Properties of Black Holes in Stellar Binary Systems

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**Abstract.** Recent X-ray timing and spectral observations of black hole binaries in outburst have redefined methods for investigating the properties of Galactic black holes and the physics of accretion flows. High-frequency X-ray QPOs in 5 systems (60–300 Hz) continue to be investigated as a possible means to constrain black hole mass and spin via interpretation as oscillations due to strong-field effects in General Relativity. In principle, black hole mass and spin may also be constrained via determination of the inner radius of the accretion disk, using spectroscopic parallax of the X-ray thermal component. However, an accurate application of this technique is fraught with difficulties. Monitoring programs that track the evolution of the thermal and power-law components in the X-ray spectrum provide new insights into modes of energy flow and the formation of relativistic jets.

1. Introduction

During the 1980’s and 1990’s, optical radial velocity studies of stellar companions in quiescent X-ray binary systems in the Galaxy identified a group of compact objects that were more massive than the theoretical upper limit (∼3 M⊙) for the mass of a neutron star (see Charles 1998). It was noted that while in outburst, these “heavy” compact objects also lack the X-ray signatures of neutron stars, viz. pulsations or type I X-ray bursts. These cases eventually gained widespread recognition as “dynamically established black hole binaries”. The measured optical mass functions were combined with estimates for the binary mass ratio and inclination angle, which were also determined from optical studies of the companion stars, to yield black hole mass estimates in the range of 5–15 M⊙. Recent additions to this group include SAX J1819.3−2525 (Orosz et al. 2001), and XTE J1118+480 (McClintock et al. 2000). There are now 13 known X-ray binaries in which the compact object is very likely to be a black hole. During X-ray outbursts, the black-hole systems often exhibit composite spectra consisting of a ∼ 1 keV thermal component and a broad power-law component that may extend well beyond 100 keV (see Tanaka & Lewin 1995). These spectral characteristics are often used to suggest that a particular source is a black hole “candidate” (BHC) when dynamical observations of the companion star are lacking, sometimes because of high extinction at optical/IR wavelengths.

Another important topic for quiescent X-ray binaries is whether the black hole systems are further distinguished (compared to neutron stars) by spectral
characteristics that can only be understood as a consequence of a black hole’s
event horizon (Narayan, García, & McClintock 1997; Menou et al. 1999). The
optical, UV, and X-ray energy distribution of quiescent black hole binaries is
inconsistent with models for thermal emission from a disk with a low rate of
mass transfer. The high-energy radiation also appears intrinsically fainter than
that of quiescent neutron-stars (McClintock & Remillard 2000). The differences
between black holes and neutron stars may then be explained as the inevitable
thermalization of infall energy (i.e. crash) at the neutron star surface, in contrast
with the flow of energy into a black hole’s event horizon. While the qualitative
aspects of quiescent spectra in black hole binaries is quite intriguing, the appli-
cation of detailed models remains controversial. The “Advection Dominated
Accretion Flow” model (e.g. Narayan & Yi 1995) can account for many of the
observed spectra, but issues of convective stability have ushered in the “Con-
vection Dominated Accretion Flow” model (Ball, Narayan, & Quataert 2001).
There are also alternative scenarios for explaining the “underluminous” spectra
of quiescent disks, e.g. by via mass loss from the system (Blandford & Begelman
1999) or by invoking magnetic instabilities in a cool disk (Nayakshin 2000).

One undesirable consequence of low radiative efficiency in quiescent tran-
sients is the limited opportunity to study black holes by observing the detailed
characteristics of the accreting matter near the event horizon. This perspective
has encouraged renewed interest in X-ray outbursts, where the highest accretion
rates are seen. Since the the launch of the Rossi X-ray Timing Explorer (RXTE)
in 1995 December, we have witnessed historical contributions to scientific stud-
ies of black holes in active states of accretion. These efforts have brought new
themes to the forefront of high-energy astrophysics, such as the application of
General Relativity (GR) to black hole binaries. In the sections below, we review
some of the ongoing efforts to use X-ray timing and spectroscopy to evaluate
black hole mass and spin, to understand the physics of black hole accretion, and
to determine the origins of relativistic jets in X-ray binary systems (i.e. the
“microquasars”).

1.1. X-ray Spectra of Accreting Black Holes

The dedication of the RXTE Mission to studies of X-ray transients is reflected
in the statistics (1996-2000) of monitoring programs for pointed observations:
81 exposures of GRO J1655−40 (1996-1998); 222 for 4U1630−47 (4 outbursts),
316 for XTE J1550−564 (3 maxima), and 618 for GRS 1915+105. The typical
observation with the PCA (2-60 keV) and HEXTE (20-200 keV) instru-
ments provides several million detections during a few ks with sub-ms time resolution.
The All Sky Monitor (ASM) independently records X-ray intensities (2-12 keV)
by scanning the celestial sphere several times per day.

Black hole binaries in states of active accretion usually show two spectral
components with a large diversity in their relative strength. This is shown in
Figure 1 for the case of GRO J1655−40 The “soft” X-ray component rep-
resents thermal emission (~1 keV) from an accretion disk, while the power-law
continuum in hard X-rays is commonly associated with inverse Compton scatter-
ing of ambient photons by energetic electrons. As the luminosity of GRO
J1655−40 exceeds ~0.2 L_{Edd}, the power-law becomes dominant and several
types of quasi-periodic oscillations (QPO) are seen in the PCA power spectrum
Figure 1. X-ray spectrum and power density spectrum of GRO J1655−40 in the “high state” (1997 Mar 24) and the “very high state” (1996 Aug 01). The very high state corresponds to episodes of highest luminosity, where the spectrum is dominated by a non-thermal X-ray power-law. In this source, QPOs at 0.1, 8, and 300 Hz are visible in the very high state.
The nature of this Compton emission, which is the dominant mechanism for radiative losses at the highest accretion rates, remains one of the fundamental mysteries of accretion energetics in black hole binaries. At luminosities of roughly $\sim 0.01 - 0.2L_{\text{Edd}}$, the thermal component (accretion disk) usually dominates the spectrum. Such “soft state” or “high state” spectra have been modelled with a multi-temperature accretion disk (Shakura & Sunyaev 1973; Mitsuda et al. 1984) with an inner radius near the marginally stable orbit predicted by GR theory. Here, a weaker Compton component is usually present, but its origin and geometry are unknown. As the luminosity evolves, unexpected variations are seen in the apparent disk temperature and radius for many sources (e.g. Sobczak et al. 1999a). The interpretation of these results requires new disk models with more sophisticated treatment of effects due to GR and radiative transfer through the disk atmosphere (see 2.2 below).

We continue to learn about the importance of the hard X-ray power law, but its behavior is fraught with complications. When the spectral characteristics and evolution of all black hole binaries is considered, it is found that the power-law component has two inherently different types (Grove et al. 1998). The spectrum associated with the very high state (Fig. 1) has a photon index $\sim 2.5$, and this component has been seen out to 1 MeV or higher without a cutoff in a few bright sources (Tomsick et al. 1999). A different power-law at lower luminosity (roughly $L_x < 0.01L_{\text{Edd}}$), with a photon index $\sim 1.7$ and an exponential cutoff near 100 keV, characterizes the “low-hard” state (e.g. Cyg X−1). Since the high-energy cutoff suggests a limit to the energy distribution of Compton electrons, it seems paradoxical that the low-hard state is associated with a steady type of radio jet (see below).

There are now considerable efforts underway (e.g. Hua, Kazanas & Cui 1999; Poutanen & Fabian 1999; Nowak et al. 1999) to deduce physical insights about the hard X-ray component by combining spectral analyses with variability measurements such as phase lags and coherence (vs. Fourier frequency) between different energy bands, as well as the properties of low-frequency QPOs. These oscillations can attain amplitudes as high as 30-40% of the average flux, e.g. at 1-5 Hz (Morgan, Remillard, & Greiner 1996; Cui et al. 1999).

Further insights can be gained by identifying repetitive patterns of correlated spectral and timing variations gained from the monitoring programs. Prior to RXTE it had been widely presumed that the emergent photon spectrum depends primarily on the black hole mass and the accretion rate. Then it was shown that the hard/soft state transition in Cyg X−1 involves almost no change in bolometric luminosity (Zhang et al. 1997). In a more general sense, it has been noted that almost all of the BHCs with persistent X-ray emission exhibit the same spectral states as X-ray transients, while extreme changes in mass accretion rate are only expected for the latter group (Wilms et al. 2001). Along the same lines, it has been shown that changes in luminosity in a single source, in different outbursts, may follow very different tracks in the way the energy divides between the accretion disk and power-law components. In the microquasar GRS 1915+105, a plot of the luminosity contributions from the disk vs. power-law components reveals two tracks: one branch shows luminosity changes occurring primarily in the disk, while an alternate track shows luminosity changes entirely diverted to the power-law. The latter track contains all of
the observations in which there are low-frequency (0.5 to 15 Hz) QPOs (Muno, Morgan, & Remillard 1999). Even more complicated tracks are seen in the BHC XTE J1550–564 (Sobczak et al. 1999b). All of these results imply that there are primary factors that have received insufficient recognition in our descriptions of the energetics of black hole accretion. The dependent variables may include conditions in the outer disk, magneto-hydrodynamic turbulence, or the presence of jets.

2. Constraints on Black Hole Properties Using General Relativity

2.1. High-Frequency Quasi-Periodic Oscillations in X-rays

The X-ray sources GRS 1915+105 and GRO J1655–40 yielded the first detections of fast X-ray oscillations thought to be signatures of strong-field GR effects in the inner accretion disk. RXTE discovered a transient QPO in GRS 1915+105 at 67 Hz (Morgan, Remillard, & Greiner 1997). When detected, the QPO frequency appears fixed, despite variations in X-ray luminosity by a factor of 4. A QPO at 300 Hz in GRO J1655–40 (Remillard et al. 1999b) was seen during ~6 observations that exhibit the highest levels of luminosity observed by RXTE from this source. The first evidence of a BHC with a fast QPO having variable frequency is found in the case of XTE J1550–564 (100-284 Hz; Remillard et al. 1999a; Homan et al. 2001). Additional high-frequency QPOs were found in the recurrent BHC transient 4U 1630–47 (184 Hz; Remillard et al. 1999c), and in XTE J1859+226 (150-187 Hz; Cui et al. 2000), again by combining power spectra over many PCA observations at high luminosity. Figure 2 illustrates these results. All of these QPOs have rms amplitudes in the range of 0.5% to 3.5% of the mean count rate.

Given those high frequencies and their display in X-rays, it is straightforward to hypothesize that the fast QPOs are produced in the inner accretion disk, near the black hole event horizon. Here, there are GR predictions of oscillations that do not exist in Newtonian gravity. The competing models for these oscillations incorporate GR effects at some level, and the QPO frequency then depends on both the mass and spin of the black hole, and possibly on the gas conditions or vertical structure of the inner disk. Some models invoke GR phenomena directly, suggesting that the QPOs represent the last stable orbit (Shapiro & Teukolsky 1983), or “frame dragging” (i.e. Lense-Thirring precession; Merloni et al. 1999), or relativistic periastron precession (Stella, Vietri, & Morsink 1999). Other models suggest a more subtle interplay between GR and fluid dynamics, such as “disks seismic modes” (Perez et al. 1997; Ortega-Rodriguez & Wagoner 2000) or inertial-acoustic instabilities (Milsom & Taam 1997). To date, there is only one of the five sources (GRO J1655–40) for which the mass of the black hole (~ 7 M⊙) is available from optical studies (Orosz & Bailyn 1997; Shahbaz et al. 1999). In this case the dimensionless spin parameter (a) could be as low as a = 0 if the QPO signifies the last stable orbit (R ~ 6GM/c²), while values closer to a = 1 are deduced for several of the other models.

The possibility that one may constrain the mass and spin of an accreting black hole using high-frequency X-ray QPOs, which are independent of the usual systematic uncertainties about distance, inclination angle, and extinction, is surely a compelling theme for vigorous scientific analyses. However, there
Figure 2. High frequency QPOs in 5 black hole candidates. Two observations for XTE J1550−564 are shown to illustrate the large variations in frequency and coherence for the fast QPO from this source. On the opposite extreme, the 67 Hz QPO in GRS 1915+105 is confined to the range of ±2 Hz during ~30 observations when a fast QPO was detected.
are many serious problems that must be addressed. All of the high-frequency QPOs appear to be stronger at higher photon energy, which resembles the X-ray power law, rather than the thermal component from the inner disk, where the QPOs are expected to originate. Therefore, detailed emissivity models are required for each type of GR oscillation, including considerations for the energetic electrons believed responsible for the X-ray power-law via inverse Compton emission. We have seen the first simulations of frame dragging oscillations and how they may survive against damping (Markovic & Lamb 1998). There are also more generalized considerations as to how these oscillations may be excited by the hydrodynamic turbulence in the accretion flow (Psaltis & Norman 2001). All of these crucial topics will continue to evolve in parallel with observational developments gained with RXTE.

2.2. Spectroscopic Inference of the Inner Radius of the Disk

Spectral analysis of the thermal component in the X-ray spectrum yields information on the radius and temperature of the inner disk, when the distance and binary inclination are well constrained, e.g. by optical and radio observations. If the accretion disk extends all the way in toward the event horizon, i.e. there are no shocks or transitions to radial accretion, then the disk is expected to terminate at the radius of the last stable orbit given by GR theory. Since the luminosity is dominated by the inner disk, there is an opportunity, in principle, to derive an absolute value for the inner disk radius and then to constrain the value of the black hole’s spin if the mass is known via binary dynamics. This is tantamount to a “spectroscopic parallax” of the inner accretion disk.

Zhang, Cui, & Chen (1997) applied this technique to observations of microquasars, while estimating corrections for effects such as radiative transfer through the disk atmosphere and GR modifications on the structure and emissivity of the inner disk. The accuracy of these corrections was strongly questioned (Merloni, Fabian, & Ross 2000). There are also complications arising from unexplained changes in the apparent radius of the inner disk in several sources (Belloni et al. 1997; Sobczak et al. 1999b; Muno, Morgan, & Remillard 1999). Finally, a number of black hole accretion models specify structural elements that contradict the assumption of an idealized accretion disk that extends all the way to the event horizon (e.g. Chakrabarti 1996; Titaarchuk, Lapidus, & Muslimov 1998).

Despite these problems, there may eventually be useful ways to derive constraints on black hole mass and spin from X-ray spectroscopy. Progress will depend, in part, on improved accretion disk models. One strategy might be to select only the spectra that exhibit a dominance of the thermal component, with perhaps an additional selection for minimal variability displayed in the power spectrum. It is also conceivable that accretion models could gain important diagnostic support from X-ray line spectroscopy, if observations from the Chandra Observatory or an anticipated re-flight of the Astro-E calorimeter establish broad Fe lines in the spectra of black hole binaries.
3. The Disk-Jet Connection

Since 1994, radio astronomers have discovered a handful of Galactic X-ray binaries that produce transient radio jets traveling at velocities $\sim 0.9c$ (Mirabel & Rodrigues 1999). These sources are referred to as "microquasars", since they appear to be scaled-down versions of the jets in AGN. Interest in microquasars is heightened by the opportunity to observe the formation and evolution of mass ejections on timescales of seconds to days, while such processes take years to millennia in quasars. Theoretical arguments favor magnetic fields as the mechanism that collimates and accelerates the ejecta. The outflow energy may originate in the spin of the black hole and/or the accretion energy in the disk (see Blandford 2000). In some microquasars, one may study the jets with knowledge of the black hole mass, which is constrained via optical studies of the mass-donor companion star.

One may describe microquasar jets as occurring in at least 4 types: explosive bipolar ejections at relativistic speed; weaker oscillatory ejections at regular intervals ($\sim 30$ min); very weak radio flares that precede X-ray flares, and steady jets which may persist from days to months. It can be argued that GRS 1915+105 and Cyg X−3 are the prototypical microquasars for their recurrent production of jets of more than one type. The X-ray (ASM) and radio (Greenbank Interferometer) light curves for these sources are shown in Figure 3.

In the case of GRS 1915+105, the "superluminal" ejections seen with the VLA and MERLIN (Mirabel & Rodriguez 1994; Fender et al. 1999a) typically reach maxima of 0.5–2.0 Jy at 2.25 GHz. Even stronger events are seen in Cyg X−3 (e.g. Newell et al, 1998). And in the case of V4641 Sgr (Hjellming et al. 2000), a dynamical black hole binary with an evolved A star companion (Orosz et al. 2001), the fast-moving, single-sided jet implies ejection at 0.99 c. The X-ray behavior associated with these rare events is not known. However, weaker ejections (0.01–0.10 Jy) may appear as series of radio flares that repeat every $\sim 30$ min (Fender & Pooley 1998; Eikenberry et al. 1998; Fender & Pooley 2000). These oscillatory ejections have brought important lessons about the crucial role of X-ray monitors in understanding the jet formation process. There are smooth IR and radio flares (to 0.02 Jy at 2.25 GHz) that represent successively delayed peaks in synchrotron emission associated with the expansion of an ejected plasma cloud. The X-ray light curve is far more complex, and yet the wild patterns also repeat every 30 min! Eikenberry et al. (1998) found similar sequences of X-ray dips, flashes, and bright flares preceding all 6 IR flares observed at both wavelengths. Spectral analysis of the X-ray dip indicates evolution from a small, hot disk to a much cooler one with larger inner radius (Belloni et al. 1997). The conclusion is that the emergence of the jet is a consequence of the rapid disappearance and followup replenishment of the inner accretion disk.

There are also reports of weaker, isolated radio or IR flares that precede X-ray flares (Eikenberry et al. 1999; Feroci et al. 1999). These are interpreted as small ejections that arise from "outside-in" instabilities, or waves that fuel a small jet before reaching the innermost region of the accretion disk.

Finally, there has been substantial recent progress in demonstrating the presence of a steady type of jet associated with the "low-hard" X-ray state seen in many X-ray binaries. Radio monitoring and ASM observations of GX 339−4
Figure 3. X-ray and radio monitoring observations of the most active microquasars: GRS 1915+105 and Cyg X–3. The X-ray light curves are binned in 1 day intervals, and the rows vertical ticks above them show the times of RXTE pointed observations.
have revealed positive correlations during the X-ray hard state, with the radio flux becoming quenched as GX 339−4 transits to its soft state (Hannikainen et al. 1998; Corbel et al. 2000). The radio emission is consistent with optically-thick synchrotron emission of extent $> 10^{12}$ cm (Wilms et al. 1999). A clear association of the hard state with a steady type of jet was gained by Fender et al. (1999b), with the detection of extended radio structure during the hard state. Simultaneous RXTE observations indicate an X-ray power law ($\Gamma \sim 1.7$) that is consistent with Comptonization via a 50-100 keV corona with radius approximately $< 100 GM/c^2$.

There are also VLBI images of a jet associated with steady X-ray and radio emission in the case of GRS 1915+105 (Dhawan, Mirabel, & Rodriguez 2000). Here the jet is visible on all dimensions between 10 and 500 AU! In addition, steady-jet properties are seen in the low-hard state of Cyg X−1 (Pooley, Fender, & Brocksopp 1999; Brocksopp et al. 1999). All of these results are focusing efforts to relate the ($\Gamma \sim 1.7$) type of power law to Compton scattering at the base of a steady jet. As might be expected, however, the detailed changes in X-ray characteristics as a function of radio flux within the low-hard state appear to be quite complicated (Muno, Remillard, & Morgan 2001).

In closing, it must be noted that the classical work to determine binary parameters and stellar constituents for the Galactic black hole systems remains a core component of this science. Confronting the high-energy phenomenology of these systems requires the knowledge and context provided by measurements of the binary system, and any practical prospects for gaining evaluations of black hole spin require the mass measurements derived from binary dynamics. As we continue to pursue all of the science of black hole mass and spin and the jets that propel matter at relativistic speeds directly from the gravitational jaws of these black holes, it is essential that we maintain a vigorous program of ground-based observations for the same X-ray transients that are studied from space.

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