Galactic Black Hole Binaries: Multifrequency Connections

S. N. Zhang**, I. F. Mirabel†, B. A. Harmon*, R. A. Kroeger‡, L. F. Rodriguez♯, R. M. Hjellming♭ and M. P. Rupen♭

*ES-84, Marshall Space Flight Center, Huntsville, AL 35812
*Universities Space Research Association
†CEA-CEN Saclay, Service D’Astrophysique, 91191 Gif-Sur-Yvette, Cedex, France
‡Naval Research Lab., MS 4151, 4555 Overlook Ave., Washington, DC 20375
♯Instituto de Astronomia UNAM, Apdo Postal 70-264, DF04510 Mexico City, Mexico
♭National Radio Astron. Obs., P.O. Box O, 1003 Lopezville Rd., Socorro, NM 87801

Abstract. We review the recent multifrequency studies of galactic black hole binaries, aiming at revealing the underlying emission processes and physical properties in these systems. The optical and infrared observations are important for determining their system parameters, such as the companion star type, orbital period and separation, inclination angle and the black hole mass. The radio observations are useful for studying high energy electron acceleration process, jet formation and transport. X-ray observations can be used to probe the inner accretion disk region in order to understand the fundamental physics of the accretion disk in the strongest gravitational field and the properties of the black hole. Future higher sensitivity and better resolution instrumentation will be needed to answer the many fundamental questions that have arisen.

INTRODUCTION

Significant progress has been made in the study of the galactic black hole binaries since the launch of the Compton Gamma Ray Observatory in April 1991. It is now widely believed that some X-ray binary systems harbor a stellar black hole at the center of the accretion disk in each system. A variety of high energy spectra and light curves have been observed from many of them. Some of them also exhibited highly relativistic jets, which are found to be in correlation with the high energy radiation. Since the first mass determination of the assumed black hole in Cyg X-1 about 25 years ago [10,108], the second property, i.e., the spins, of black holes have also been inferred recently [116], and are considered to be the missing link in the proposed unification scheme of all types of black hole binaries [116].

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Several review articles on galactic black hole binaries now exist, including those in the same proceedings. In this review article, we try to avoid any significant overlapping with other review articles, by focusing on (a) summarizing these new and important multiwavelength observations, and (b) exploring the physical connections between observations made at different wavelengths to obtain more complete pictures of these systems.

**BASIC HIGH ENERGY CHARACTERISTICS**

All of these galactic black hole binaries were originally discovered in either X-ray (1-10 keV) or hard X-ray (20-300 keV) bands. Their X-ray or hard X-ray luminosity dominates their total electromagnetic radiation energy output. In this section we discuss briefly their basic high energy emission characteristics, in order to explore the multiwavelength aspects of these systems.

**High Energy Continuum Spectra**

The high energy spectra of galactic (candidate) black hole binaries are made of primarily only two components – a blackbody-like soft component and a power-law-like hard component (see [111] for a review of high energy continuum spectra
observed in black hole and neutron star X-ray binaries), as shown in figure 1 for the superluminal jet and black hole source GRO J1655-40 [115]. In some sources, the soft component is absent above 1 keV and the hard power-law component becomes harder with a break between 50-200 keV, as shown in the same figure for GROJ0422+32. The soft component is believed to be emitted from the inner accretion disk region and can be well described by the so-called multi-color disk blackbody spectral model [60,70], in which the total emitted spectrum is the integration of the local blackbody emission from each annulus with a temperature $kT_{bb} \propto r^{-3/4}$. To obtain the physical parameters of the inner accretion disk, corrections for the relativity and spectral hardening effects must be taken into account [116]. The observed peak blackbody temperatures of the multi-color disk blackbody spectra vary between 0.1 to 2.5 keV (see figure 5 and the corresponding section for details).

The origin of the power-law-like hard component is still not well understood, although inverse Compton up-scattering of low energy photons by high energy electrons are usually believed to be involved. The nature and origins of both the low energy photons and the high energy electrons are still not identified unambiguously yet, despite the existence of many models. There usually exists an anti-correlation between the soft component luminosity and the hardness or flatness of the power-law whose photon spectral index varies between -1.5 to -3.5. Usually the power-law component is observed to fall into one of the two states: a hard state corresponding to a minimum luminosity ($< 5 \times 10^{36}$ ergs/s) [114] or the absence of soft X-ray component [22], with a photon spectral index between -1.5 to -2.0 and spectral break above 50-200 keV; or a soft state corresponding to a higher soft X-ray component luminosity [22,35,115,114], with a photon spectral index between -2.5 to -3.5 and no detectable spectral break up to 300-600 keV [35]. Figure 1 illustrates a typical spectrum of each type (soft or high state for GROJ1655-40 and hard or low state for GROJ0422+32). However, a source may remain in a different state for a time, and the transition or evolution between the states is usually continuous, for example in Cyg X-1 [114].

Both the soft and the hard components have been used as signatures or indicators of black hole binary systems. Similar components have, however, also been detected from neutron star binary systems, such as the type I X-ray burster 4U1608-52 [69,112], although the absolute hard X-ray luminosity is found to be systematically higher in black hole systems than in neutron star systems [5].

### High Energy Long Term Light Curves

A variety of high energy light curves have been observed from galactic black hole binaries [18]. These light curves can be placed conveniently into three classes: transients with nova-like light curves, which form the majority of the black hole binaries, such as A0620-00, GS2000+25, GS1124-68, GS2023+23, H1705-250, GROJ0422+32, GROJ1719-24 = GRS1716-249 and GRS1739-278, with a fast rise (a few days) and slow exponential decay (a few tens of days); transients with mul-
multiple outbursts, such as the superluminal jet sources GRS1915+105, GROJ1655-40 and a possible jet source GX339-4; persistent sources such as Cyg X-1, LMC X-1, LMC X-3. We shall call them type I or nova-like, type II or multiple-outbursts and type III or persistent high energy light curves in the following discussion. Samples of some BATSE hard X-ray light curves, together with some optical, radio and soft X-ray light curves are shown in figures 2-4. Please refer to the references where some of the original light curves were published for more details. (Note that some of the sources listed above, i.e., GROJ1719-24, GRS1739-278 and GX339-4, are not yet dynamically established black hole binaries with the compact object masses in excess of 3 $M_\odot$). These different types of light curves cannot be understood with high energy observations alone. In the following, we will try to understand some of their high energy behaviors using multifrequency data.

**OPTICAL AND INFRARED STUDIES**

In this section we discuss briefly the application of optical and infrared observations to the understanding of the properties of inner accretion disk regions and the black holes.
FIGURE 3. Radio [45,100,109] (Hjellming & Rupen 1995, Tavani et al. 1996, Wu & Hunstead 1996), Optical [2,3,76,78,80] (Bailyn et al. 1995a, 1995b, Orosz 1996, Orosz & Bailyn 1997, Orosz et al. 1997a, 1997b), soft and hard X-ray [90] (Robinson et al. 1997) light curves of a type II or multiple-outbursts source GROJ1655-40.
FIGURE 4. Radio, soft and hard X-ray light curves of the type III or persistent source Cygnus X-1 [114,117] (Zhang et al. 1997).
TABLE 1. Dynamically Established Black Hole Binary Systems.

| Source Name | Alternate Name | $f_M$ ($M_\odot$) | $i$ (deg) | $M_{BH}$ ($M_\odot$) | Star | $M_c$ ($M_\odot$) | X-ray Type | Radio Properties | Ref. |
|-------------|----------------|-------------------|----------|----------------------|------|------------------|------------|------------------|------|
| 0538-641 LMC X-3 | 0.14 | 50°–60° | 7–14 | B3 Ve | 4–8 | S | III | 19,23 |
| 0540-697 LMC X-1 | 2.3±0.3 | 40°–63° | 4–10 | O7–9 III | 20–25 | S | III | D | 23,48,97 |
| GRO J0422+32 XN Per 1992 | 1.21±0.06 | 48°±3° | 3.57±0.34 | M2 V | 0.4 | H | I | T | 15,31,37,77 |
| A 0620–00 XN Mon 1975 | 2.91±0.08 | 66°±4° | 4.9–10 | K4 V | 0.4–0.7 | S | I | T | 43,46,62,81,94 |
| GRS 1124–683 XN Mus 1991 | 3.01±0.15 | 54°–65° | 5.0–7.5 | K2 V | 0.8 | S, H | I | T | 56,79 |
| GRO J1655–40 XN Sco 1994 | 3.16±0.15 | 69°.5±0°.08 | 7.62±0.22 | F3–F6 IV | 1.2–1.5 | S | II | J, M | 3,45,78,101,103, |
| H 1705–250 XN Oph 1977 | 4.0±0.8 | 70°±10° | 4.9±1.3 | K3 V | 0.7 | S | I | 61,87,88 |
| 1956+350 Cyg X-1 | 0.24±0.01 | 10°–40° | 7–20 | O9.7 Iab | 20–30 | H, S | III | P | 10,33,34,53,82, |
| GS 2000+25 XN Vul 1988 | 4.97±0.10 | 65°±9° | 8.5±1.5 | K2–K7 V | 0.4–0.9 | S | I | T | 12,46 |
| GS 2023+338 V404 Cyg | 6.08±0.06 | 56°±2° | 12.3±0.3 | K0 IV | 0.9 | H | I | T | 13,14,38,53,93, |
| GS 2023+338 V404 Cyg | | | | | | | 95,106,107 |

Note: (3) mass function; (4) system inclination angle; (5) black hole mass; (6) optical/infrared spectral type; (7) companion mass; (8) high energy spectral type (‘S’: soft or high state, ‘H’: hard or low state); (9) high energy light curve type (I: nova-like transient, II: multiple outbursts, III: persistent); (10) radio properties (‘P’: persistent, ‘T’: transient, ‘M’: multiple-episodes, ‘D’: positive detection, but long term behavior unknown, ‘J’: superluminal jets.); (11) references: the numbers are referred to their order as appeared in the reference section of this paper. (Part of this table is adapted from the table 1 of Chen, Shrader and Livio 1997 [18].)
Determining the Black Hole Masses

Ellipsoidal optical and infrared light curve modulations of the companions in these systems can be used to determine their orbital periods. Spectroscopic measurements of the Doppler shifts of some spectral line features can be used to obtain their mass functions, i.e., their mass lower limits. Detailed modelling of their light curves allows the determination of the system inclination angles. The spectral types of the companion provide information on the nature of the companion stars. Therefore in principle the complete system parameters, such as the orbital periods, orbital separations, masses of both the companions and the compact objects (the black hole for the systems we are discussing in this article) can be determined from optical and infrared observations [83]. Perhaps the best example and success of this technique is the precise black hole mass ($7 \, M_{\odot}$) and other system parameters determination in GROJ1655-40 [103,78].

Up to now, reliable dynamical mass determinations from optical and infrared observations have resulted in ten systems in which the compact object masses are most likely greater than $3.2 \, M_{\odot}$ (see table 1, which lists also their radio and X-ray properties discussed in the following sections), the observational and theoretical upper limits of a neutron star. In several systems, the lower limits to the compact object masses are already above $3.2 \, M_{\odot}$. Arguably these constitute so far the strongest evidence of the existence of black holes in binary systems. Although probing only the surface of the companion star and the outer disk region, these optical and infrared studies can also be used for understanding the high energy emission (from the inner-most region of the disk) behaviors of these systems, especially the three types of light curves we mentioned in the previous section.

Understanding Their High Energy Light Curves

The companion stars in the systems producing the Type III or persistent light curves are all high mass ($10-30 \, M_{\odot}$) O or B stars. The type III light curves are apparently due to the high mass transfer rates from their high mass companions, either through Roche-lobe overflow or stellar wind accretion. Apparently they are all accreting below the Eddington rate. There are, however, some significant differences between the three sources listed above. Cyg X-1 spends most of its time in a hard state, in which the total luminosity is dominated by the hard power-law. Occasionally the source enters into its soft state, in which a prominent soft component (with a higher temperature than that in the hard state) appears, nearly simultaneous with the softening of the power-law [114]. LMC X-1 and LMC X-3, on the other hand, always remain in the soft state with prominent soft X-ray components and steeper power-law components, similar to the soft state of Cyg X-1. Even between LMC X-1 and LMC X-3, there exists also some major differences. For example, in LMC X-1 the soft X-ray component remains rather stable, while the power-law component can vary substantially [23]. While in LMC X-3, the
two components may vary substantially and independently, and the intensity and spectral hardness below 13 keV show a positive correlation [25]. It is also interesting to note that LMC X-3 and Cyg X-1 are the only black hole binaries exhibiting long term periodic variations in their optical and X-ray light curves. In particular, orbital modulations in both the soft and hard X-ray bands have been seen from Cyg X-1 [53,82,85,113]. Although the soft X-ray flux modulation may be interpreted as the modulation of the column density (ionized or neutral) due to stellar wind [53], the hard X-ray modulation is inconsistent with this interpretation [82,86]. Since $\sim 30\%$ of the total hard X-ray component is estimated to be made of the reflection of an input power-law component [21], one possible origin of the observed orbital modulation is that its companion star also contributes to the total reflection component. Then the contribution from the companion would produce orbital modulations, similar to the optical and infrared ellipsoidal modulations.

The companion stars in all these systems producing the Type I or nova-like light curves are low mass ($< 1 M_\odot$) main sequence stars, and no such low mass companion black hole binaries are known to produce other types of light curves. The transient nature of such systems has been explained as due to their sufficiently low mass transfer rate and that the mass accretor is a black hole [51,105]. The outburst trigger mechanism is likely due to the thermal instability in the outer part of the disk [57]. In the quiescence state, the material is steadily transferred at a very low rate from the companion to the accretion disk via Roche-lobe overflow and a significant portion of the material is accumulated in the disk. Thus the quiescence state disk is quasi-steady. When an instability is developed in the disk, an outburst occurs, during which the accumulated material is transferred to the black hole with a much higher rate. In this scenario the rise time would correspond to the sound propagation time from the outer disk to the inner disk [65,92]: $t_{\text{rise}} = R(\alpha C_s)^{-1}$ (where $R$ is the outer disk radius, $\alpha$ the dimensionless viscosity parameter and $C_s$ the sound speed) which is on the order of a day for $\alpha \sim 0.1$. The decay time would correspond to the viscous time scale of the hot state disk, $t_{\text{vis}} = (R/H)^2(\alpha \Omega)^{-1}$ (where $H$ is the vertical height of the disk and $\Omega$ the angular speed of disk at radius $R$), which is on the order of 100 days for $\alpha \sim 0.1$.

There are still some fundamental questions concerning the quiescent disk structure. The standard thin disk extending to the last stable orbit of the black hole is problematic, because the inner part of the disk cannot stay in the ‘cold’ branch of the ‘S’ curve (inferred from the observed quiescence X-ray emission), which is essential for the disk instability model [57]. The most recent version of the advection dominated disk model [73,42] with the cooling dominated inner part truncated is much more successful than the standard thin disk model, but also has some problems. First, location of the inner disk boundary, critical in the model, is not determined self-consistently, although the thermal instability condition can be applied to produce a constrain. Second, it cannot explain the delayed hard X-ray outburst in GROJ1655-40 [90], with respect to the soft X-ray outburst after the initial optical on-set [80]. Therefore a more consistent quiescent state disk model is still not available yet.
The companion stars in the Type II or multiple-outbursts systems may be intrinsically different from that in the Type I systems (the companion star in GX339-4 has not been identified yet). Although also called a low mass system, GRO J1655-40 has an evolved companion star of \(2.3 \, M_\odot\) [3]. Usually such donor stars would have sufficiently high mass transfer rate, preventing the system from having a transient nature. This discrepancy has been reconciled by assuming that GRO J1655-40 is in a short-lived evolutionary stage where the mass transfer rate is sufficiently low to allow instabilities to occur [55]. This is a possible way to explain the rarity of this type of systems. Its multiple outbursts are not periodic and so apparently not related to its orbital motion, but most likely due to another instability after the initial outburst is triggered. Perhaps the X-ray heating of the companion star induces the so-called mass transfer instability [20,41] or 'echoes' [1]. This may be due to its peculiar type (much massive and larger than other companion stars) of this companion star. Comparing the the K(2.2\,\mu m) spectra of GRS1915+105 observed at different epochs [16,30,68], one finds the characteristic HeI and Br\(\gamma\) emission lines of O-Be stars [68] with time variable intensity. It has been shown that the absolute infrared magnitude, time variability, and spectral shape of GRS1915+105 is comparable to that of SS 433 and other high mass X-ray binaries [17]. Furthermore, the infrared afterglow of an X-ray/radio outburst observed on August 1995 revealed that at that time GRS1915+105 was enshrouded in a dusty nebula of \(~10^{16}\) cm radius [67]. In summary, the infrared observations suggest that the donor star belongs to the class of massive stars with transitional spectral classification due to the dynamically unstable stellar atmosphere or wind [72]. If this is confirmed, GRS 1915+105 would be a black hole with a peculiar massive companion which is losing mass at rates of \(10^{-6}-10^{-5}\, M_\odot\, \text{yr}^{-1}\). Further more definitive observations are still needed to clarify its companion star type, which may be critical for understanding the nature of the system. Despite that GROJ1655-40 is the only one of the Type II sources whose companion is unambiguously identified to be a peculiar star, it is worthwhile to explore the relationship between the properties of the companions and the high energy behaviors of the systems.

**RADIO STUDIES**

Radio fluxes from these systems originate in the incoherent synchrotron radiation of high energy electrons. The radio emission region is usually comparable or larger than the size of the accretion disk or the whole binary system. For a typical source of 0.1 Jy at 3 kpc, since the surface brightness temperature cannot exceed \(10^{12}\) K, the minimum size of the radio emission region is about \(10^{12}\) cm. The size of a typical black hole binary with an orbital period of order one day is also about \(10^{12}\) cm. For those spatially resolved systems, i.e., those jet sources, their sizes are usually between \(10^{14}\) to \(10^{16}\) cm. Therefore the radio emission region can be significantly larger than the whole binary system. At a distance far away from the accretion disk, the strength of the magnetic field is most likely of order \(10^{-3}\) Gauss,
therefore the typical electron energy is of order \(10^9\) eV for a characteristic radiation frequency of \(10^{10}\) Hz. Therefore the radio emission from black hole binary systems is usually produced by high energy electrons far away from the central region of the accretion disk.

Corresponding to the three types of X-ray light curves, there are also three types of radio light curves, with similar morphologies. The systems producing the type I or nova-like X-ray light curves produce usually also type I radio light curves with fast rises (although their radio flux on-sets are rarely caught) and slow exponential decays, in good correlation with the X-ray light curves (see ref. [44] for a review). The radio emission regions in this class of systems are never spatially resolved and have been modelled as synchrotron bubble events, i.e., expanding spherical bubbles of relativistic plasma. The origin and acceleration mechanism of the high energy electrons is still not identified, but is believed to be related to the enhanced mass accretion rate in the inner accretion disk region, inferred from the correlation between the radio and X-ray light curves. It is worthwhile to note that such mass accretion and radio emission correlation cannot be firmly established in those active galactic nuclei (AGN), since the dynamical time scales in AGN are typically larger by a factor of \(10^6-9\) than the black hole binary systems.

The radio light curve of Cyg X-1 is very similar to its X-ray light curve, i.e., persistent, variable and with two distinct states. Its high radio flux state corresponds to its hard X-ray high and soft X-ray low flux state, i.e., the so-called hard/low state [114,117]. Although the hard/low state mass accretion rate may be slightly lower than that in its soft/high state, any changes in mass accretion rate through the inner accretion disk region may not play a strong role [114]. Therefore the observed radio, soft and hard X-ray correlation suggests that the radio flux increase is not simply related to the mass accretion rate increase. Instead, the radio flux seems to respond to the hard X-ray flux positively. It is therefore possible that the much higher energy \((10^9\) eV) electrons responsible for the radio flux production are somehow related to the much lower energy \((10^5\) eV) electrons, despite that the former population of electrons are distributed far away from the central region of the disk, where the hard X-ray photons are produced. Perhaps the much higher energy electrons originate from the lower energy electrons and they share the same initial acceleration mechanism. Exactly how these electrons are accelerated and why the acceleration process can be maintained stably still remain poorly understood. Another type-III X-ray light curve source, LMC X-3, has never been observed at any radio frequencies, with an upper limit of \(< 0.3\) mJy at 3 and 6 cm [30]. This would not be surprising if its radio luminosity is similar to that from Cyg X-1, since it is located at about a factor of 20 farther away than Cyg X-1 and the radio flux from Cyg X-1 is only between a few and tens of mJy. The detection of a strong radio flux has been reported from the third type III source LMC X-1 at 81 mJy at 6 cm [97]. Assuming isotropy, its absolute luminosity is about a factor of 3000 \textit{stronger} than Cyg X-1, about a factor of 2 \textit{brighter} than the peak luminosity of the superluminal jet sources GROJ1655-40, and \textit{comparable} to the peak luminosity of the other superluminal jet source GRS1915+105. We caution the readers that a
later observation of LMC X-1 with the same instrument did not detect the source at an upper limit of \(\sim 1\) mJy [30]. Therefore more radio observations of the source are still needed to clarify the situation.

The radio light curves of the two superluminal jet sources, i.e., GROJ1655-40 [45,101] and GRS1915+105 [66], exhibit close, but complicated relationships with their type II X-ray light curves. Their peak radio luminosity is also much higher than most of the type I or III systems discussed above. In GRS1915+105, there seems to exist an almost one to one correspondence between the radio flares and the hard X-ray outbursts [32]. However, there seems to be three different kinds of radio flare states [32]. The relationship between the particular type of the radio flare and the hard X-ray emission properties is not clear. The correlation between radio intensity and the hard X-ray intensity is positive below about 100 mJy; above this level, the correlation becomes negative [39]. In GROJ1655-40, a dynamically confirmed black hole binary, the initial hard X-ray outburst [110] was accompanied with a bright radio flare resulting from superluminal jet ejection [45,101]. All first three hard X-ray outbursts were well correlated with radio flares (superluminal ejection events) [40], although the overall level of the radio emission followed a slow exponential decay. Two subsequent hard X-ray outbursts, however, were not accompanied with any detectable radio emission above 5 mJy between 1.5-15 GHz [100]. Therefore, this seems to indicate that significant hard X-ray production is a necessary, but not sufficient condition for jet ejection. Therefore models [58,63] involving hard X-ray production from the relativistic jets seem unlikely [115]. Nevertheless, what we have learned from the radio and hard X-ray correlations are still important for understanding some problems.

The positive X-ray and radio flux correlation indicates that jet ejection events are related to increased mass accretion. It is widely accepted that a magnetic field should be an essential ingredient in the jet formation according to the Blandford and Payne model [6,7]. Therefore it is very likely that rather strong magnetic fields exist in these systems. If the hard X-ray component is indeed produced by the long suspected Comptonization in an optically thin (inferred from the rather steep power law) corona, then the correlation also supports the jet production model in which the jets are produced from the interaction between the corona and the magnetic field [64].

The black hole (candidate) binary system GX339-4 is also a variable radio source [96]. Intense (\(\sim\) Jy) radio flares similar to those from GROJ1655-40 and GRS1915+105 have never been observed. We, however, cannot conclude that the source has never produced radio flares because of the rather sporadic observations from the southern hemisphere. Because of this, the relationship between its radio and X-ray fluxes is not completely clear. The recent observation of a possible radio jet in GX339-4 [29], during an X-ray active state, may provide evidence that its radio behavior is similar to the two superluminal jet sources. We may eventually be able to conclude that all the type II or multiple-outbursts systems share some common radio emission properties, related to their high energy, especially their hard X-ray, behavior.
An essential question to be answered concerns the physical connections between the types of the companion stars, orbital separations, optical and IR light curves, X-ray and hard X-ray light curves, and radio light curves. A possible scenario follows: their companion stars and orbital separations determine the mass transfer property from the companion stars to the outer regions of the disk, this in turn controls their optical properties, at least during the initial outburst after a quiescence period. The mass flow rates through the inner disk boundary onto the black hole modulate their soft and hard X-ray light curves. The soft X-ray photons are emitted from the optically thick inner accretion disk region, and the hard X-ray photons are believed to be produced by inverse Compton up-scattering of low energy photons (probably the soft photons from the disk) by higher energy electrons, although the origin of the electrons is still not unambiguously identified. Somehow at least a portion of these electrons are accelerated to higher energies and move far away from the central disk region to produce radio fluxes via incoherent synchrotron radiation. This global picture agrees qualitatively to the three types of X-ray and radio light curves, through our investigations of the multifrequency connections in these systems. The correlation between the three types of companion stars and their corresponding light curves suggest that in the type II or multiple-outbursts systems another instability, possibly the mass overflow instability in the companion star caused by the X-ray heating of the central soft and hard X-ray sources, may play a major role in the subsequent outbursts since the initial one. In the type III or persistent systems, perhaps the feedback of the X-ray heating to the high mass companion stars reaches a steady state so that these systems become persistent sources.

The above picture does not explain why some systems produce powerful jets, while others apparently do not do so. It is possible that in GROJ1655-40 the inferred mass transfer rate from the X-ray observations is only a portion of the total mass transfer rate from its peculiar companion star. The rest of the material is not transferred through the disk, but instead forms a disk ‘wind’, available for producing the powerful jets. In other systems the disk ‘wind’ may be very weak. In GRS1915+105, although the exact type of its companion is unknown as we discussed above, there indeed appears to be some evidence for a significant wind from the system [68]. This scenario, however, still does not explain why the outflows in GROJ1655-40 and GRS1915+105 are highly collimated. This may be partially explained by the properties of the black holes, as will be discussed below.

**X-RAY PROBING OF THE INNER DISK REGION**

X-ray observations at keV energies can be used for probing the accretion disk very close to the black hole horizon, thus providing important tools for testing accretion disk models and some general relativistic effects. This is because the peak emission energy of the blackbody spectra from the inner disk region is between one-tenth and several keV [116], and that these X-ray photons are much more penetrating.
than EUV photons emitting from the inner disk regions of AGNs. Because of the interactions between the black holes and the accretion disks, X-ray observations can also be used for studying the properties of the black holes [116]. In this section we will discuss three aspects of probing the accretion inner disk regions with X-ray observations.

Continuum X-ray Spectra

As we mentioned before, the continuum X-ray spectrum from the inner accretion disk region is well described by the multi-color disk blackbody model [60,70]. The spectrum depends only upon the location of the inner accretion boundary, mass of the black hole and the mass flow rate through the inner disk region. For a steady disk in a high mass accretion rate state, the inner disk boundary is assumed to be the last stable orbit of the black hole, beyond which the material falls into the black hole with near radial trajectories. For the purpose of the spectral fitting, the free parameters are the peak blackbody temperature, absorption column density, and the normalization at a given energy. The inner disk radius and the disk inclination angle are coupled in the normalization parameter, so they cannot be determined independently. In some cases the system inclination angle and/or the black hole mass can be well constrained through the optical light curve modelling and spectroscopic measurements (to determine the companion star type). Therefore the size of the inner disk boundary can also be constrained. The values of the black hole mass,
spin and the rotation direction of the material moving around it are all coupled into the size of the inner disk boundary, since the location of the last stable orbit of a black hole depends upon all of them. If the mass of the black hole is also known from optical observations, we then have the possibility to constrain the spin of the black hole. It should be noted that various correction factors to account for spectral hardening (due to electron scattering) and relativity effects have to be included in this process. This has been done recently in a number of black hole systems, whose system parameters have been well constrained from optical observations [116]. In figure 5, the peak blackbody temperature is shown as the functions of the black hole mass, spin and mass accretion rate.

It has been found that the two superluminal jet sources GROJ1655-40 and GRS1915+105 (by combining the interpretation of its 67 Hz QPOs as the \( g \)-mode oscillations [75]) contain most likely a black hole spinning at near the maximally allowed rate, while several other black holes with the observed soft components, but no relativistic jets, contains slowly or non-spinning black holes. It is also proposed that several ‘hard’ X-ray transients, i.e., no soft component has ever been observed from them, may contain rapidly spinning black holes with retrograde disks [116]. Therefore all types of observed black hole binary systems are naturally unified within one simple scheme. The state transitions in Cyg X-1 are proposed to be due to the disk rotation direction reversal, caused by the so-called ‘flip-flop’ type instability in wind accreting systems [116]. Future higher sensitivity observations, especially below 1 keV, are needed to test this scheme.

**Iron Line Diagnostics**

The first spectral line feature from a black hole binary system was detected with the *EXOSAT GSPC* in Cyg X-1 [4]. Since then the Cyg X-1 spectral line feature has been observed with *Tenma* [54], *Ginga* [24,99] and more recently with *ASCA* [26]. From the high resolution ASCA observations [26], the overall feature can be modelled by a narrow (equivalent width 10-30 eV) iron \( K \) emission line at 6.4 keV and an iron \( K \) edge at 7 keV representing a reflection component, from the outer part of the accretion disk. The disk is inferred to be ionized, with a covering angle \( \Omega/2\pi \sim 0.2 - 0.4 \). Due to the limited statistics, minor contribution due to the reflections from the companion star and/or fluorescence emission from the inner accretion disk region cannot be excluded. The small or null contribution from the inner disk region may be due to the much higher degree of ionization of the inner disk region. However, it should be noted that these observations were made during the regular hard/low state of Cyg X-1. In the hard/low state, its inner disk radius is probably larger than \( 3R_s \) [114]. Therefore the inner disk contribution to the observed line profile is expected to be less important in the hard/low state. Moreover, the broadening and skewness of the expected line profile from the inner disk region is less significant for a small inclination angle (only 10°-40° in Cyg X-1). Future higher sensitivity and better resolution instruments are required for
unambiguously identifying these different components in its iron line profile.

Recently, iron line features have also been observed from the two superluminal jet sources GROJ1655-40 and GRS1915+105 with ASCA [27], as shown in figure 6. Except during a light curve ‘dip’ in GROJ1655-40, all other observed line profiles show strong absorption features at around 7 keV. A possible interpretation is that the continuum spectrum passes through a slab-like ionized absorption medium (accretion disk corona) at a distance about 10^{10} cm away from the original X-ray source [102]. The degree of ionization of the corona increases for a higher continuum luminosity, indicating that the ionization is also caused by the X-ray illumination. This is perhaps the first evidence of the existence of a hot corona in a black hole binary system. It should be noted that these observed absorption features are significantly different from the apparent emission feature observed in Cyg X-1. It is not clear if this is due to the differences in their nature (for example, jet vs. non-jet systems), or the inclination angle difference (70° vs 10°-40°).

On the other hand, the apparent emission feature in the ‘dip’ spectrum of GROJ1655-40 should not be ignored completely. This feature is very similar to the broadened and skewed line profiles observed from many Seyfert I galaxies (e.g. ref. [28,49,98]). The only difference seems to be the much higher peak energy at \sim 7.0 keV, possibly blue-shifted, if the original peak is also the 6.4 iron K_{\alpha} line. This is actually expected due to the much higher inclination angle of 70° in GROJ1655-40. It is also unlikely that the whole complex line features of other spectra (non-‘dip’) of the sources can be explained completely with absorptions alone. It is possible that the non-‘dip’ line profiles consist of both the absorption by the disk-corona and the iron fluorescence emission (relativistically broadened and skewed) from the inner disk region, which is believed to be around 1 R_s [115,116]. One possible scenario is that during the ‘dip’ period the emitted X-ray luminosity from the central region of the disk becomes lower, due to perhaps the reduced mass transfer rate. The lower X-ray flux therefore changes the properties of the disk-corona (geometry and ionization state), so that the resonance absorption of X-ray photons by iron ions becomes negligible.

It is clear from the above discussion that rich information may be derived from iron line diagnostics of black hole binary systems. Many of the current interpretations are, however, quite uncertain, due primarily to the limited number of detections and the poor statistical quality of past observations.

**Timing Diagnostics**

Rapid variability studies of their X-ray light curves provide essential information about many dynamic processes in the central region of the accretion disk and in the corona. Many of the earlier results were reviewed by van der Klis [104]. Some recent results are reviewed in a companion review article in the same proceedings [36]. Here we only review briefly the high frequency QPOs detected from the two superluminal jet sources GROJ1655-40 at \sim 300 Hz [89] and GRS1915+105 at \sim 67
FIGURE 6. Iron line features from Cyg X-1 [26] (Ebisawa et al. 1996), GRS1915+105 [27] (Ebisawa 1996) and GROJ1655-40 [102] (Ueda et al. 1997) observed with ASCA.
An important feature in these QPOs is their stable frequency, compared to the majority of other QPOs observed in black hole and neutron star binaries, with the exception of the stable 34 Hz QPO in the bursting pulsar GROJ1744-28 [118].

It is thus natural to relate these QPOs to the last stable orbit of the black hole. Assuming that the QPO frequencies are actually the Keplerian frequencies of the last stable orbit, the masses of the assumed non-spinning black holes are around 33 $M_\odot$ and 7 $M_\odot$ (consistent with its dynamical mass estimate), in GRS1915+105 and GROJ1655-40, respectively. However, since the spin of the black hole in GROJ1655-40 is inferred to be near its maximal rate from X-ray spectroscopic measurements as we discussed above [116], the non-spinning black hole assumption is not likely to be valid and thus neither is this Keplerian frequency interpretation. The other interpretation is to attribute these QPOs to the $g$-mode oscillations due to the general relativity effects [74,75,84]. When applied to GROJ1655-40, the inferred black hole spin rate is remarkably consistent with that obtained from independent spectroscopic measurements [116]. Taking the same approach, the implied black hole spin in GRS1915+105 would also be near its maximal rate and the black hole mass is around 30 $M_\odot$. In this model, however, it is not clear why the QPOs seem to be associated with the hard X-ray component [71,89].

**SUMMARY**

We have reviewed the recent progress in the investigations of the multifrequency properties and connections of galactic black hole binaries. There is now sufficient evidence for the existence of stellar mass black holes in at least 10 systems. Their high energy and radio light curves are well correlated and can be divided into three classes, which may be related to their respective types of companion stars. Their X-ray spectral properties may be related closely to the spins of the black holes, in a newly proposed unification scheme of all types of black hole binaries. The correlation between the hard X-ray and radio flares suggests that the radio emission and therefore the associated outflows are related to the corona in the inner disk region. Iron line studies in the two superluminal jet sources provide possible evidence of a hot disk-corona. Only the black holes in the jet systems are found to be likely spinning at nearly the maximal rates, suggesting that the highly relativistic jets are related to the spin of the black hole. This supports strongly the previously suggestions that the highly relativistic jets in AGNs might be related to the rapid black hole spins [8,9,59]. Therefore the eventual unification of all types of black hole systems (galactic and extra-galactic) becomes possible using the black hole spin as one of the key parameters.

However, many of the current interpretations are still quite uncertain, due to both of our limited theoretical understanding of the detailed physics involved and the limitations of the current observations. Therefore more theoretical investigations and future multifrequency observations are required. Nevertheless, such
recent progress suggests that the current observational and theoretical studies of the galactic black hole binary systems have begun to show the premise of using these systems as the laboratories for testing some physical laws in the strongest gravitational field. Compared to AGNs in which similar studies can also be carried out and in fact were started much earlier, the galactic black hole binary systems are more advantageous because a) the dynamical time scales in them are much shorter; b) their inner disk regions are directly observable in the X-ray frequency range; c) the fine details of their jets are observable because they are much closer to us; and d) the system parameters can be measured through optical/infrared observations.

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REFERENCES

1. Augusteijn, T., Kuulkers, E. & Shahams, J. 1993, A&A, 279, L13
2. Bailyn, C.D. et al. 1995, Nature, 374, 701
3. Bailyn, C.D. et al. 1995, Nature, 378, 157
4. Barr, P., White, N.E. & Page, C.G. 1985, MNRAS, 216, 65
5. Barret, D., McClintock, J.E. & Grindlay, J.E. 1997, ApJ, 473, 963
6. Blandford, R. 1976, MNRAS, 176, 465
7. Blandford, R. & Payne, D. 1982, MNRAS, 199, 883
8. Blandford, R. & Znajek, R.L. 1977, MNRAS, 179, 433
9. Blandford, R. & Levinson, A. 1995, ApJ, 441, 79
10. Bolton, C.T. 1972, Nature, 258, 307
11. Callanan, P.J. et al. 1996, ApJ, 461, 351
12. Callanan, P.J. et al. 1996, ApJ, 470, L57
13. Casares, J., Charles, P. A., & Naylor, T. 1992, Nature, 355, 614
14. Casares, J., Charles, & P. A. 1992, MNRAS, 255, 7
15. Casares, J. et al. 1995, MNRAS, 276, L35
16. Castro-Tirado, A.J., Geballe, T.R. & Lund, N. 1996, ApJ 461, L99
17. Chaty, S. et al. 1996 A&A, 310, 825
18. Chen, W., Shrader, C. & Livio, M. 1997, ApJ, in press.
19. Cowley, A.P. et al. 1983, ApJ, 272, 118
20. Chen, W., Livio, M. & Gehrels, N. 1993, ApJ, 408, L5
21. Done, C. et al. 1992, ApJ, 395, 275
22. Ebisawa, K., Titarchuk, L. & Chakrabarti, S.K. 1996, PASJ, 48, 59
23. Ebisawa, K., Mitsuda, K. & Inoue, H. 1989, PASJ, 41, 519
24. Ebisawa, K. et al. 1992, Frontiers of X-ray Astronomy, ed. Y. Tanaka & K. Koyama (Tokyo: University Academy Press), p.301
25. Ebisawa, K. et al. 1992, in ApJ, 367, 213
26. Ebisawa, K. et al. 1996, ApJ, 467, 419
27. Ebisawa, K. 1996, in X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas, ed. F. Makino & K. Mitsuda ((Tokyo: University Academy Press), p.427
28. Fabian, A.C. et al. 1995, MNRAS, 277, L11
29. Fender, R.P. et al. 1997, MNRAS, 286, L29
30. Fender, R.P. 1997, private communication
31. Filippenko, A.V. Matheson, T. & Ho, L.C. 1995, ApJ, 455, 614
32. Foster, R.S. et al. 1996, ApJ, 476, L81
33. Gies, D.R. & Bolton, C.T. 1982, ApJ, 260, 240
34. Gies, D.R. & Bolton, C.T. 1986, ApJ, 304, 371
35. Grove, J.E., Kroeger, R.A. & Strickman, M.S. 1996, in Second Integral Workshop, The Transparent Universe, St. Malo, France, ESA SP-382
36. Grove, J.E. et al. 1997, in The 4th Compton Symposium, these proceedings
37. Han, X. & Hjellming, R.M. 1992, IAUC, 5593
38. Han, X. & Hjellming, R.M. 1997, ApJ, in press (submitted in 1994)
39. Harmon, B.A. et al. 1997, ApJ, 477, L85
40. Harmon, B.A. et al. 1995, Nature, 374, 703
41. Hameury, J.-M., King, A.R., & Lasota, J.-P. 1986, A&A, 161, 71
42. Hameury, J.-M. et al. 1997, ApJ, in press.
43. Haswell, C.A. et al. 1994, ApJ, 411, 802
44. Hjellming, R.M. & Han, X. in X-ray Binaries, Eds. Walter H.G. Lewin, Jan van Paradijs & P.J. van den Heuvel, Cambridge University Press, 1995, ch. 7
45. Hjellming, R.M. & Rupen, M.P. et al. 1995, Nature, 375, 464
46. Hjellming, R.M. et al. 1988, ApJ, 355, L75
47. Hjellming, R.M. et al. 1997, in preparation
48. Hutchings, J.B. et al. 1987, AJ, 94, 340
49. Iwasawa, K. et al. 1997, MNRAS, 279, 837
50. Kesteven, M.J. & Turtle, A.J. 1991, IAUC, 5181
51. King, A.R., Kolb, U. & Szuszkiewicz, E. 1997, ApJ, 488, in press
52. Kitamoto, S. et al. 1990, in Accretion Powered Compact Binaries, ed. C.W. Mauche (Cambridge University Press), p.21
53. Kitamoto, S. et al. 1990, PASJ, 42, 85
54. Kitamoto, S. et al. 1997, submitted to ApJ
55. Kolb, U. et al. 1997, ApJ, 485, L33
56. Kroeger, R.A. et al. 1996, A&AS, 120, C117
57. Lasota, J.P. 1997, in Accretion Phenomena and Related Outflows, ed. D.T. Wickramasinghe, G.V. Bicknell & L. Ferrario, ASP Conf. Series Vol. 121
58. Levinson, A. & Blandford, R. et al. 1996, ApJ, 456, L29
59. Livio, M. 1997, in Accretion Phenomena and Related Outflows, ed. D.T. Wickramasinghe, G.V. Bicknell & L. Ferrario, ASP Conf. Series Vol. 121
60. Makishima, K. et al. 1986, ApJ, 308, 185
61. Martin, A.C. et al. 1995, MNRAS, 274, L46
62. McClintock, J.E. & Remillard, R.A. 1986, ApJ, 308, 110
63. Meier, D. 1996, ApJ, 459, 185
64. Meier, D. et al. 1997, Nature, 388, 350
65. Mineshige, S. 1996, PASJ, 48, 93
66. Mirabel, I.F. & Rodriguez, L.F. 1994, Nature, 371, 46
67. Mirabel, I.F. et al. 1996, ApJ, 472, L111
68. Mirabel, I.F. et al. 1997, ApJ, 477, L45
69. Mitsuda, K. et al. 1989, PASJ, 41, 97
70. Mitsuda, K. et al. 1984, PASJ, 36, 741
71. Morgan, E.H., Remillard, R.A. & Greiner, J. 1997, ApJ, 482, 993
72. Morris, P.W. 1997, ApJ, in press
73. Narayan, R. 1997, in Accretion Phenomena and Related Outflows, ed. D.T. Wickramasinghe, G.V. Bicknell & L. Ferrario, ASP Conf. Series Vol. 121
74. Nowak, M.A. & Wagoner, R.V. 1993, ApJ, 418, 187
75. Nowak, M.A. et al. 1996, ApJ, 477, L91
76. Orosz, J.A. 1996, PhD Thesis, Yale University
77. Orosz, J.A., & Bailyn, C.D. 1995, ApJ, 446, L59
78. Orosz, J.A. & Bailyn, C.D. 1997, ApJ, 477, 876
79. Orosz, J.A. et al. 1996, ApJ, 468, 380
80. Orosz, J.A. et al. 1997, ApJ, 478, L83
81. Owen, F.N. et al. 1976, ApJ, 203, L15
82. Paciesas, W.S. et al. 1997, in The 4th Compton Symposium
83. van Paradijs, J. & McClintock, J. E., in X-ray Binaries, Eds. W.H.G. Lewin, J. van Paradijs & P.J. van den Heuvel, Cambridge University Press, 1995
84. Perez, C.A. et al. 1995, ApJ, 476, L15
85. Priedhorsky, W.C. et al. 1983, ApJ, 270, 233.
86. Priedhorsky, W.C. et al. 1995, A&A, 300, 415
87. Remillard, R.A. et al. 1994, BAAS, 26, 1483
88. Remillard, R.A. et al. 1996, ApJ, 459, 226
89. Remillard, R. 1996, in Texas in Chicago, Texas Symposium, Chicago
90. Robinson, C.R. et al. 1997, in The 4th Compton Symposium
91. Rodriguez, L.F. & Mirabel, I.F. 1997, ApJ, 474, L123
92. Rubin, B.C. et al. 1997, ApJ, in press
93. Sanwal, D., et al. 1996, ApJ, 460, 437
94. Shahbaz, T., Naylor, T., & Charles, P.A. 1994, MNRAS, 268, 756
95. Shahbaz, T. et al. 1994, MNRAS, 271, L10
96. Sood, R. & Campbell-Wilson, D. 1994, IAUC, 6006
97. Spencer, R.E. et al. 1997, Vistas in Astronomy, 41(1), 37
98. Tanaka, Y. et al. 1995, Nature, 375, 659
99. Tanaka, Y. 1991, in Lecture Notes in Physics 385, Iron Line Diagnostics in X-ray Sources, ed. A. Treves (Berlin: Springer), 98.
100. Tavani, M. et al. 1996, ApJ, 473, 103
101. Tingay, S.J. et al. 1995, Nature, 374, 141
102. Ueda, Y., et al. 1997, ApJ, in press
103. van der Hoofft, F. et al. 1997, MNRAS, 286, 43
104. van der Klis, M., in X-ray Binaries, Eds. Walter H.G. Lewin, Jan van Paradijs & P.J. van den Heuvel, Cambridge University Press, 1995, ch. 6, pp. 252-307.
105. van Paradijs, J. 1996, ApJ, 464, L39
106. Wagner, R.M. et al. 1990, in Accretion Powered Compact Binaries, ed. C.W. Mauche (Cambridge University Press), p.
107. Wagner, R.M. et al. 1992, ApJ, 401, L97
108. Webster, B.L. & Murdin, P. 1972, Nature, 235, 37
109. Wu, K. & Hunstead, R. W. 1997, in Accretion Phenomena and Related Outflows, ed. D.T. Wickramasinghe, G.V. Bicknell & L. Ferrario, ASP Conf. Series Vol. 121
110. Zhang, S.N., et al. 1994, IAUC, 6046
111. Zhang, S.N. 1997, in Accretion Phenomena and Related Outflows, ed. D.T. Wickramasinghe, G.V. Bicknell & L. Ferrario, ASP Conf. Series Vol. 121
112. Zhang, S.N., et al. 1996, A&A, 120, C279
113. Zhang, S.N., Robinson, C.R. & Cui, W. 1996, IAUC, 6510
114. Zhang, S.N., et al. 1997, ApJ, 477, L95
115. Zhang, S.N., et al. 1997, ApJ, 479, 381
116. Zhang, S.N., Cui, W. & Chen, W. 1997, 482, L155
117. Zhang, S.N., et al. 1997, ApJ, to be submitted.
118. Zhang, W., et al. 1995, ApJ, 449, 930