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Preface

This work had its genesis in a topical meeting on short-period binaries held during the 208th meeting of the American Astronomical Society in June, 2006. In spite of its origins it is not a meeting proceedings, but rather a series of contributions by experts in subfields of the discipline. Like the topical session, the contributions provided here are from researchers in various fields whose subject of interest is short–period binary stars. Some authors address the properties of short–period binary systems in general and others describe the behavior of specific systems.

The purpose of this contributed volume is to highlight the techniques and methodologies used in their respective studies. In addition the observational and theoretical state of knowledge of a broad realm of interacting binary stars, covering the gamut from unevolved binaries to black hole systems is presented in this volume.

1 Why are Binary Stars of Interest?

Many, if not most of the stellar objects in the Universe are members of multiple star systems. Indeed Cox (2000), §16.18, cites two sources to argue that the numbers of binaries are very impressive:

> "Indications are that some 40–60% of all stars are members of double or multiple systems (Herczeg, 1982), with some estimates running as high as 85% (Heintz 1969)."

It has long been known that novae are produced by interacting binary stars. Now that the frequency of hierarchies of multiple star systems has been found to be larger than previously thought, one can expect that phenomena once thought to be rather rare in occurrence may be more common and this provides justification for the search of such phenomena. One of the most common types of short–period eclipsing binaries is the W Ursae Majoris (W UMa) class. Recent ideas concerning these binaries are discussed here by Van Hamme and Wilson in this book. These objects are in direct contact, joined by a neck of material that varies in thickness from system to system, and for this reason, their physical configuration is referred to as "over–contact" (and by others merely as "contact"). [1] These objects are thought to be on their way to full merger. Such systems are very old — with ages of billions of years, judging from the galactic distribution of the systems outside of star clusters, their abundance in the very old globular clusters, and their relative paucity in the typically younger "open" clusters of the galactic plane. The contact or over–contact objects may have been born with relatively low amounts of angular momentum; why that should be the case has long been a problem in binary star research. A new study by Pribulla and Rucinski (2006) strongly suggests that all such systems may be triple star systems, in which a wide–orbit companion is in a longer–period orbit with the W UMa pair. In any case, a significant percentage of over–contact systems are involved in triple systems.

Aside from an argument based on numbers, however, binaries are important because their gravitational interactions provide precise information about the masses of the components. If we are lucky enough to observe eclipses, we gain also precise knowledge of the sizes and geometric shapes. Moreover, we can investigate the details of the surfaces, namely, the umbrae and plage regions, and, in special cases, prominences, surges, jets, and streams between or around the stars. Accurate and precise data from eclipsing and spectroscopic binaries provide the challenge needed to test theories of both stellar structure and evolution, and orbital variations can provide critical tests of basic physics.

2 Why *Short–period* Binaries?

The range of stellar masses is quite restricted, so a short orbital period implies component proximity. When the stars are sufficiently well–separated that there is no material link between them, they are referred to as "detached systems." Well–studied detached systems provide us with the most precise stellar parameters, the ultimate aim of the most refined light–curve analyses; the most recent techniques of such analyses are discussed by Milone and Kallrath in this volume. If the stars' radii are more than an order of magnitude smaller than their separation, the light curve of an eclipsing pair of stars will appear flat outside of the eclipses (unless the temperatures are disparate, in which case an increase in brightness around the eclipse of the cooler star due

[1] Astronomers who prefer the term "over–contact" reserve the term "contact" for the case where both objects are just in contact, that is, with an infinitesimally narrow neck of material connecting them; both sides concede that this latter case must be exceedingly rare, and, indeed, no definitive example is known.

to the “reflection effect” may be apparent). With decreasing separation, the stellar shapes become increasingly non–spherical, a feature that can be determined by light curve analysis. As stars age, and reach a stage where their central reserves of hydrogen become depleted, they undergo changes in size and temperature, so that their brightness and color change. On the Hertzsprung–Russell diagram, they evolve toward the regime of the cooler and more luminous stars as they enter the red giant phase. As such a swelling star in a short–period binary system approaches a limiting Lagrangian surface, a zero-potential surface, that effectively defines what belongs to the star and what does not, it loses both mass and angular momentum, certainly to its companion, but possibly also to the external universe. The mass loss can be effected by this “Roche–Lobe Overflow” and/or by stellar winds. A system in which one of the components has reached its critical lobe stage is known as a “semi-detached” system.

The mass–gaining star may gain so much additional mass from its shedding companion that it winds up with more mass than the donor star. If the separation is large enough, the envelope dissipates with only some orbital decay by the mass–gainer. In this circumstance we see a paradoxical condition: the more massive star appears to be the less evolved, and, indeed it is, because prior to Roche–lobe mass exchange, it had less mass than its companion. This is the *Algol paradox*, now readily understood because of studies of short–period binaries.

In some cases, the outer distended atmosphere of the more evolved component envelops the companion. The viscous drag contributes to orbital decay of the less massive component, that results in a spiraling inward, and, ultimately, collision. Ron Webbink takes a fresh look at this scenario in his paper.

Magnetic interactions between short–period binary components give rise to complex, large–scale and long–lasting spot activity cycles, which can be observed. Mass loss through Roche–lobe overflow and stellar winds (from both hot and cool stars), can be probed and studied with detailed Doppler modeling. Following the red–giant and asymptotic–giant phases, the system may wind up with a white dwarf as a component. Interacting systems involving a very–low mass (and thus very slowly evolving) component and a white dwarf can give rise to interesting interactions, leading to novae or even supernovae. Finally, in some cases, the supernova explosions may result not in merely a debris field, but a compact remnant — a neutron star, or a black hole. Determining the properties of objects in these systems is now an important priority of binary star research, as the discussion of the usefulness of X-Ray timings by Wilson, et al., in this volume indicates.

Binaries composed of such highly compact constituents (i.e. black holes, neutron stars and perhaps even quark stars), provide natural laboratories for testing the validity of general relativity and other alternative theories of gravity. Once again given the large percentage of objects found in multiple star systems provides us with the optimism that there are many more binary neutron star and hopefully binary black hole systems to be discovered.

Currently twenty-one X-ray sources can be identified with stellar mass black hole binary systems. The current state of knowledge concerning these objects is presented by Jeffrey McClintock, who also discusses what the future might hold in terms of our understanding of the fundamental physics associated with the dynamics of black holes interacting with their binary star companions.

Whereas the change in the period of the Hulse-Taylor system, PSR 1913+16, has provided indirect evidence of the existence gravitational radiation (and direct evidence that binary systems are of interest in Stockholm), the article by Anderson and Creighton describes the methods currently used to search for the gravitational waves produced by such systems.

The "double pulsar system", PSR J0737-3039AB, has been called the answer to many a relativist's dream. With both pulsar beams being observable, $\sin i \approx 1$ and an orbital period of 2.4^h, one could not ask for a better binary system with which to observe general relativistic effects. Ingrid Stairs and her colleagues, provide a description of this (so far) unique binary system. In the contribution by Hobill, *et al*, who introduce a method for studying the gravitational lensing of pulsar sources, that technique is applied specifically to the double pulsar system.

There has a been a recent surge of activity in the study of the behavior of accreting neutron stars, powered primarily by observations in the X-ray region of the electromagnetic spectrum. Much of this has been done with the Rossi X-ray Timing Explorer with studies of the luminous accreting low (companion) mass X-ray binary systems ($LMXB$s). Observations of kilohertz quasiperiodic oscillations (QPOs) and the latest theoretical work are described in the contribution by Lamb and Boutloukos. These are now combining to yield new inferences on the extreme conditions in the inner accretion disks around the neutron stars in these systems.

For the lower luminosity and higher companion mass X-ray pulsar binaries, analysis of disk precession light curves is now giving detailed information on the accretion disk geometry. Analysis of orbital light curves in X-ray, optical and ultraviolet traces different emission components in the binary system: companion; illuminated face of companion; accretion stream from companion to disk; accretion disk; inner disk edge; and accretion stream from inner disk to neutron star surface. The article by Leahy describes progress and methods in modeling various components of the accretion flow for X-ray pulsars.

An accreting white dwarf in close orbit with a low-mass secondary is known as a cataclysmic variable (CV). CVs display a variety of regularities in their light curves and spectra caused by regular geometrical viewing changes as the system orbit rotates the binary with respect to the observer. Recently, as the contribution by Szkody explains, new ultraviolet observation of the hot components in CVs are being physically modeled with spectacular success. Howell's article discusses the nature of the cool components in CVs, and the implications for the nature and evolution of CVs. As for much of astrophysics, spectra provide the most detailed observational information on physical conditions in CVs. The contribution by Linnell discusses the nature of CV accretion disk spectra and a general purpose program for calculating synthetic spectra and light curves for CVs.

A final argument for studying short–period binaries is that we see many cycles in short intervals of time. Somewhat analogous to the value of fruit flies to a genetics lab, CVs permit us to study the orbital and system changes from all sides of the orbit without having to wait a significant fraction of a human lifetime to collect the data! Short–period binaries can have exceedingly short orbital periods. For example X-ray binaries RX J0806.3+1527 and RX J1914.4+2456 have periods of 321^s and 569^s, respectively. Such ultra–short period binaries provide challenges to both theorists and observers in their attempt to understand the extreme nature of such systems. With orbital periods on the order of just a few minutes, the enormous amount of data accumulated over a relatively short interval is clearly advantageous.

3 More to Learn!

We still have much to learn about short–period objects, however. A recent paper (Pinsonneault and Stanek, 2006) promotes the notion that massive binaries are highly likely to involve "twin," components that are essentially identical in mass and other physical properties. These authors discovered in a sample of 21 detached systems in the Small Magellanic Cloud, with median mass ratio 0.87. They argue further that the frequency of twins may be generally as high as 50% in systems with periods less than 10^d, and possibly even as high as 35% for those with periods less than 1000^d. Because mass is the principal property determining rate of evolution, this finding has implications for production rates of white dwarf binaries, Type Ia supernovae, blue stragglers, binary neutron stars, and neutron star–black hole binaries.

Some of this volume is devoted to research on relatively unevolved binaries, and the state of the art of the analytical techniques for determining stellar parameters and system elements. Other contributions describe systems with highly evolved components. Study of all of these objects can benefit from an examination of techniques and results from other sub–field disciplines. Therefore it is our hope that this volume will provide an overview of the many aspects of research on short-period binaries that will be useful to all researchers and students.

Finally, it is a pleasure to thank the contributors for their interesting and timely contributions. We would also like to acknowledge both the assistance and patience of Sonja Japenga and Vaska Krabbe from Springer-Verlag who were instrumental in the completion of this project.

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Part I

Compact Relativistic Binary Systems

Black Hole Binaries: The Journey from Astrophysics to Physics

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1 Introduction

This paper is based on a talk presented at the 208th Meeting of the American Astronomical Society in the session on Short-Period Binary Stars. The talk (and this paper in turn) are based on a parent paper, which is a comprehensive review by Remillard and McClintock (2006; hereafter RM06) on the X–ray properties of binary stars that contain a stellar black-hole primary. We refer to these systems as black hole binaries. In this present paper, which follows closely the content of the talk, we give sketches of some of the main topics covered in RM06. For a detailed account of the topics discussed herein and a full list of references (which are provided only sketchily below), see RM06 and also a second review paper by McClintock & Remillard (2006; hereafter MR06). There is one subject that is treated in more detail here than in the two review papers just cited, namely, the measurement of black hole spin; on this topic, see McClintock et al. (2006) for further details and references.

There are a total of 21 stellar black holes with measured masses that are located in X–ray binary systems. Nearly all these systems are X–ray novae – transient systems that are discovered during their typically year-long outbursts. There are an additional ∼20 binaries that likely contain stellar black holes based on their X–ray behavior; however, firm dynamical evidence is lacking in these cases, and we refer to these compact primaries as black hole candidates (RM06).

These black holes are the most visible representatives of an estimated population of ∼300 million stellar-mass black holes that are believed to exist in the Galaxy. These stellar-mass black holes are important to astronomy in numerous ways. For example, they are one endpoint of stellar evolution for massive stars, and the collapse of their progenitor stars enriches the universe with heavy elements. Also, the measured mass distribution for even the small sample of 21 black holes featured here are used to constrain models of black hole formation and binary evolution. Lastly, some black hole binaries appear to be linked to the hypernova believed to power gamma–ray bursts (MR06).

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In astronomy, for all practical purposes a black hole is completely specified in General Relativity (GR) by two numbers, its mass M and its specific angular momentum or spin $a = J/cM$, where J is the black hole angular momentum and c is the speed of light. The spin is usually expressed in terms of a dimensionless spin parameter, $a_* \equiv a/M = a/R_{\rm g}$, where $R_{\rm g} \equiv GM/c^2$. The spin is an important property of a black hole because it sets the geometry of space-time, whereas mass simply supplies a scale. The value of a_* is bounded to lie between 0 for a Schwarzschild hole and 1 for a maximally-rotating Kerr hole. The defining property of a black hole is its event horizon, the immaterial surface that bounds the interior region of space-time that cannot communicate with the external universe.

The event horizon, the existence of an innermost stable circular orbit ($ISCO$), and other properties of black holes are discussed in many texts (e.g., Shapiro & Teukolsky 1983). The radius of the event horizon of a Schwarzschild black hole ($a_* = 0$) is $R_{\rm S} = 2R_{\rm g} = 30$ km$(M/10M_\odot)$, the $ISCO$ lies at $R_{\rm ISCO} = 6R_{\rm g}$, and the corresponding maximum orbital frequency is $\nu_{\rm ISCO} = 220$ Hz$(M/10M_\odot)^{-1}$. For an extreme Kerr black hole ($a_* = 1$), the radii of both the event horizon and the ISCO (prograde orbits) are identical, $R_{\rm K} = R_{\rm ISCO} = R_{\rm g}$, and the maximum orbital frequency is $\nu_{\rm ISCO} = 1615$ Hz$(M/10M_\odot)^{-1}$.

This paper is organized as follows. In the following section we describe and catalog the 21 black hole binaries. In §§3-5, we present a brief review of spectral and timing observations of these binaries, focusing on the three X–ray states of accretion defined by MR06 and RM06. In §6, we sketch a scenario for the potential impact of timing/spectral studies of accreting black holes on physics. In §§7-8, we discuss a current frontier topic, namely, the measurement of black hole spin.

2 The Twenty-one Black Hole Binaries

The names and some selected properties of the 21 black hole binaries are given in Table 1. The binaries are ordered by right ascension (column 1). Column 2 gives the common name of the source (e.g., LMC X–3) *or* the prefix to the coordinate name that identifies the discovery mission (e.g., XTE J, where a "J" indicates that the coordinate epoch is J2000). For X–ray novae, the third column gives the year of discovery and the number of outbursts that have been observed. The spectral type of the secondary star is given in column 4. Extensive optical observations of this star yield the key dynamical data summarized respectively in the last three columns: the orbital period, the mass function, and the black hole mass. Additional data on black hole binaries are given in Tables 4.1 & 4.2 of MR06.

An observational quantity of special interest is the mass function, $f(M) \equiv P_{\rm orb}K_2^3/2\pi G = M_1 \sin^3 i/(1+q)^2$ (see Table 1, column 6). The observables on the left side of this equation are the orbital period $P_{\rm orb}$ and the half-amplitude

Table 1. Twenty-one confirmed stellar black holes[a]

Coordinate Name	Common[b] Name/Prefix	Year[c]	Spec.	$P_{\rm orb}$ (hr)	f(M) ($M_\odot$)	M_1 ($M_\odot$)
0133+30[d]	M33 X-7	–	O	82.9	0.41±0.08	>8
0422+32	(GRO J)	1992/1	M2V	5.1	1.19±0.02	3.7–5.0
0538–641	LMC X–3	–	B3V	40.9	2.3±0.3	5.9–9.2
0540–697	LMC X–1	–	O7III	93.8[d]	0.13±0.05[e]	4.0–10.0:[f]
0620–003	(A)	1975/1[g]	K4V	7.8	2.72±0.06	8.7–12.9
1009–45	(GRS)	1993/1	K7/M0V	6.8	3.17±0.12	3.6–4.7:[e]
1118+480	(XTE J)	2000/2	K5/M0V	4.1	6.1±0.3	6.5–7.2
1124–684	Nova Mus 91	1991/1	K3/K5V	10.4	3.01±0.15	6.5–8.2
1354–64	(GS)	1987/2	GIV	61.1[g]	5.75±0.30	–
1543–475	(4U)	1971/4	A2V	26.8	0.25±0.01	8.4–10.4
1550–564	(XTE J)	1998/5	G8/K8IV	37.0	6.86±0.71	8.4–10.8
1650–500	(XTE J)	2001/1	K4V	7.7	2.73±0.56	–
1655–40	(GRO J)	1994/3	F3/F5IV	62.9	2.73±0.09	6.0–6.6
1659–487	GX 339–4	1972/10	–	42.1[j,k]	5.8±0.5	–
1705–250	Nova Oph 77	1977/1	K3/7V	12.5	4.86±0.13	5.6–8.3
1819.3–2525	V4641 Sgr	1999/4	B9III	67.6	3.13±0.13	6.8–7.4
1859+226	(XTE J)	1999/1	–	9.2 :[e]	7.4±1.1:[e]	7.6–12.0:[e]
1915+105	(GRS)	1992/Q[h]	K/MIII	804.0	9.5±3.0	10.0–18.0
1956+350	Cyg X–1	–	O9.7Iab	134.4	0.244±0.005	6.8–13.3
2000+251	(GS)	1988/1	K3/K7V	8.3	5.01±0.12	7.1–7.8
2023+338	V404 Cyg	1989/1[g]	K0III	155.3	6.08±0.06	10.1–13.4

[a]See Remillard & McClintock 2006 plus additional reference given below.
[b]A prefix to a coordinate name is enclosed in parentheses.
The presence/absence of a "J" indicates that the epoch of the coordinates is J2000/B1950.
[c]Year of initial X–ray outburst/total number of X–ray outbursts.
[d]Preliminary results based on a private communication by J. Orosz; also Pietsch et al. 2006.
[e]Period and f(M) corrections by AM Levine and D Lin, private communication.
[f]Colon denotes uncertain value or range.
[g]Additional outbursts in optical archives: A 0620 (1917) and V404 Cyg (1938, 1956).
[h]"Q" denotes quasi-persistent intervals (e.g., decades), rather than typical outburst.

of the velocity curve of the secondary K_2. On the right, the quantity of greatest interest is M_1, the mass of the black hole primary (given in column 7); the other parameters are the orbital inclination angle i and the mass ratio $q \equiv M_2/M_1$, where M_2 is the mass of the secondary. The value of $f(M)$ can be determined by simply measuring the radial velocity curve of the secondary star, and it corresponds to the absolute minimum allowable mass of the compact object.

An inspection of Table 1 shows that 15 of the 21 X–ray sources have values of $f(M)$ that require a compact object with a mass $\gtrsim 3\ M_\odot$. This is a widely agreed limit for the maximum stable mass of a neutron star in GR (e.g., Kalogera & Baym 1996). For the remaining five systems, some additional data

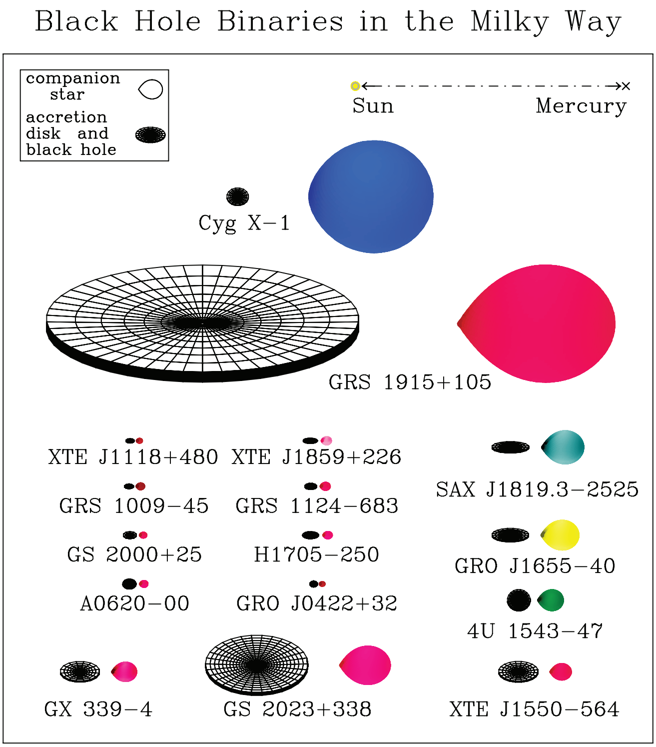

Fig. 1. Scale drawings of 16 black hole binaries in the Milky Way (courtesy of J. Orosz). The Sun–Mercury distance (0.4 AU) is shown at the top. The estimated binary inclination is indicated by the tilt of the accretion disk. The color of the companion star roughly indicates its surface temperature. Reprinted with permission from Volume 44 of Annual Reviews of Astronomy & Astrophysics (RM06).

are required to make the case for a black hole. Historically, the best available evidence for the existence of black holes is dynamical, and the evidence for these 21 systems is generally very strong, with two cautionary cases: LMC X–1 and XTE J1859+226 (see MR06). Thus, assuming that *GR* is valid in the strong-field limit, we choose to refer to these compact primaries as black holes, rather than as black hole candidates.

Figure 1 is a schematic sketch of 16 Milky Way black hole binaries with reasonably accurate dynamical data. Their diversity is evident: there are long-period systems containing hot and cool supergiants (Cyg X–1 and GRS 1915+105) and many compact systems containing K-dwarf secondaries. Considering all 21 black hole binaries (Table 1), only 4 are persistently bright X–ray sources (Cyg X–1, LMC X–1, LMC X–3 and M33 X–7). The 17 transient sources include 2 that are unusual. GRS 1915+105 has remained bright for more than a decade since its first known eruption in August 1992.

GX 339–4 undergoes frequent outbursts followed by very faint states, but it has never been observed to fully reach quiescence.

Nearly all black hole binaries are X–ray novae (Table 1) that are discovered when they first go into outburst. The X–ray light curves of nearly all of these black hole transients, which are frequently referred to as black hole X–ray novae, can be found either in MR06 or in a review paper on pre-*RXTE* X–ray novae by Chen et al. (1997). For X–ray outbursts that last between ∼20 days and many months, the generally accepted cause of the outburst cycle is an instability that arises in the accretion disk. This model predicts recurrent outbursts; indeed, half of the black hole binaries are now known to recur on timescales of 1 to 60 years (Table 1). For details on the properties of X–ray novae, see Chen et al. (1997), MR06 and RM06.

3 X–ray Spectral and Timing Observations of Black Hole Binaries

It has been known for decades that the energy spectra of black hole binaries often exhibit a composite shape consisting of both a thermal and a nonthermal component. Furthermore, black hole binaries display transitions in which one or the other of these components may dominate the X–ray luminosity (e.g., Tanaka & Lewin 1995). The thermal component is well modeled by a multitemperature blackbody, which originates in the inner accretion disk and often shows a characteristic temperature near 1 keV (see §7). The nonthermal component is usually modeled as a power law (*PL*). It is characterized by a photon index Γ, where the photon spectrum is $N(E) \propto E^{-\Gamma}$. The *PL* generally extends to much higher Photon energies (E) than does the thermal component, and sometimes the *PL* suffers a break or an exponential cutoff at high energy. X–ray spectra of black hole binaries may also exhibit an Fe Kα emission line that is often relativistically broadened (§8.2.3). For further details and references, see MR06 and RM06.

An important resource for examining the near-vicinity of a black hole is the rapid variations in X–ray intensity that are so often observed (van der Klis 2005; MR06). The analysis tool commonly used for probing fast variability is the power–density spectrum (*PDS*). The continuum power in the *PDS* is of interest for both its shape and its integrated amplitude (e.g., 0.1–10 Hz), which is usually expressed in units of rms fluctuations scaled to the mean count rate. *PDS*s of black hole binaries also exhibit transient, discrete features known as quasi-periodic oscillations (*QPO*s) that may Range in frequency from 0.01 to 450 Hz. *QPO*s are generally modeled with Lorentzian profiles, and they are distinguished from broad power peaks using a coherence parameter, $Q = \nu/FWHM \gtrsim 2$ (van der Klis 2005).

4 A Quantitative Three-State Description for Active Accretion

In MR06, a new framework was used to define X–ray states (for an historical discussion of X–ray states, see MR06 and RM06). In Figure 2, we illustrate

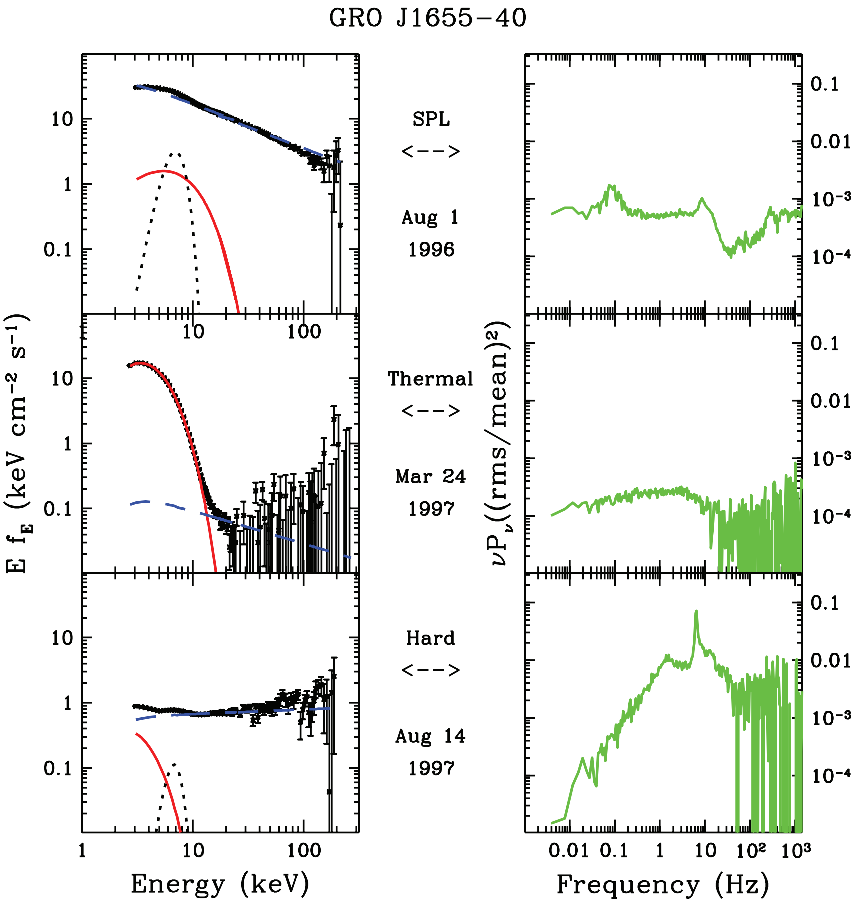

Fig. 2. Examples of the 3 states of active accretion for the black hole binary GRO J1655-40. Left panels show the energy spectra, with model components attributed to thermal-disk emission (red solid line), a power-law continuum (blue dashes) and a relativistically broadened Fe K–*alpha* line (black dotted). Power-law components for the *SPL* and hard states are distinguished by different values of the photon index (i.e. slope). The *PDS* (green solid lines) are shown in the right panels. A strong, band-limited continuum characterizes the hard state, while *QPO*s and the absence of the intense, broad continuum are usually seen in the *SPL* state. Reprinted with permission from Volume 44 of Annual Reviews of Astronomy & Astrophysics (RM06).

the character of each state by showing examples of *PDS*s and energy spectra for the black hole binary GRO J1655–40. The relevance of X–ray states fundamentally rests on the large differences in the energy spectra and *PDS*s that can be seen in a comparison of any two states.

4.1 The Thermal State

For extended periods of time during a transient outburst, the emission is observed to be dominated by thermal radiation from the inner accretion disk accompanied by a near-absence of complicating temporal variability. This well-defined "thermal" state (formerly "high/soft" state) is defined by the following three conditions: (1) the fraction f of the total 2–20 keV emission contributed by the accretion disk exceeds 75%, (2) there are no *QPO*s present with integrated amplitude above 0.5% of the mean count rate, and (3) the integrated power continuum is low, with rms power $r < 0.06$ averaged over 0.1–10 Hz.

For the thermal state there is a satisfactory paradigm, namely, thermal emission from the inner regions of an accretion disk. The best-known hydrodynamic model of a radiating gas orbiting in the gravitational potential of a compact object is the steady-state, thin accretion disk model (Shakura & Sunyaev 1973). This model leads to a temperature profile $T(R) \propto R^{-3/4}$ and the conclusion that the inner annulus in the disk dominates the thermal spectrum because $2\pi R dR\ \sigma T^4 \propto L(R) \propto R^{-2}$. This result has a striking observational consequence: X–ray astronomy is the window of choice for probing strong gravity near the horizon of an accreting stellar-mass black hole.

Our understanding of the thermal state is developing quickly as a result of observation, the development of fully-relativistic accretion disk models, and magnetohydrodynamic (*MHD*) simulations.

4.2 The Hard State

In the "hard" state, the accretion-disk component is either absent or it is modified in the sense of appearing comparatively cool and large. The hard state has been clearly associated with the presence of a steady type of radio jet. Transitions to either the thermal state or an *SPL* state effectively quench this radio emission. Thus, the presence of the jet is an important defining feature of this state. The definition of the hard state is based on three X–ray conditions: (1) $f < 0.2$, i.e. the power-law contributes at least 80% of the unabsorbed 2–20 keV flux, (2) $1.5 < \Gamma < 2.1$, and (3) the *PDS* yields $r > 0.1$.

Multiwavelength studies of XTE J1118+480 with its very low column density showed directly that in the hard state the thermal disk radiation is truncated at a large radius. Nevertheless, the physical condition of material within this radius remains somewhat uncertain. The presence of a hot advective flow that feeds the jet is one leading model. Both synchrotron and Compton components contribute to the broadband spectrum, with the Compton emission presumed to originate at the base of the jet. See RM06 for details and references.

4.3 The Steep Power Law State

The steep power law (*SPL*) component was first linked to the power-law "tail" found in the thermal state, and it was widely interpreted as inverse Compton radiation from a hot corona somehow coupled to the accretion disk. The picture became more complicated when X–ray *QPO*s were first detected with Ginga for two sources: GX 339-4 (6 Hz) and X–ray Nova Muscae 1991 (3–8 Hz). The *QPO*s, the high luminosity, and the strength of the power-law component prompted the interpretation that the *QPO*s signified a new black hole state, which was originally named the "very high" state (MR06). *RXTE* observations later showed that X–ray *QPO*s from black hole binaries are much more common than had been realized.

As noted above, *CGRO* observations have shown that the *SPL* may extend to photon energies as high as 800 keV). This forces consideration of nonthermal Comptonization models. The *QPO*s impose additional requirements for an oscillation mechanism that must be intimately tied to the electron acceleration mechanism (in the inverse Compton scenario), since the *QPO*s are fairly coherent ($\nu/\Delta\nu \sim 12$) and are strongest above 6 keV. Despite a wide range in *SPL* luminosities, the *SPL* tend to dominate as the luminosity approaches the Eddington limit. Furthermore, the occasions of high-frequency *QPO*s at 100-450 Hz in 7 black hole binaries almost always coincide with a strong *SPL* spectrum. Overall, the many fundamental differences between the thermal and *SPL* properties indicate that one cannot invoke some alternative state description that unifies thermal and *SPL* observations under a single "soft" state.

The physical origin of the *SPL* state remains one of the outstanding problems in high-energy astrophysics. It is crucial that we gain an understanding of this state, which is capable of generating *HFQPO*s, extremely high luminosity, and spectra that extend to $\gtrsim$1 MeV.

5 X–ray Quasi-Periodic Oscillations

X–ray *QPO*s are specialized and extraordinarily important avenues for the study of accreting black holes. They are transient phenomena associated with the nonthermal states and state transitions. For definitions of *QPO*s and analysis techniques, see van der Klis (2005). *QPO*s play an essential role in several key science areas, such as probing regions of strong field and defining the physical processes that distinguish X–ray states. In the following, we discuss in turn low-frequency *QPO*s (*LFQPO*s) and high-frequency *QPO*s (*HFQPO*s).

5.1 Low-Frequency Quasi–Periodic Oscillations

Low-frequency *QPO*s (*LFQPO*s; roughly 0.1–30 Hz) have been detected on one or more occasions for 14 of the 18 black hole binaries considered in Table 4.2 of MR06. They are important for several reasons. *LFQPO*s can have high amplitude (integrated rms/mean values of $a > 0.15$) and high coherence (often $Q > 10$), and their frequencies and amplitudes are generally correlated with the spectral parameters for both the thermal and *PL* components. With the exception of Cyg X–1, *QPO*s generally appear whenever the *SPL* contributes more than 20% of the flux at 2–20 keV, which is one component of the definition of the *SPL* state.

5.2 High-Frequency Quasi–Periodic Oscillations

High-frequency *QPO*s (*HFQPO*s; 40–450 Hz) have been detected in seven sources (5 black hole binaries and 2 black hole candidates). These oscillations are transient and subtle ($a \sim 0.01$), and they attract interest primarily because their frequencies are in the expected range for matter in orbit near the *ISCO* for a $\sim 10\ M_\odot$ black hole.

The entire sample of *HFQPO*s with strong detections ($>4\sigma$) is shown in Figure 3. Three sources have exhibited single oscillations. The other four sources display pairs of *HFQPO*s with frequencies that scale in a 3:2 ratio. Most often, these pairs of *QPO*s are not detected simultaneously. The four sources are GRO J1655–40 (300, 450 Hz), XTE J1550–564 (184, 276 Hz), GRS 1915+105 (113, 168 Hz), and H 1743–322 (165, 241 Hz). GRS 1915+105 also has a second pair of *HFQPO*s with frequencies that are not in a 3:2 ratio (41, 67 Hz).

*HFQPO*s are of further interest because they do not shift freely in frequency in response to sizable luminosity changes (factors of 3–4). There is evidence of frequency shifts in the *HFQPO* at lower frequency (referring to the 3:2 pairing), but such variations are limited to 15%. This is an important difference between these black hole binary *HFQPO*s and the variable-frequency kHz QPOs seen in accreting neutron stars, where both peaks can shift in frequency by a factor of two. Overall, black hole binary *HFQPO*s appear to be a stable and identifying "voice-print" that may depend only on the mass and spin of the black hole.

All of the strong detections ($>4\sigma$) above 100 Hz occur in the *SPL* state. In three of the sources that exhibit *HFQPO*s with a 3:2 frequency ratio, the $2\nu_0$ *QPO* appears when the *PL* flux is very strong, whereas $3\nu_0$ appears when the *PL* flux is weaker. Currently, there is no explanation for this result.

The commensurate frequencies of *HFQPO*s suggests that these oscillations are driven by some type of resonance condition. Abramowicz and Kluzniak (2001) proposed that orbiting blobs of accreting matter could generate the harmonic frequencies via a resonance between a pair of the coordinate frequencies given by *GR*. Earlier work had used *GR* coordinate frequencies and

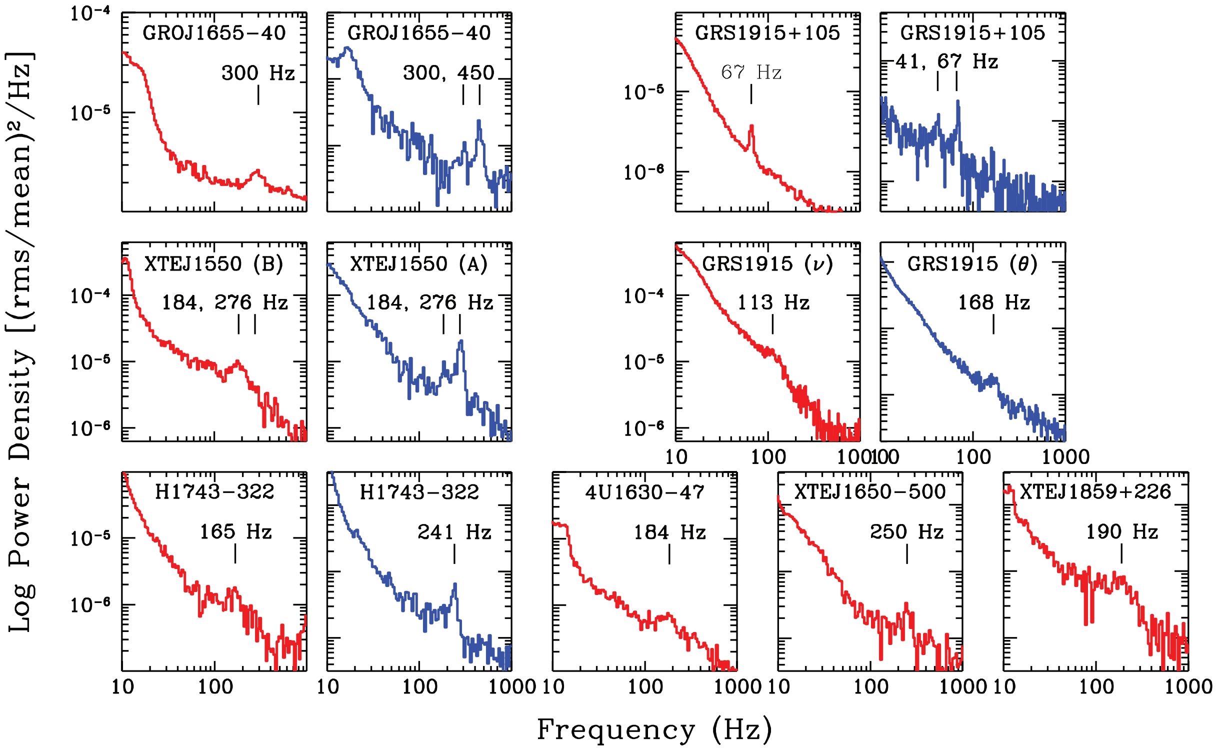

Fig. 3. High-frequency quasi-periodic oscillations (*HFQPO*s) observed in black hole binary and black hole candidate systems. The traces in blue show power density spectra (*PDS*s) for the range 13–30 keV. Red traces indicate *PDS*s with a broader energy range, which may be either 2–30 or 6–30 keV. Reprinted with permission from Volume 44 of Annual Reviews of Astronomy & Astrophysics (RM06).

associated beat frequencies to explain fast *QPO*s in both neutron-star and black hole systems (Stella et al. 1999), but without invoking a resonance condition. Current work on resonances as a means of explaining *HFQPO*s includes more realistic models for fluid flow in the Kerr metric. Resonance models are considered in more detail in §6.2.

6 Accreting Black Holes as Probes of Strong Gravity

The continuing development of gravitational wave astronomy is central to the exploration of black holes. In particular, we can reasonably expect that *LIGO* and *LISA* will provide us with intimate knowledge concerning the behavior of space-time under the most extreme conditions. Nevertheless, gravitational wave detectors are unlikely to provide us with direct information on the formation of relativistic jets, on strong-field relativistic *MHD* accretion flows, or on the origin of high-frequency *QPO*s or broadened Fe lines. Accreting black holes – whether they be stellar-mass, supermassive or intermediate mass – promise to provide detailed information on all of these topics and more. In short, accreting black holes show us uniquely how a black hole interacts with its environment. In this section, we first sketch a scenario for the potential impact of black hole binaries on physics, and we then discuss a current frontier topic, namely, the measurement of black hole spin.

6.1 The Journey from Astrophysics to Physics

Numerous examples can be given of how a discovery in astrophysics has impacted physics, such as Newton's and Einstein's theories of gravity and the quest to understand dark matter and dark energy. Likewise, studies of astrophysical black holes - the only type of black hole we are likely to ever know about - have the potential to revolutionize the foundations of frontier physics. We see a distinct possibility that the study of black hole binaries can make a significant contribution to such a revolution. In the following we provide an outline in five stages of how this development is presently unfolding and where it may ultimately lead.

Phase I—*Identify Dynamical Black Hole Candidates*: As discussed in §2, much has already been done during the past 20 years to secure the masses of many stellar black holes. This is extremely important because mass is the most fundamental parameter of a black hole. Obviously obtaining additional mass measurements and increasing the quality of the existing measurements is of great importance. However, the dynamical measurement of mass does not probe the space-time near the black hole, and we therefore curtail the discussion of this step.

Phase II—*Establish that the Candidates are True Black Holes*: The defining property of a black hole is its event horizon, and establishing its existence is the straight path to demonstrating that a black hole candidate is a bona