Chapter 2
Relativistic Jets in Stellar Systems

Elena Gallo

Abstract Albeit their nature remains elusive, relativistic, collimated outflows of energy and particles appear to be a nearly ubiquitous feature of accreting black holes. As evidence accumulates for a dominant role of the jet in dissipating the liberated accretion power, questions around their powering mechanism and even composition remain unanswered. In this chapter, I will describe the main observational properties of relativistic jets from black hole X-ray binaries, with a particular emphasis on recent developments around three main topics: (i) the role and relative importance of the accretion flow, relativistic jet and equatorial wind; (ii) the existence of global luminosity-luminosity correlation(s) in quiescent and hard state black hole X-ray binaries, and their interpretation(s); (iii) (ways of estimating) the total jet power, and its relation to black hole spin.

2.1 Review of Observations

2.1.1 Black Hole X-Ray Binary Outbursts

Though tens of thousands of such systems are thought to exist throughout the Galaxy (Fender et al. 2013), black hole X-ray binaries become detectable to most ground- and space-based telescopes when they enter an outburst phase, that is, when their luminosity increases by several orders of magnitude at all wavelengths. There is general agreement that black hole X-ray binary outbursts are triggered by a relatively sudden increase of the accretion disk viscosity, caused in turn by a rise in the ionization degree of hydrogen in the disk (see Lasota 2001, and reference therein for a review, and Coriat et al. 2011 for a recent test of the disk instability model). In what follows, I will give a very brief description of our phenomenological understanding of the properties of outbursting black hole

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X-ray binaries. For comprehensive reviews, the reader is directed to Remillard and McClintock (2006) and Fender (2006), on X-ray states and relativistic jets, respectively.

2.1.2 Accretion Modes and Relativistic Jets I: Hard State Steady Jets

A useful and practical tool to visualize the evolution of the global properties of black hole X-ray binaries across a typical outburst is to rely on the so-called hardness-intensity diagram, shown schematically in Fig. 2.1. Plotted here is the X-ray spectral evolution of a prototypical system throughout an outburst (GX339–4), in the form of X-ray hardness (typically 2–10 keV over 0.1–2 keV count rate) as a function of integrated X-ray luminosity (or more simply count rate).

Black hole X-ray binary systems spend the overwhelming majority of their lifetime in a 'quiescent' state, with X-ray luminosities $\lesssim 10^{30-32}$ erg s^{-1}. This stage corresponds to the bottom right corner of the diagram in Fig. 2.1. Once an outburst

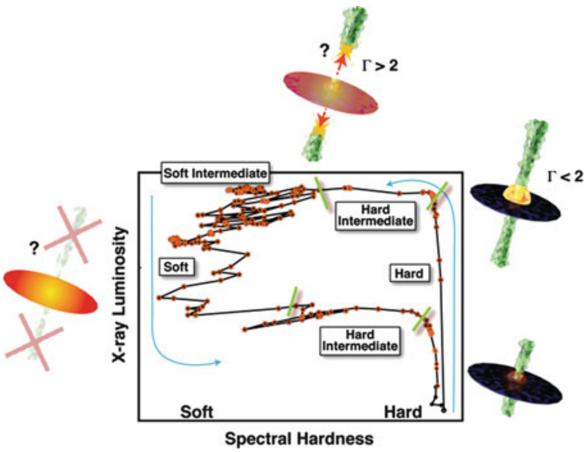

Fig. 2.1 This sketch illustrates our basic understanding of how different accretion modes of black hole X-ray binaries, as traced by the X-ray continuum, are known to map into different 'varieties' of relativistic outflows, traced by the radio-IR emission. Specifically, persistent, synchrotron emitting jets with flat-to-inverted radio-IR spectra are routinely observed in hard X-ray states; such 'steady jets' are quenched once the transition to the soft state is made. During the hard-to-soft X-ray state transition, bright radio flares are often observed, arguably in relation to the ejection of highly relativistic material. Fast moving 'blobs', i.e. the flaring jets, are then observed moving away from the binary system in opposite directions after the transition to the soft state has taken place (sometimes with apparent superluminal velocities); they expand adiabatically, display optically thin radio spectra, and only last a few days-weeks; they are thus refereed to as 'flaring jets' (From: http://www.issibern.ch/teams/proaccretion/)

begins, the source X-ray luminosity can rise up to $\sim 10^{38}$ in timescales of days. All throughout this phase the broadband X-ray spectrum is well represented by a power-law with photon index $\Gamma \sim 2.1 - 1.6$, with the spectrum gradually hardening as the system increases in luminosity (Plotkin et al. 2013; Reynolds et al. 2014). The X-ray spectrum also shows a cutoff around a few tens of keV, and is generally ascribed to thermal Comptonization of thermal disk photons off of a population of hot electrons/positrons within a compact 'corona' that enshrouds the inner accretion disk. Strong X-ray variability (up to 40 % r.m.s. in the Fourier frequency range 0.01–100 Hz) is typically associated with the hard state (although the X-ray spectral evolution is not dramatic over this phase, it is likely accompanied by more substantial variations in the ultraviolet band, which is unfortunately unaccessible for most Galactic X-ray binaries).

Hard/quiescent state black hole X-ray binaries are associated to weak but persistent radio emission, with a flat-to-inverted ($\alpha \sim 0 - 0.5$, where flux density is proportional to ν^{α}) spectrum. In analogy with compact extragalactic radio sources, the relative flux steadiness, flat spectrum, low degree of polarization and high brightness temperature indicate that this emission originates in a (nearly-) continuously replenished, partially self-absorbed, synchrotron-emitting outflow, a.k.a. jet. This interpretation has been directly confirmed for two (bright) systems; for both GRS 1915+105 and Cyg X-1, the compact, persistent, hard state radio source has been resolved into a $\sim$10 A.U., highly collimated jet with very long based interferometry (Stirling et al. 2001; Dhawan et al. 2000, respectively).

2.1.3 Accretion Modes and Relativistic Jets II: Hard-to-Soft Transition – Flaring Jets

As the source reaches an X-ray luminosity of $\sim 10^{37}\,\mathrm{erg\,s^{-1}}$, it is very likely to make a transition to the soft state (albeit many 'failed' state transition have been reported for multiple systems). The hard-to-soft state transition can take place in the face of relatively little change in the broadband X-ray luminosity, while significant evolution is observed in the power density spectrum (see, e.g., Casella et al. 2005 for a thorough study of the broad band noise and quasi-periodic oscillations during state transitions). For the purpose of this review, the most important feature of the state transition is its association with bright, radio flare(s) (occurring sometimes singly and sometimes in sequences). These events are thought to be associated with ejections of synchrotron emitting, adiabatically expanding plasmons, which are (occasionally) later resolved as highly relativistic 'flaring', or ballistic, jets, i.e., moving away from the binary system in opposite directions out to thousands of A.U., and fading away over time scales of days or weeks (Mirabel and Rodríguez 1999; Fender et al. 1999; Miller-Jones et al. 2012).

As discussed in Fender and Gallo (2014), “there have been a number of attempts to associated the ‘moment of jet launch’ with an associated change or event in the accretion flow [...], in particular with the occurrence of the type-B quasi-periodic oscillations, but no convincing one-to-one relation could be firmly established and whether or not there exists a key signature of the moment of launch remains unclear”. The possibility remains that the flaring jet(s) may be a more complex phenomenon resulting from rapid – but not instantaneous – changes in the inner disk/outflowing gas properties, and the suppression of the hard X-ray power law. Nevertheless, there has been considerable interest around these events, in that the peak luminosity of the hard-to-soft state transition radio flares has been adopted by Narayan and McClintock (2012) as a proxy for the total jet power, and shown to correlate with the inferred spin parameter value for a handful of black hole X-ray binaries. This is further discussed in Sect. 2.3.

2.1.4 Accretion Modes and Relativistic Jets III: Soft State Winds

The X-ray spectrum of black hole X-ray binaries in the soft state (left portion of the diagram in Fig. 2.1) is well represented by a blackbody-like component which peaks around 1 keV, combined with a steep power law that accounts for less than 10 % of the integrated luminosity. In this state, the overall X-ray variability drops to below 5 %. All these features are well understood in terms of an optically thick, geometrically thin accretion disk extending very close to innermost stable circular orbit of the black hole, with a residual corona of thermal and quasi-thermal particles responsible for a minimal level of Comptonization. The core radio, mm and near-infrared emission all drop below detectable levels in the soft state (Fender et al. 1999; Russell et al. 2011), strongly indicative that the core jet emission has switched off.

A major, recent breakthrough in understanding X-ray states and their connection with outflows is represented by the work of Ponti et al. (2012), who demonstrated that accretion disk winds (revealed by absorption lines in high resolution X-ray spectra) appear to be uniquely observed in *edge-on soft-states*, thus indicating a broad equatorial geometry (see Fig. 2.2; see also Miller et al. 2006, 2008; Neilsen and Lee 2009; King et al. 2013).

In summary, observations indicate a *bimodal regime, whereby, as they transition from the hard to the soft state, black hole X-ray binaries move from a jet-dominated regime with no evidence (so far) of strong winds, to the opposite regime, where the onset of a strong wind coincides with the quenching the steady, relativistic radio jet*. As noted by Ponti et al., however, these two regimes are not likely to tap into the same energy reservoir, with the soft state wind likely being more mass-loaded

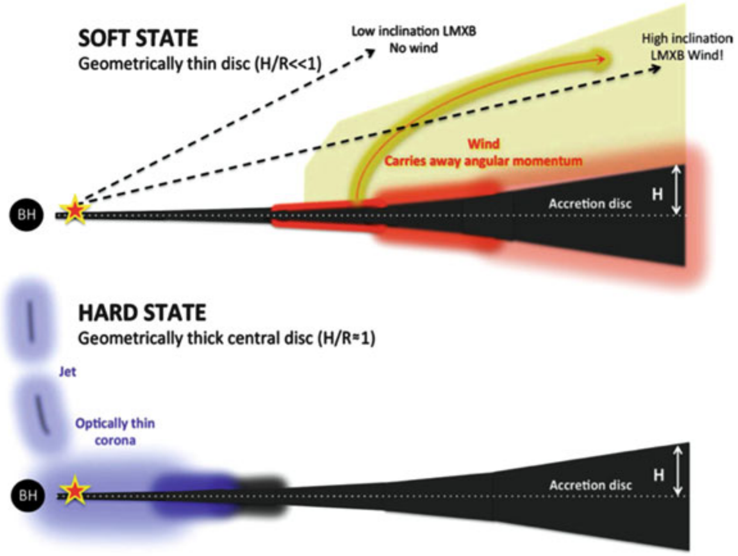

Fig. 2.2 Schematic illustrating the geometry of X-ray winds from soft state black hole X-ray binaries. This follows from the realization that high inclination (dipping) sources show absorption lines every time they are in the soft state and upper limits in the hard states, whereas lines are never detected in low inclination (non dipping) sources (From Ponti et al. (2012; see also their figure 2))

and yet carrying less kinetic energy than the steady hard state jet (Fender et al. in preparation).

2.1.5 Accretion Modes and Relativistic Jets IV: Caveats and Other Recent Developments

As noted by Fender and Gallo (2014), whereas there is general agreement around the physical mechanism that is responsible for the onset of the outburst, the associated 'spectral hysteresis' effect is far from being understood. Figure 2.3, from Dunn et al. (2010), serves to illustrate the broad range of observed luminosities for the hard-to-soft vs. soft-to-hard state transitions for a sample of 24 black hole X-ray binaries observed by the Rossi X-ray Timing Explorer over a period of 13 year. In a recent model put forward by Begelman and Armitage (2014), this hysteresis pattern is driven by an increase in turbulent stress in a disk that is threaded by a net magnetic field, combined with the ability of geometrically thick (but not thin) disks to advect such a field in the radial direction. In this framework, the transition to the soft stare

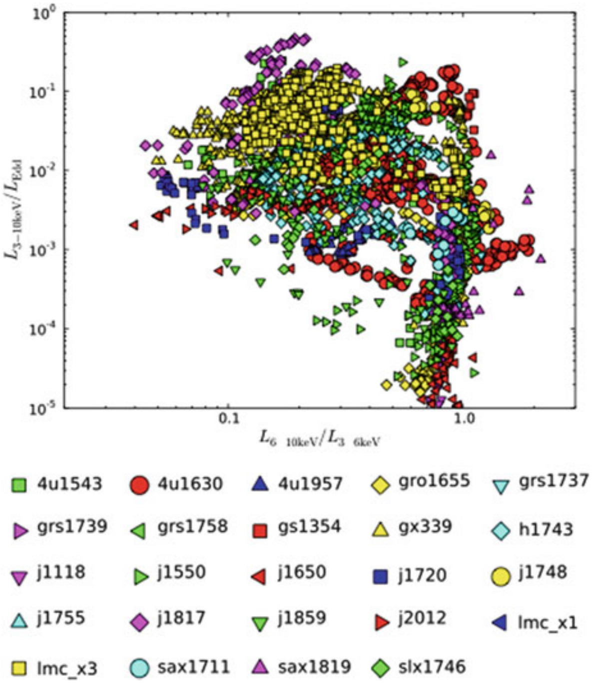

Fig. 2.3 Hardness-intensity diagram for 24 black hole X-ray binaries as observed by the Rossi X-ray Timing Explorer over a period of 13 years (From Dunn et al. (2010))

occurs when the total accretion power luminosity, which in turn is proportional to the second power of the alpha parameter, approaches the Eddington luminosity.

The same hysteresis behavior can also be visualized via a (model-dependent, unlike the hardness-intensity-diagram)'reflection-intensity' diagram (see Fig. 2.4), where the flux in the hard X-ray power law component is shown as a function of the flux in the reflection component during the outburst evolution. Overall, the hard state (in blue) is characterized by a weak reflection component; at the same time, though, the ratio of reflection to power law component (i.e., the reflection fraction) increases as the source luminosity rises. In contrast, the soft state (in red) is found to be reflection-dominated. In the hard state, the reflection fraction can be increased by progressively decreasing the size of the inner radius of the accretion disk, i.e., by moving the disk closer and closer to the innermost stable circular orbit. In contrast, the scale-height of the corona above the disk decreases in the soft state, leading to an increase in the fraction of back-scattered, hard X-ray photons, and hence of the reflection fraction. The role of the jet in this picture remains to be explored.

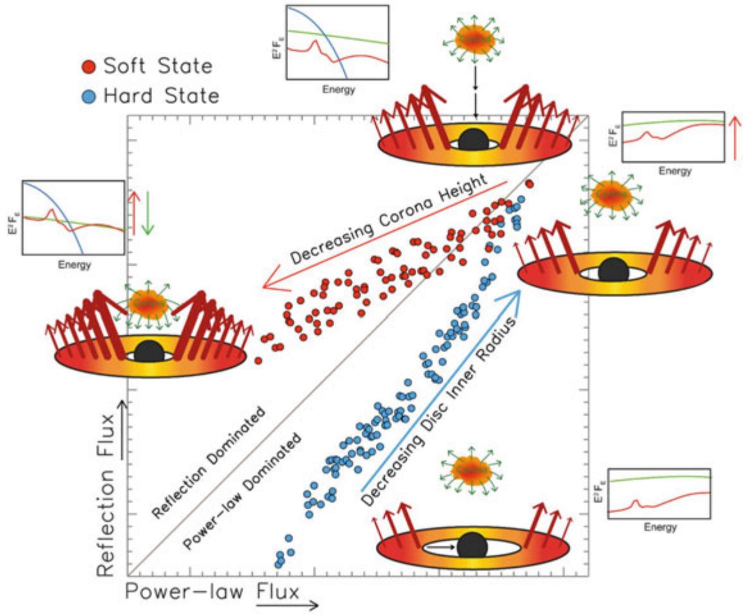

Fig. 2.4 Reflection-intensity diagram of the black hole X-ray binary GX339–4 as observed by the Rossi X-ray Timing Explorer during three of its outbursts. The evolution of the power law and reflection fraction are interpreted in terms of two main varying parameters: the extent of the inner accretion disk radius and the height of the Comptonizing corona above/below the disk (From Plant et al. (2014))

2.2 The Radio/X-Ray Domain of Hard and Quiescent State Black Hole X-Ray Binaries

Coordinated radio and X-ray monitoring of hard and quiescent state black hole X-ray binaries have proven to be a powerful observational tool for studying the connection between accretion and the production of steady jets in these systems. A tight and repeating correlation between the radio and X-ray luminosity (with L_X being proportional to $L_r^{0.7\pm0.1}$) was first established for the black hole X-ray binary GX339-4 in the hard state by Corbel et al. (2003), and later confirmed with data from 7 outbursts over a period of 15 year by Corbel et al. (2013) (with a revised slope of 0.62 ± 0.01; see Fig. 2.5). A similar relation, with slope in the range 0.5–0.7 and holding over several orders of magnitude in L_X, has also been established for the black hole X-ray binary V404 Cyg (Gallo et al. 2003, 2005; Corbel et al. 2008), and, more recently, XTE J1118+480 (Gallo et al. 2014; see Fig. 2.6). A great deal of work has been carried out to identify possible causes for the different normalisations among different systems; however, to date no convincing evidence has been reported for a dependence of the normalisation on orbital parameters, relativistic beaming,

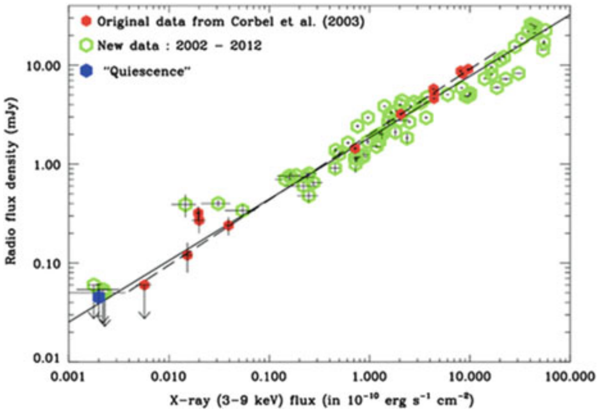

Fig. 2.5 Radio-X-ray correlation for the black hole X-ray binary GX339-4 in hard state: $L_X \propto L_r^{0.62\pm0.01}$. (Data are taken from 7 different outbursts spanning over 15 year. From Corbel et al. (2013))

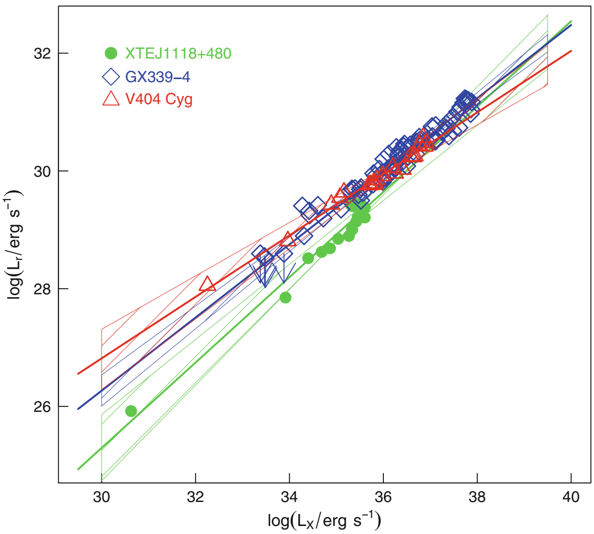

Fig. 2.6 Radio-X-ray correlation for the black hole X-ray binaries GX339-4 (in *blue*, same data set as in Fig. 2.5), V404 Cyg (*red*) and XTE J1118+480 (*green*), with slopes: 0.62±0.04, 0.52±0.07, and 0.72 ± 0.09, respectively (From Gallo et al. (2014))

black hole spin and/or black hole mass (see Soleri and Fender 2011; Gallo et al. 2012, 2014).

Additionally, despite the tightness of the relation for the three individual sources, its 'universality' (cf. Gallo et al. 2003) has recently come under severe scrutiny, and rightly so. Figure 2.7 summarizes the current state of the problem by assembling what is likely the most complete data collection as of today (data

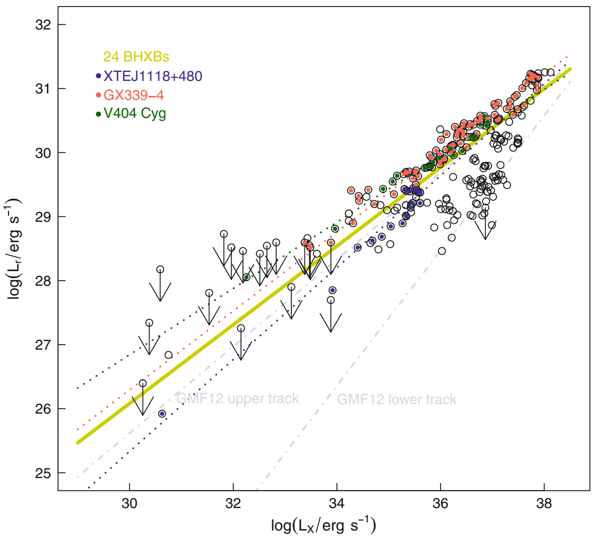

Fig. 2.7 The radio/X-ray luminosity plane of 24 hard and quiescent state black hole X-ray binaries. The *dashed grey lines* indicate the best-fit relations to the upper and lower tracks as identified in the clustering analysis of Gallo et al. (2012). Also highlighted are the three sources for which a tight non-linear correlation has been reported over a wide range in X-ray luminosity, i.e. GX339–4, V404 Cyg and XTE J1118+480 (shown individually in Fig. 2.6). The best-fitting slope for the whole data set is $\beta = 0.61 \pm 0.03$, with an intrinsic scatter of 0.31 ± 0.03 dex (From Gallo et al. (2014))

from Gallo et al. 2003, 2012, 2014; Corbel et al. 2003, 2008, 2013, and references therein). The existence of a cluster of 'outliers' at X-ray luminosities between $\sim 10^{35-37}$ erg s^{-1} is apparent, so much so that Gallo et al. (2012) suggested the existence of statistically significant, separate tracks (labeled as upper and lower track; shown in gray in Fig. 2.7).

Regardless of whether a second track or a genuinely large scatter to a single relation provides a more meaningful description of the data, particularly at high X-ray luminosities, it is worth stressing that at least two sources have been observed declining along the (allegedly) steeper, lower track to then re-join the upper track. For example, the black hole X-ray binary H1743–22, as observed during the decline of its 2008 outburst (Jonker et al. 2010; Miller-Jones et al. 2012; Miller et al. 2012), started off as under-luminous in the radio band during the initial decay phase ($10^{36} \lesssim L_X \lesssim 10^{38}$ erg s^{-1}), proceeded to make a nearly-horizontal excursion toward lower X-ray luminosities (between $10^{36} \lesssim L_X < \lesssim 10^{36}$ erg s^{-1}), and finally reached a comparable radio luminosity level (for the same L_X) as GX339–4 and V404 Cyg (somewhere below $\simeq 10^{34}$ erg s^{-1}).

Coriat et al. (2011) interpreted the behavior of H1743−22 and other radio-quiet systems as due to the temporary onset radiatively efficient accretion. In a more theoretical work, Meyer-Hofmeister and Meyer (2014) argue that thermal photons from a weak inner accretion disk could be responsible for enhancing the photon bath available for Comptonization, and hence the hard X-ray flux, in bright hard states. Within this model, the condensation of optically thin accreting gas into an inner, keplerian disk is expected above a critical mass accretion rate once thermal conduction and Compton cooling are properly taken into account in the energy balance equations (for reasonable values of the viscosity parameter the threshold can be set around 10^{-3} times the Eddington limit; Meyer et al. 2007; Liu et al. 2006, 2007). Such disk would cease to exist at low accretion rate, as also indicated by observations (Miller et al. 2006; Reis et al. 2010; Reynolds 2013). In the context of this model, the 'radio quiet' track is thus better described as 'X-ray bright'.

Shortly after Corbel et al. (2003) reported on the non-linear radio/X-ray luminosity correlation for GX339-4 and Gallo et al. (2003) extended the analysis to a larger sample of systems, claiming the existence of a universal correlation for hard state black hole X-ray binaries, Merloni et al. (2003) and, independently, Falcke et al. (2004) presented the first evidence that, with the addition of a mass term, a similar scaling holds for super-massive black holes in radiatively inefficient AGN. Since, the so-called 'Fundamental plane of black hole activity' has become a standard tool for estimating the nature of compact radio and X-ray sources of unknown mass (see, e.g., Mïller and Gültekin 2011; Gültekin et al. 2014), and is generally taken as strong evidence for a common physics driving the jet-accretion coupling across the mass scale.

2.2.1 X-Ray/Optical-IR Correlation

Mounting evidence supports the claim that, while in the hard state, the steady jet extends all the way up to IR and often optical frequencies (Fender 2001; Chaty et al. 2003; Gallo et al. 2007; Russell et al. 2006, 2010, 2013b; Brocksopp et al. 2010; Malzac et al. 2004; Hynes et al. 2004, 2006, 2009; Casella et al. 2010). In a comprehensive work, Russell et al. (2006) assembled nearly-simultaneous IR-optical and X-ray observations of 33 X-ray binaries (black holes and neutron stars) and estimated the relative contributions of various IR/optical emission processes (companion star, direct disk emission, irradiated disk emission, jet) as a function of the X-ray luminosity. Again, evidence for a positive, non-linear correlation was found, of the form $L_{\rm opt-IR} \propto L_{\rm X}^{0.6}$, extending all the way from the peak of the hard state down to the quiescent regime. The radio/IR correlation is shown in Fig. 2.8.

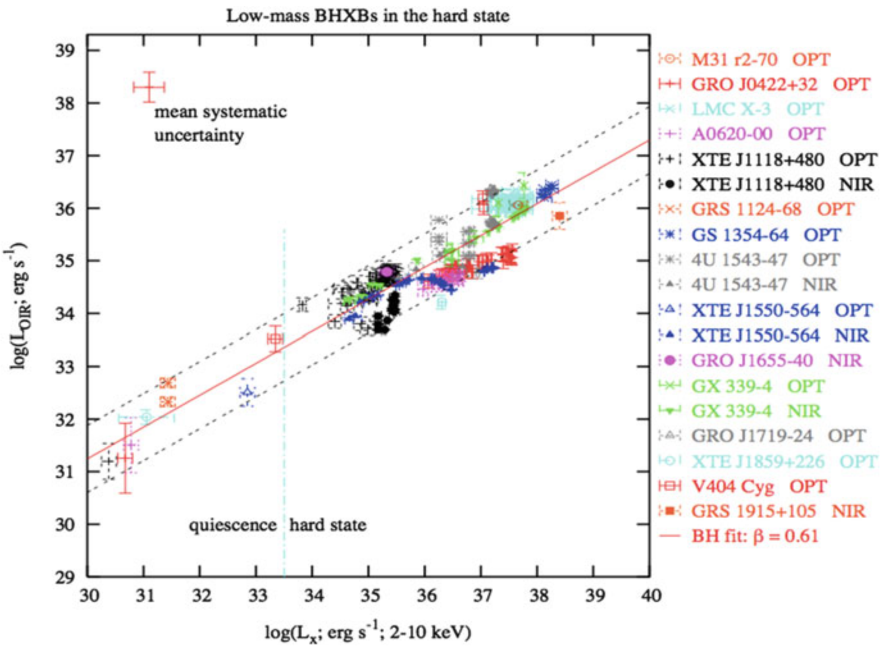

Fig. 2.8 The X-ray/optical-IR luminosity correlation for hard state black hole X-ray binaries, with $L_{\rm opt-IR} \propto L_{\rm X}^{0.6}$ (From Russell et al. (2006))

2.3 Relation Between Jet Power and Black Hole Spin

The powering mechanism of relativistic jets remains one of the most important and elusive questions in high energy astrophysics. For the purpose of modeling the evolution of galaxies and their nuclear super-massive black holes, the more powerful jets, i.e., those of radio galaxies, are often *assumed* (e.g., Sikora et al. 2007) to be powered by black hole spin, i.e. via the 'Blandford-Znajek' mechanism (Blandford and Znajek 1977). In contrast, Seyfert galaxies and lower luminosity jets in general may be powered by differential rotation coupled with magnetic fields ('Blandford-Payne' mechanism; Blandford and Payne 1982). However (for super-massive black hole at least), there is no compelling observational evidence for this to be the case.

In this respect, albeit the much lower statistics, black hole X-ray binaries offer the advantage of a neater environment (and higher count rate) to comfortably apply X-ray spectral fitting techniques for measuring the temperature, and thus the extent, of the inner accretion disk, by fitting either the reflection and iron line complex in bright hard states (hereafter reflection-fitting), or the thermal continuum in soft states (hereafter continuum-fitting; see Reynolds et al. 2014, and McClintock et al. 2013, respectively, for recent, detailed reviews; notice that the latter method can only be applied to stellar mass black holes, as the thermal disk peaks in the UV band for super-massive black holes in AGN). This translates into a measurement of the black hole spin parameter, a, which – in principle – can be compared against jet power, P_{j} to test the presence of a relation of the form, $P_{\mathrm{j}} \propto a^2$, predicted for spin-powered jets.

2.4 Measures of Jet Power

Though several modeling uncertainties are at play in estimating the black hole spin parameter via fitting techniques, the uncertainties that affect jet power estimates for steady jets are undeniably much more severe. Simply put, the steady jet radio emission is known to be at best a poor indicator of total (kinetic plus electromagnetic) jet power.

This is readily apparent from a number of considerations; as clearly shown in Fig. 2.7, the radio luminosity of steady hard state jets varies by orders of magnitude during an outburst cycle, while the black hole spin, obviously, remains constant. To add to this, the radiative efficiency of the synchrotron process is known to be lower than a few per cent at most (Fender 2001), making any determination of jet power based on radio luminosity alone (either integrated or single frequency) highly unreliable (this might not be the case for flaring jets, though, as discussed below).

In order to circumvent this well know problem, and test for the presence of a relation between jet power and spin parameter in a sample of black hole X-ray binaries with measured spin parameter, Fender et al. (2010) adopted the relative normalization of the radio/X-ray correlation for individual sources as a proxy for their total jet power. No evidence for a positive correlation emerged. This result can be easily interpreted as due the large uncertainties in jet power, and/or, to a second extent, spin determinations (see however King et al. 2013, who report on a marginally significant correlation between the mass-scaled radio luminosity and spin parameter across a sample of 11 stellar mass black holes and 37 super-massive black holes in Seyfert galaxies). Alternatively, taken at face value, it argues against the black hole rotational energy as the main supply of power for steady jets.

The jet power proxy adopted by Fender et al. (2010) was admittedly "susceptible to errors resulting from poor sampling of events, uncertainties in Doppler boosting, assumptions about equipartition, etc." Ideally, radio lobes and/or cavities, of the kind of those that are observed around powerful radio galaxies or brightest center galaxies in galaxy clusters, provide the best (and possibly only) reliable diagnostics for the jet power, allowing for a direct measurement of the amount of work exerted by the jets on the surrounding medium. However, primarily due to the highly under-dense environment of black hole X-ray binaries (compared to AGN), such jet-ISM interaction regions are very rare among X-ray binaries (Heinz 2002). In fact, only three such structures are known in the Galaxy, and only one of those surrounds a dynamically confirmed black hole accretor, i.e. Cyg X-1 (Gallo et al. 2005).

The above considerations are largely centered around steady jets. In a recent work however, Narayan and McClintock (2012) claimed evidence for a positive correlation between spin parameter – as measured from continuum fitting – and jet power *for flaring (or ballistic) jets*. The correlation, shown in Fig. 2.9, appears to be consistent with a scaling of the form $P_\mathrm{j} \propto \Omega_H^2$, as predicted for 'Blandford-Znajek' jet-powering (dashed line, where $\Omega_H = a(c^3/2GM)/(1+\sqrt{1-a^2})$, is the angular frequency of the black hole horizon[1]). Here, the (mass- and distance-scaled) peak 5 GHz luminosity of the bright radio flare associated with the hard-to-soft state transitions (Sect. 2.1.3), S_ν, is taken as proxy for jet power: $P_\mathrm{j} = D^2(\nu S_\nu)/M_\mathrm{BH}$, where M_BH is the black hole mass and D its distance. Unlike the radio/X-ray correlation normalization adopted by Fender et al. (2010) for steady jets, this is indeed a model-independent quantity.

In a subsequent work, however, Russell et al. (2013a) argued against there being a significant correlation. The core of the controversy is illustrated in Fig. 2.10, most notably the bottom left panel (see Fig. 2.9 for a direct comparison with Narayan and McClintock 2012). Compared to Narayan and McClintock (2012), Russell et al. (2013a) include several additional data points that, taken at face value, do not fit the spin-powering relation. The interested reader who wishes to form an unbiased opinion on whether the above-mentioned points ought to be included in the analysis, or not, is directed to the discussion in Russell et al. (2013a), Narayan

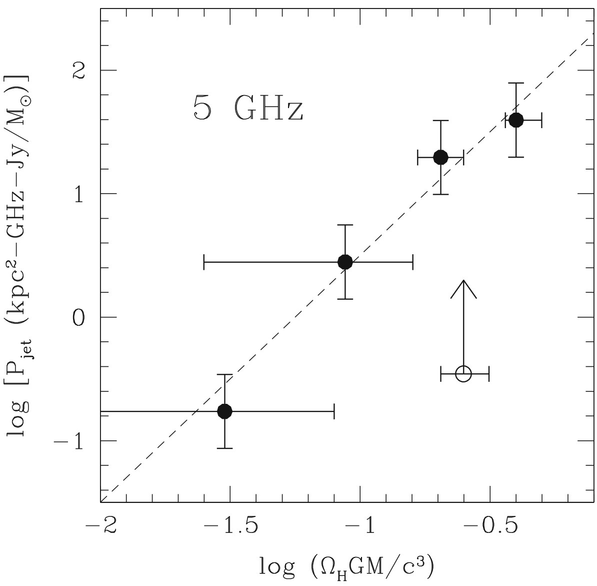

Fig. 2.9 Jet power vs. angular frequency of the black hole horizon, Ω_H, for a sample of five black hole X-ray binaries. The *dashed line* represents a scaling of the form $P_\mathrm{j} \propto \Omega_H^2$, as expected from Blandford and Znajek (1977) (From Narayan and McClintock (2012))

[1]The 'standard' $P_\mathrm{j} \propto a^2$ scaling relation is formally correct only for slowly spinning black holes; see Tchekhovskoy et al. (2011) for a full relativistic treatment.

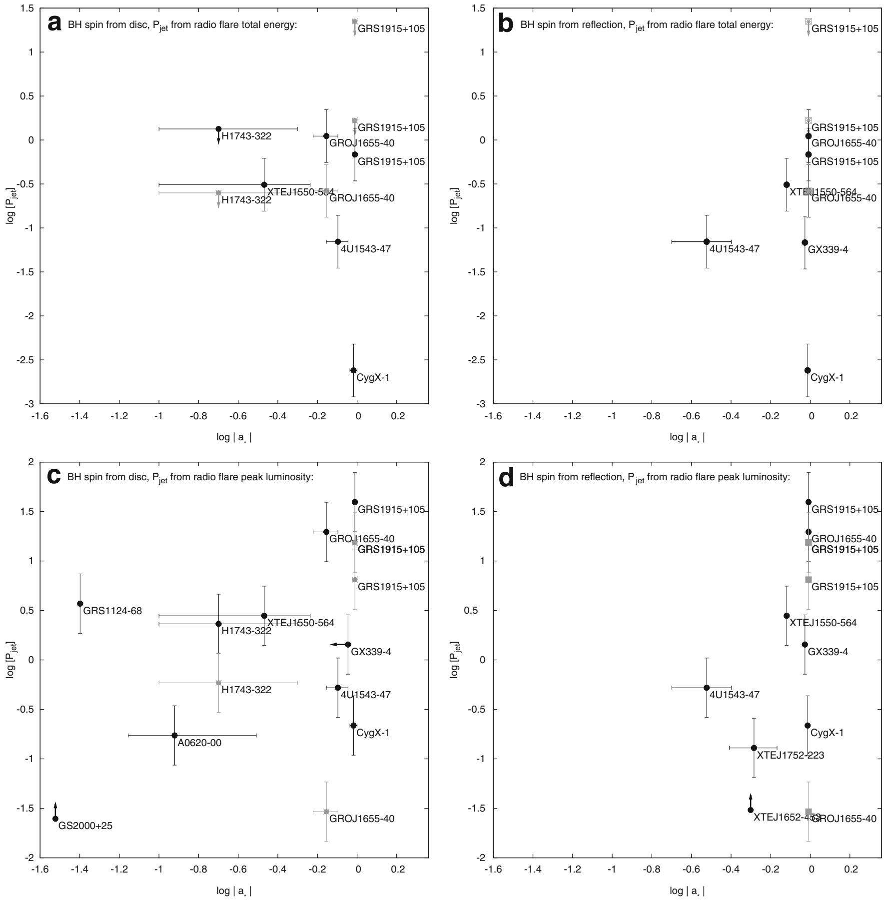

Fig. 2.10 Black hole spin measured via the disk continuum method are plotted in the *left panels*; black hole spin measured via the reflection method are plotted in the *right panels*. The jet powers estimated from total energy arguments (following Fender et al. 2010 for flaring, ballistic jets) and peak radio luminosity (following Narayan and McClintock 2012) are shown in the *upper* and *lower panels*, respectively. The *bottom left panel* allows a direct comparison with Narayan and McClintock (2012) and Fig. 2.9 (From Russell et al. (2013a))

and McClintock (2012) and Steiner et al. (2013), respectively (with regard to the right panels of Fig. 2.10, it is important to keep in mind the fact that the reflection-fitting method does not return a correlation with jet power that is consistent with the spin-powering mechanism should not be taken as evidence in favor, or against, either method).

As recognized by both groups of authors, much of the uncertainty revolves around the small number of observations of Eddington-limited systems (see discussion in Steiner et al. 2013). A further source of disagreement – this one more conceptual than practical – has to due with the implicit assumption, by Narayan and McClintock (2012), that the average duration of the bright radio flare does not vary significantly between different outbursts of the same source (this assumption is at the base of equation B15 in Steiner et al. 2013), which in turn is presented as the physical motivation for using the peak flare luminosity as proxy for jet power. While new data will likely settle the debate around this potentially groundbreaking discovery over the next few years, a word of caution is in order for the moment, as any extraordinary (important) discoveries ought to be supported by extraordinary (robust) evidence.

2.4.1 Multi-wavelength Spectral Modeling and Jet Power

Extrapolating the integrated radio luminosity to total (i.e. radiative plus kinetic) jet power relies on a number of assumptions, most importantly on the location of the optically-thin-to thick jet break, and the location of the cooling break. Standard synchrotron theory predicts the jet break frequency, ν_b, here defined as the location where the jet partially self-absorbed spectrum becomes optimally thin, to scale with the mass accretion rate and black hole mass (Heinz and Sunyaev 2003; Markoff et al. 2001, 2003, 2005). It follows that, under the reasonable assumption that the magnetic field value does not vary by orders of magnitude, ν_b is expected to scale with X-ray luminosity as $L_{\mathrm{X}}^{1/3}$. Based on a systematic literature search for coordinated multi-wavelength data of hard and quiescent state black hole X-ray binaries, however, Russell et al. (2013b) found no evidence for such a relation.

More recently, high cadence, multi-wavelength monitoring of the 2011 outburst of MAXI J1836–194 (Russell et al. 2014), showed even more severe discrepancies between the data and the expected scaling of break frequency with L_{X}, suggesting a much higher degree of complexity in the jet spectral energy distribution evolution.

As discussed in greater detail in Fender and Gallo (2014), this multi-wavelength campaign also led to the first (albeit indirect) observational inference of the high energy synchrotron cooling break for this system ($3.2 \times 10^{14} \lesssim \nu_c \lesssim 4.5 \times 10^{14}$ Hz). For X-ray binaries, the cooling break is expected to move from the UV to the hard X-ray band as the outburst luminosity rises towards bright X-ray states (Pe'er and Markoff 2012), while the reported value for MAXI J1836–194 falls into the optical band, implying (if correct) a substantial reduction of the radiative jet power.

The importance of obtaining high quality, multi-wavelength coverage for understanding the interplay between accretion and relativistic outflows has been highlighted in several instances throughout this review. One last example to illustrate the power of this 'multi-messenger' approach is offered by the recent, multi-wavelength campaign targeting the high Galactic latitude black hole X-ray binary XTE J1118+480 in a quiescent system, close to 10^{-9} times its Eddington luminosity. Along with the nearby system in A0620-00 (Gallo et al. 2006), XTE J1118+480 is the only other system for which we can probe whether the jet extends all the way into quiescence, and, if so, if and how the hard state and quiescent

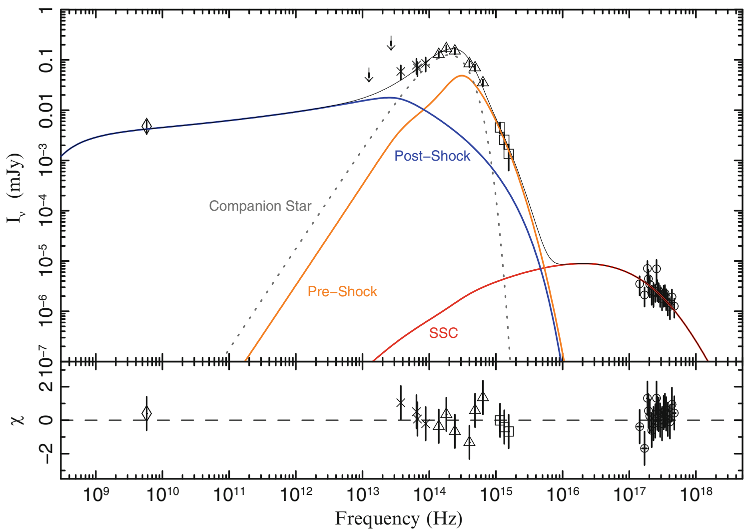

Fig. 2.11 Broadband spectral energy distribution of the black hole X-ray binary XTE J1118+480 in quiescence ($L_X/L_{Edd} \simeq 10^{-8.5}$). Fitting the data with a multi-zone jet model (Markoff et al. 2005) indicates that the jet is only weakly accelerated in this regime. As a consequence, non-thermal particle do not contribute substantially to the high energy radiation emissions and the X-ray spectrum arises from synchrotron self-Compton (From Plotkin et al. (2014))

jets differ in any physically meaningful way. The simultaneous radio (Very Large Array), NIR (William Herschel Telescope), UV (Swift) and X-ray (Chandra) data of XTE J1118+480 are shown in Fig. 2.11, along with non-simultaneous FIR data (from Spitzer and WISE). Our best-fitting jet model (cf. Markoff et al. 2005 and references therein) suggests that jet particle acceleration is weaker in quiescence compared to the hard state (see Markoff et al. 2001 for the same model fit to the hard state spectrum of XTE J1118+480). The jet base is also less magnetically dominated and more compact in quiescence, in agreement with broadband modeling for the stellar mass black hole in A0620-00 (Gallo et al. 2007), as well as the Galactic Center super-massive black hole, Sgr A*, and the super-massive black hole in M81 (Markoff et al. 2008).

A consistent picture is thus starting to emerge whereby, in quiescence, black hole jets that are too weakly accelerated for non-thermal particles to contribute significant amounts of X-rays. Conversely, the jet acceleration and magnetization appear to increase as the overall luminosity rises, leading to a significant contribution from optically thin synchrotron to the high energy radiation in the canonical hard state.

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