the assumption of an optically thick disk may not be valid. If the disk is optically thin, estimating the accretion rate from the X-ray luminocity is not straightforward. Nonetheless, as discussed in the next section, the observed results still support mass accumulation in the outer disk.

3.2 *Mass Accretion During Quiescence*

The mass accretion during X-ray quiescence is a whole new subject. The origin of the observed soft X rays during quiescence is still quite uncertain. If the observed X rays are indeed blackbody radiation, the area of the emitting region is $\sim$ 1–10 km^2 for all except GS 2023+338 (which measures $\sim$400 km^2). This excludes an optically thick inner accretion disk for the possible site of the soft X-ray emission, because the inferred areas are much too small for the size of the inner accretion disk. Moreover, the observed blackbody temperature ($\sim$0.2–0.3 keV) is too high for the inner disk at $\dot{M} \sim 10^{11}$–10^{13}

g s^{-1}. According to the standard accretion disk model (Shakura & Sunyaev 1973), a disk will become optically thin below a certain accretion rate, which depends on the viscosity parameter α. The above result may imply that the inner accretion disk is no longer optically thick.

Narayan et al (1995) have introduced a stable disk model for low accretion rates that consists of an optically thick outer disk and an optically thin advection-dominated inner disk. Most of the thermal energy released by viscous dissipation is advected into the compact object, and only a small fraction ($\sim 10^{-4}$–10^{-3}) of the energy is radiated from the disk. Therefore, in a black-hole system, the X-ray luminosity will be far lower than that when the disk is optically thick. This can account for a very low X-ray luminosity against a relatively large $\dot{M}$ (e.g. $\sim 6 \times 10^{15}$ g s^{-1} for A 0620−003; McClintock et al 1995). This model can reproduce the observed spectra of the quiescent black-hole systems in the optical, UV, and X-ray bands. In this model, the soft X rays are mainly Comptonized synchrotron photons in the inner hot disk. Note that this model predicts a substantial flux of hard X rays and soft γ rays due to Comptonization.

The situation is very different in a neutron-star system, depending on whether or not the accretion flow reaches the neutron star. As long as the flow reaches the neutron star, the advected energy is eventually released on the surface and all goes into blackbody radiation. In other words, the conversion factor $L_X/\dot{M}$ is essentially the same for both an optically thick disk and an optically thin advection-dominated disk. Hence, for whichever disk, accretion at the optically inferred rate will give rise to an X-ray luminosity that is orders of magnitude higher than observed: e.g. for $\dot{M} = 10^{15}$ gs^{-1}, $L_X \sim 10^{35}$ erg s^{-1} with $kT \geq 0.3 f^{-1/4}$ keV, where f is the fraction of the X-ray emitting area of the neutron star surface. (The spectrum is not necessarily a blackbody spectrum, but may well be modified by Comptonization.) Thus, in this case, the advection-dominated disk is inadequate at least for the neutron-star systems, and the mass accretion rate through the inner disk is indeed low and cannot exceed the value inferred from the observed X-ray luminosity, i.e. $\sim 10^{12}$–10^{13} g s^{-1}.

However, there is a possibility that the accretion flow stops at some distance from the neutron star surface. Accretion onto a neutron star can occur only if the gravitational attraction is stronger than the centrifugal force exerted by the magnetosphere (the "propeller effect"; see Illarionov & Sunyaev 1975). This situation requires that the rotation speed of the magnetospheric boundary (the Alfvén surface) is slower than the local Keplerian velocity, which sets a minimum rate $\dot{M}_{min}$ to allow continued accretion onto the neutron star as

$$\dot{M}_{min} \simeq 2 \times 10^{16} \left(\frac{B}{10^9 \text{ G}} \right)^2 \left(\frac{P}{10^{-2} \text{ s}} \right)^{-7/3} \text{g s}^{-1},$$

for a 1.4 $M_\odot$ neutron star of 10^6 cm radius with the surface magnetic field B and a spin period P. Therefore, for such a neutron star as those of millisecond radio pulsars, accretion onto the surface will be prevented below a rate of the order of 10^{16} g s^{-1}.

Suppose accretion is blocked ($\dot{M} < \dot{M}_{\rm min}$) at the Alfvén radius, which is given approximately by

$$r_{\rm A} \sim 10^7 \left(\frac{B}{10^9 {\rm G}}\right)^{4/7} \left(\frac{\dot{M}}{10^{16}\,{\rm gs}^{-1}}\right)^{-2/7} {\rm cm}$$

$$\simeq 10^7 \left(\frac{P}{10^{-2} s}\right)^{2/3} \left(\frac{\dot{M}}{\dot{M}_{\rm min}}\right)^{-2/7} {\rm cm}$$

If the accretion disk is advection dominated and the soft X rays come from the hot inner disk (Narayan et al 1995), the X-ray luminosity of the neutron-star systems will be systematically lower than those of the black-hole systems for a given accretion rate. Because the disk terminates far away ($\geq 10^7$ cm unless P $\ll 10^{-2}$ s^{-1}) from the neutron star, the available gravitational energy will be an order of magnitude less. This may also cause a difference in the spectral shape. However, the observed results for both systems are strikingly similar to each other and do not show such systematic differences.

Although the hypothesis of an advection-dominated inner disk cannot be ruled out, such a disk with a relatively high mass-flow rate ($\sim 10^{15}$–10^{16} g s^{-1} as optically inferred) is not entirely consistent with the observed similarities between the neutron-star systems and the black-hole systems. The main origin of the soft X rays is probably not an advection dominated disk. On the other hand, any other structure of the inner disk will give a much higher X-ray luminosity for this accretion rate than observed. Thus, regardless of the disk structure, consistency with the observed results seems to require that the accretion rate through the inner disk is much lower than the optically inferred rate, lending support for mass accumulation in the outer disk.

The remarkable similarities in the X-ray and optical properties, particularly the ratio of the X-ray to optical disk luminosities, between the neutron-star systems and the black-hole systems in quiescence seem to argue for a common origin of the observed soft X rays for both systems. One possible origin of the soft X rays is the inner disk which is not entirely optically thick but is a gray body, i.e. the emissivity is less than that of a blackbody disk. This would resolve the problem arising in the blackbody calculation, where the emitting area obtained comes out too small. Verbunt et al (1994) interpreted the observed small emitting area of Aql X-1 to be either the magnetic polar caps or a boundary layer. However, because of the similarities between the neutron-star systems and the black-hole systems, X rays from the neutron star would comprise at most a fraction of those from the disk. Alternatively, the soft X rays might originate in the outer disk. A simple estimation from the gravitational potential shows that to obtain $L_X \sim 10^{32}$ erg s^{-1} for an optically inferred $\dot{M}$ of $\sim 10^{15}$–10^{16} g s^{-1}, the inner radius of the disk must be $\leq 10^{10}$ cm for a neutron-star system. (This inner radius scales with mass of the compact object.) This disk should not be optically thick, otherwise the temperature is far too low to account for the observed result. Both these possibilities remain speculative and require detailed examination.

At present, whether or not accretion onto neutron stars continues during X-ray quiescence is still an open question. As discussed below, this has an important relation to the subject of millisecond pulsars. The recycled pulsar scenario postulates that the neutron-star LMXBs are the progenitors of millisecond radio pulsars: The weakly magnetized neutron stars have been spun up by the accretion torque during the X-ray binary lifetime (for a review, see e.g. Bhattacharya 1995). Yet, there has been no direct proof, such as X-ray pulsation, that the neutron stars in LMXBs are rotating at millisecond periods. If indeed accretion onto a neutron star is confirmed, it provides a strong limit on the rotation period of the neutron star and its magnetic field (e.g. Stella et al 1994, Verbunt et al 1994). The observed X-ray luminosity gives an upper limit to $\dot{M}$ onto the neutron star: $\dot{M} < 10^{12}$–10^{13} g s^{-1}. Assuming that the soft X rays of Aql X-1 come from the neutron star, Verbunt et al (1994) state that it is not spinning at a rate of millisecond pulsars, even if $B \sim 10^8$ G, or alternatively that the magnetic fields are even weaker (see the equation above for $\dot{M}_{\rm min}$). Thus, the confirmation of soft X-ray emission from the neutron star would lead to a conclusion that at least transient LMXBs are not suitable progenitors of recycled millisecond radio pulsars.

The absence of a detected radio millisecond pulsar from Cen X-4 during X-ray quiescence is also consistent with slow rotation or low magnetic fields of the neutron star in this system (Kulkarni et al 1992). If a millisecond-rotator with $B \sim 10^8$–10^9 G is present, the mass accretion rate for the obtained X-ray luminosity upper limit at that time (5×10^{32} erg s^{-1}) should be low enough to allow the neutron star to function as a radio pulsar (Shaham & Tavani 1991). Yet, the absence of a millisecond pulsar is not entirely definitive: Some propagation effects may exist that quench the radio pulsation. More radio observations of the neutron-star LMXBs in quiescence are important.

3.3 *Outburst Mechanism*

Two competing models have been discussed to explain outbursts of X-ray novae: 1. disk instability models (Osaki 1974; Meyer & Meyer-Hofmeister 1981; Cannizzo et al 1982, 1985; Cannizzo 1993; Lin & Taam 1984; Huang & Wheeler 1989; Mineshige & Wheeler 1989) and 2. mass transfer instability models (Osaki 1985; Hameury et al 1986, 1987, 1988, 1990). The recent observations, especially those in quiescence (see Sections 2.4 and 3.1), set important constraints on these models and also on the mass accretion process.

3.3.1 DISK INSTABILITY MODELS Thermal instability triggers the outburst in the disk instability models. This instability arises from a very steep temperature dependence of the opacity in a partially ionized accretion disk.

An accretion disk is stable both in a cool, neutral state and in a hot, fully ionized state. However, when the mass inflow rate onto the outer part of a disk is within a critical range, the disk undergoes a thermal limit cycle. In a quiescent state, the accretion disk is in the cool state. As matter accumulates in the disk, both the surface density and temperature increase. When the surface density reaches an upper critical value, a thermal instability sets in. The disk jumps to the hot state, which gives rise to a high accretion rate, causing rapid infall of matter onto the compact object and hence an X-ray outburst. When the surface density drops below a lower critical value, the disk returns to the cool state.

The disk instability models can fairly well explain the observed properties of X-ray nova outbursts: the rise, decay, and recurrence times of outburst. The decay time of an outburst is determined by the diffusion time of matter in the hot state, whereas the recurrence period is determined by the diffusion time in the cool state. Since the diffusion time is proportional to the mass of the compact object, systematically longer decay and recurrence times are expected for black-hole systems than for neutron star systems (Mineshige & Kusunose 1993). Note that, under standard assumptions, the light curve expected in the disk instability models is a power-law function of time, if the total angular momentum is conserved (Lyubarskii & Shakura 1987). However, Mineshige et al (1993) and Cannizzo (1994) argue that mass and angular momentum are rapidly transferred outward from the inner hot region to the outer cool region, due to an abrupt change in temperature and hence kinematic viscosity across the thermal transition front. This effect yields an exponential decay of the disk luminosity.

The secondary and tertiary maxima seen in the light curves of some black-hole X-ray nova outbursts (see Figure 3) may also hold important clues. The decay times are similar before and after the secondary maximum. This implies a sudden supply of extra mass into the disk. Possible mechanisms proposed for the sudden mass supply are: 1. evaporation of matter by X rays near the inner Lagrangean point (L_1) when the disk and ionized clouds become incapable of blocking X rays from the central region (Chen et al 1993, Mineshige 1994) and 2. a mass transfer instability caused by hard X-ray heating of the subphotospheric layers of the secondary during an outburst (Chen et al 1993). Mineshige (1994) points out that an abrupt heating of the outer portion of the disk by X rays is also required to explain the fast rise of the secondary maximum.

There is evidence supporting a disk thermal instability as the mechanism of X-ray nova outbursts. As described in Section 3.1, the optical observations indicate continued mass transfer into the outer disk during quiescence at a rate of 10^{15}–10^{16} g s^{-1}. This value is similar to that derived from the time-averaged outburst luminosities (Table 4). Hence, it is consistent with the idea that most of the transferred mass remains in the disk during quiescence and the total mass accumulated since the last outburst is consumed in an outburst. The low X-ray luminosities observed during quiescence are interpreted to show that only a small fraction of the transferred mass goes onto the compact object. (See the discussion in Section 3.2.)

However, some problems with the disk instability models have been pointed out. In order to explain recurrence times as long as ~ 50 y, the viscosity parameter α in quiescence must be extremely small: $\alpha \leq 10^{-4}$ (Hameury et al 1986, 1993; Mineshige & Wheeler 1989; Mineshige & Kusunose 1993). However, α is expected to be ~ 0.01 for those systems with recurrence times of the order of 1 year. This large difference in α between the systems whose other properties are similar to each other is difficult to explain. Furthermore, for such cases as A 0620-003, the small α-value ($\sim 10^{-4}$) inferred from a long recurrence time is not compatible with the $\alpha \sim 0.01$ required to reproduce the observed amplitude and duration of the outburst (Mineshige & Kusunose 1993).

3.3.2 MASS TRANSFER INSTABILITY MODELS In mass transfer instability models, the subphotospheric layers of a companion star are considered to be heated up by relatively hard (> 7 keV) X rays from a compact object. These layers slowly expand and ultimately bring the atmosphere into an unstable regime, which leads to a sudden mass transfer. An accretion disk builds up and thickens as the mass transfer rate from the secondary increases. Consequently, the mass inflow from the outer region of the disk onto the compact object is suddenly enhanced, giving rise to an outburst. The mass loss instabiltiy will cease, when the L_1 region is shielded by the accretion disk, and the outburst ends when all of the matter in the disk has been accreted onto the compact object. Once the system settles back into a quiescent state, it will take a long time for X rays to heat and expand the atmosphere of the secondary until it reaches the unstable condition again (next outburst).

The calculated results show that the mass transfer instability models can also account for the main characteristics of outbursts such as the light curve and the recurrence time (Hameury et al 1986, 1988, 1990). However, recent observational results impose a severe problem on the mass transfer instability models. In order for a mass transfer instability to trigger an outburst, the hard X-ray flux at the L_1 point must exceed the intrinsic stellar flux: $L_X(> 7\text{ keV}) > 2.5 \times 10^{34}(M_c/M_\odot)^2$ erg s^{-1}, where M_c is the mass of the companion (Mineshige et al 1992). However, as described in Section 2.4, the X-ray spectra during quiescence are all very soft, with a blackbody temperature $kT \sim 0.2$–0.3 keV, and the X-ray luminosities are mostly in the range 10^{31}–10^{33} erg s^{-1}. Thus, the hard X-ray flux appears far insufficient to induce a mass transfer instability.

As discussed above, the observed results seem to be more in support of a disk instability than a mass transfer instability for the mechanism of triggering an outburst. Nonetheless, a mass transfer instability may still be a viable mechanism for the secondary (and tertiary) maxima during decay. Also, many outbursts exhibit complex multipeaked light curves (see Section 2.2). Some X-ray novae (e.g. GRS 1915+105, GRO J1655−40) remain active for years, repeating outbursts. These complex activities may well be due to the secondary mass transfer from the companion as a consequence of X-ray heating. A further interesting case is the outbursts of 1608–522. Some of the outbursts of this source occur even when it is persistently on (see Section 2.2.1). This aspect is difficult to explain in terms of a disk instability.

3.4 *How Many LMXBs are Still in Quiescence?*

In the past 20 years, about 30 low-mass transients have been discovered. The discovery rate has increased substantially since late 1980s owing to a continued sky watch with *Ginga*, *GRANAT*, and *CGRO*. The average rate of detection of X-ray nova outbursts is approximately 2 y^{-1} in the past five years. There must be many more low-mass binaries that are currently in quiescence but that eventually undergo an outburst. An attempt to estimate the total number of them was made previously by Tanaka (1992a).

In estimating the total number of such low-mass binaries, the largest unknown is the average recurrence period for all X-ray novae. The recurrence period is largely different from source to source, distributed in a very wide range from ~ 1 y to more than 50 y. There is no apparent difference between the neutron-star systems and the black-hole systems. In fact, most X-ray novae were observed only once. From the available data, an average period shorter than 10 y is unlikely. Here we assume it to be 10–50 y.

For most X-ray novae observed, the estimated distances are less than 5 kpc. Even if distance estimates are not available, the assumption that the observed peak luminosity is $\sim 10^{38}$ erg s^{-1} gives distances < 5 kpc. There are only a few detected X-ray novae that are more distant (e.g. GRS 1915+105, 1730−335).

This is obviously due to a detection bias toward bright outbursts. Considering the fact that 90% of the observed low-mass transients are within a galactic longitude range of $\pm 80^\circ$ (showing that almost all the low-mass transients lie within ~ 8 kpc of the Galactic center), the effective coverage of the Galactic plane would be $\sim 10\%$.

With the above considerations, the total number of LMXBs in quiescence is estimated to be ~ 200 for a modest average recurrence period of 10 y and ~ 1000 for an average period of 50 y. Although these estimates are crude, it is certain that the currently known LMXBs are but a minor fraction of the whole LMXB systems. In addition, it is remarkable that most of the bright X-ray novae observed thus far are black-hole systems. Although current statistics are still insufficient, it seems probable that the number of (quiescent) black-hole LMXBs is at least as many as or even greater than that of (quiescent+persistent) neutron-star LMXBs.

There is another striking difference between neutron-star LMXBs and black-hole LMXBs. As mentioned in Section 2.1, ~ 80 neutron-star LMXBs are known to be persistent, whereas not a single persistent black-hole LMXB has yet to be found. The reason for this distinct difference remains unclear. According to the discussion in Section 3.1, this difference implies that the doner stars of the black-hole low-mass systems are somehow unable to achieve a mass transfer rate $> 10^{16}$ g s^{-1} required to make them persistent sources. Yet, the optically inferred mass transfer rates of the observed black-hole LMXBs are only slightly lower than this critical rate. There is no noticeable difference in the types of secondary stars or in the orbital period distribution between the black-hole LMXBs and the neutron-star LMXBs. Although the conditions that determine the accretion rate are not yet clear, the subtle difference in the accretion rate may be a consequence of possible differences in the evolutionary state between the two classes of low-mass binary system.

The above results may provide important clues to the problems of formation and evolution of LMXB systems (for a review, see Verbunt & van den Heuvel 1995).

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