'Disc-jet' coupling in black hole X-ray binaries and active galactic nuclei

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Summary. In this chapter I will review the status of our phenomenological understanding of the relation between accretion and outflows in accreting black hole systems. This understanding arises primarily from observing the relation between X-ray and longer wavelength (infrared, radio) emission. The view is necessarily a biased one, beginning with observations of X-ray binary systems, and attempting to see if they match with the general observational properties of active galactic nuclei.

Black holes are amongst the most esoteric objects conceived of by man. They do not however lurk only in our imaginations or at the fringes of reality but appear, as far as we can tell from the objective interpretation of astrophysical observations, to play a major role in the history of the entire universe.

In particular, feedback from accreting black holes, in the form of both radiation and kinetic energy (ie. jets and winds) has been a key element throughout cosmic evolution. This is summarised in Fig. 1, and some key phases can be identified as:

- **Reionization:** By redshift of $z \sim 10$, less than a billion years after the big bang, UV and X-ray radiation from the first accreting black holes (as well as the first stars) undoubtedly played a key role in ending the so-called 'Dark Ages' and reionizing the universe.
- **The epoch of Active Galactic Nuclei:** Following reionization, supermassive black holes at the centres of Active Galactic Nuclei (AGN) grew rapidly, probably fed by galactic mergers. The peak of AGN activity occurred around a redshift of $z \sim 2$, around 4 billion years after the big bang. Radiation from the accretion flows around these AGN formed what we now observe as the cosmic X-ray background. Kinetic feedback from AGN also acted to stall and reheat cooling flows at the centres of galaxies, and to regulate the growth of galaxies.
- **The epoch of stellar mass black holes:** In the nearby Universe feeding of the supermassive black holes has declined, and their feedback to the ambient medium is dominated by kinetic power. The X-ray luminosity of galaxies is now dominated by accretion onto black holes of mass $M_{\rm BH} \sim 10_\odot$ in binary systems (as well as neutron stars).

Black holes, it seems, despite their oddness, are a key formative component of the Universe. It is essential for our understanding not only of the history of the Universe
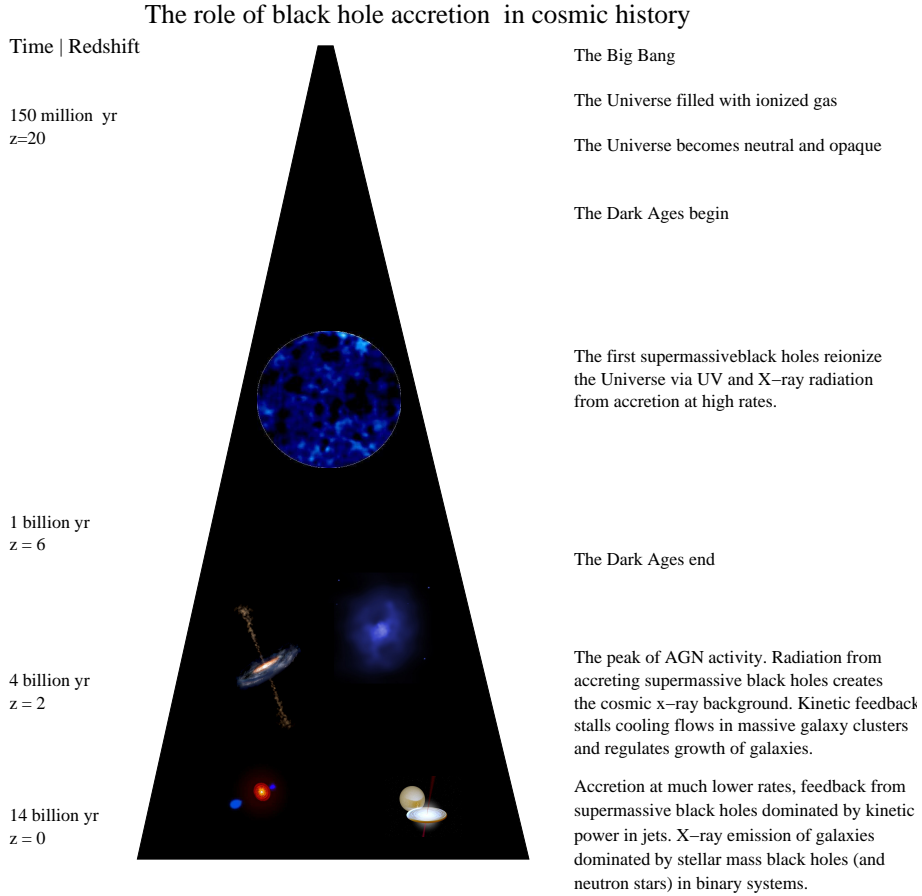
The role of black hole accretion in cosmic history

Time	Redshift		
		The Big Bang
150 million yr z=20		The Universe filled with ionized gas
		The Universe becomes neutral and opaque
		The Dark Ages begin
		The first supermassiveblack holes reionize the Universe via UV and X–ray radiation from accretion at high rates.
1 billion yr z = 6		
		The Dark Ages end
4 billion yr z = 2		The peak of AGN activity. Radiation from accreting supermassive black holes creates the cosmic x–ray background. Kinetic feedback stalls cooling flows in massive galaxy clusters and regulates growth of galaxies.
14 billion yr z = 0		Accretion at much lower rates, feedback from supermassive black holes dominated by kinetic power in jets. X–ray emission of galaxies dominated by stellar mass black holes (and neutron stars) in binary systems.

Fig. 1. The role of feedback from black hole accretion, in the form of both radiation and kinetic energy, has played a key role in the evolution of our Universe.

to this point, but also of the future evolution of the universe, that we understand how these objects behave. In fact, they do one thing, and one thing only, of major significance:[1] they convert gravitational potential energy to radiation and kinetic energy, which feeds back into the universe.

This accretion process is in principle quite simple, as outlined in the next section. However, observationally we find that it has its subtleties and nuances, which manifest themselves most clearly in how the black hole distributes its feedback between radiation and kinetic power. The rest of this chapter explores what we can learn about these idiosyncrasies of black hole accretion by studying low-mass ($M < 20M_\odot$), rapidly varying, black holes in binary systems in our galaxy, and how we might apply that to understanding how supermassive black holes have helped shape the observable Universe.

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[1] Not counting information trapping on their surfaces (e.g. [90])

In addition to the flow of energy and feedback, which are the foci of this review, the physics associated with jet formation and the associated particle acceleration, as well potential tests of general relativity associated with studying black hole accretion are all extremely interesting astrophysical topics in their own right. See suggestions for further reading at the end of the chapter.

1 Simple physical theory

The maximum energy release associated with the accretion of matter from infinity to a body of mass M and radius R is given by GM/R. It is the ratio M/R which determines the efficiency of the accretion process.

A non-rotating, or Schwarzschild black hole has an event horizon at

$$r_s = 2GM/c^2 = 2r_g$$

where r_g is referred to as the gravitational radius.

This linear dependence on black hole mass means that all non-rotating black holes have the same maximum potential accretion efficiency, regardless of their mass. There is an $i$nnermost stable circular orbit, or ISCO, around such black holes, within which matter will plummet rapidly across the event horizon, and this is at $3r_S$, also independent of mass.

Spinning black holes have smaller event horizons and ISCOs than non-rotating black holes: a maximally rotating or Maximal Kerr black hole has an event horizon and ISCO both at $r_g = \frac{1}{2}r_s$. This means that for a black hole of any mass, the ratio M/R is the same to within a factor of six. This ratio is dwarfed by the enormous range of masses of black holes we have observed in the universe, from $\leq 10M_\odot$ to $\geq 10^9 M_\odot$. Beyond mass and spin, black holes possess only one more property, that of electric charge. Given the lack of observation of large-scale charged objects in the universe, it is assumed that black holes are electrically neutral. Fig. 2 summarizes the relative sizes of neutron stars, non-rotating and maximally rotating black holes.

This amazing scale invariance of the theoretical accretion efficiency coupled with the inability of a black hole to possess any other distinguishing characteristics drives us to speculate that the process of accretion onto black holes of all scales should be very similar.

However, the physical conditions in the innermost regions of the accretion flow are $n$ot expected to be identical. The fixed M/R ratio necessarily implies that the density of the inner accretion flow (and in fact of the black hole itself) must decrease with increasing mass. Put very simplistically, unless there are strong changes in accretion geometry with mass, then the surface area through which matter with significant angular momentum will accrete will scale as M^2. So for two black holes, one 'stellar mass' ($\sim 10M_\odot$) and one 'supermassive' ($\sim 10^9 M_\odot$), accreting at the same Eddington ratio, which scales linearly with mass, the density of the accreting matter should scale as $\rho \propto \dot{m}/M^2 \propto M^{-1}$, i.e. a factor of 10^7 more dense in the case of the stellar mass black hole. Similarly, the effective temperature of the accretion disc varies with mass. This can be illustrated simply as follows: for the same Eddington ratio the luminosity released in radiatively efficient accretion $L \propto M$, and is emitted over a disc area which scales as M^2. For black body radiation $L \propto AT^4$
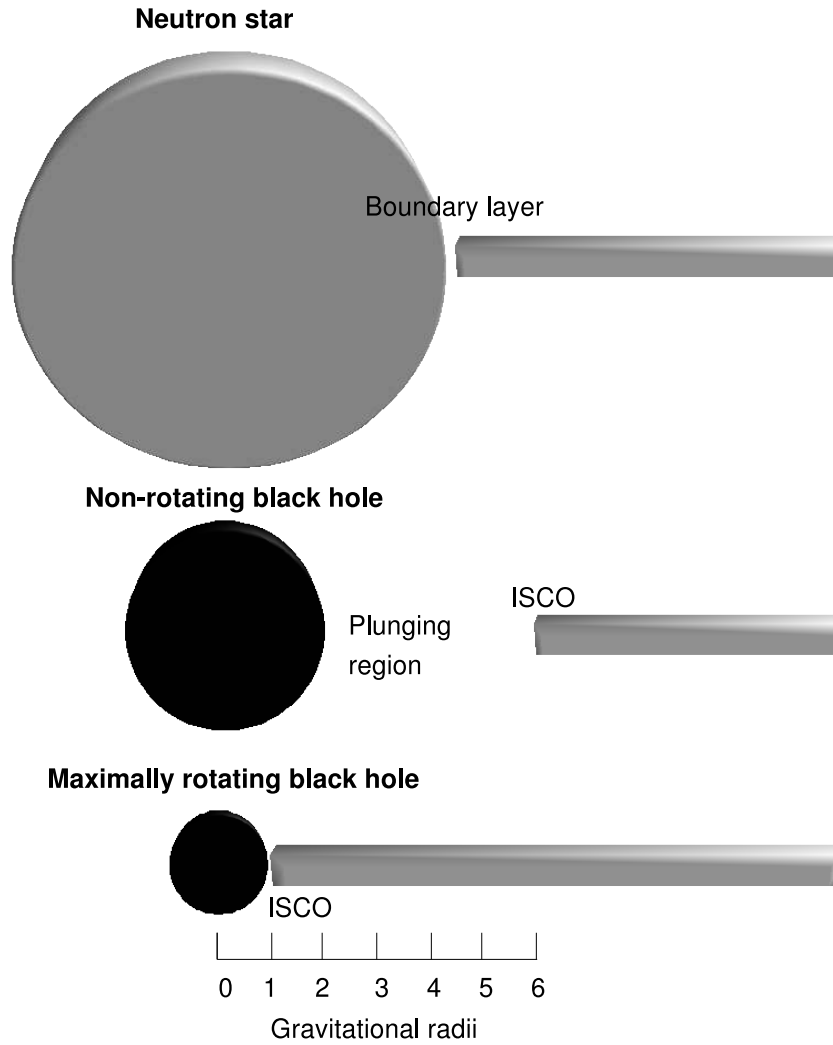
Neutron star

Boundary layer

Non-rotating black hole

Plunging
region

ISCO

Maximally rotating black hole

ISCO

0   1   2   3   4   5   6

Gravitational radii

Fig. 2. Relative sizes of a neutron star, non-rotating and maximally rotating black hole in units of gravitational radii $R_{\mathrm{G}} = GM/c^2$. The figure is correct for black holes of any mass. A neutron star of 1.4 $\mathrm{M_\odot}$ mass and 10 km radius has a surface at about 4.8 R_{G}. The accretion disc may extend all the way to the surface where there will be a boundary layer between the inner disc edge and the surface, which will be rotating more slowly. For a non-rotating black hole the event horizon will lie at $2R_{\mathrm{G}}$ and there will be an innermost stable circular orbit (ISCO) at $6R_{\mathrm{G}}$. Inside of the ISCO matter will plunge across the event horizon. For a maximally rotating black hole the event horizon and ISCO lie at $1R_{\mathrm{G}}$. Most black holes will be somewhere between these two extremes. If we naively assume radiation only from a disc-like radiatively efficient accretion flow, we can see that accretion onto a neutron star can be more efficient than that onto a non-rotating black hole, but that accretion onto a black hole with significant spin can be the most efficient process.

(where A is emitting area and T temperature), and so we find $T \propto M^{-1/4}$. Therefore, accretion discs in the most luminous AGN should be 100 times cooler than those in the most luminous X-ray binaries [86]. In Fig. 3 we present the expected simple scaling of size (both of the black hole and inner accretion disc), luminosity, disc temperature, disc density (also mean density of the matter within the event horizon) and also orbital frequency as a function of mass, for black holes accreting radiatively efficiently at the same Eddington ratio, and with the same spin. As we shall see later in this article, the requirement for radiative efficiency probably implies an Eddington ratio ≥ 0.01.
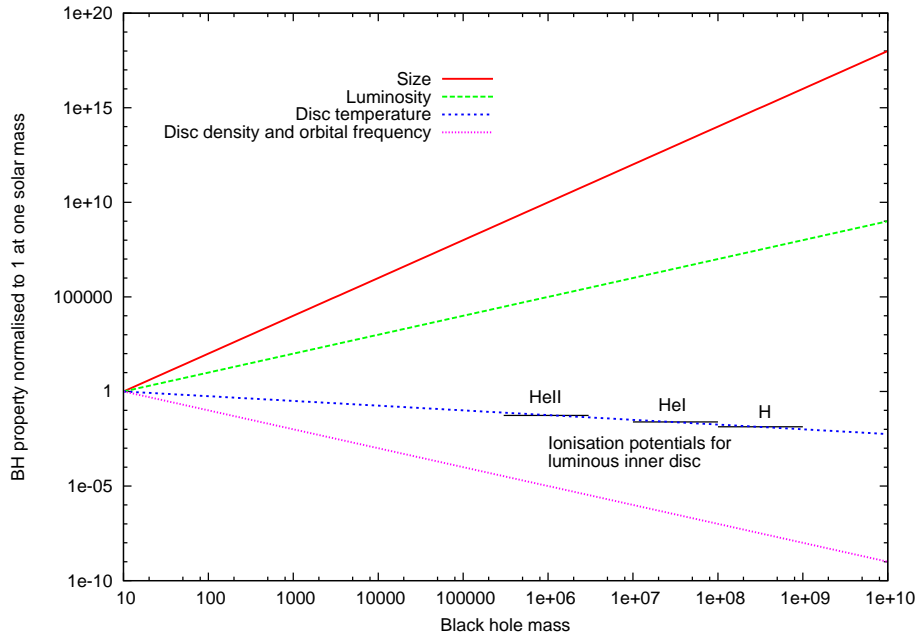
Fig. 3. The simple scaling of size (both of event horizon and inner disc), luminosity, disc temperature, disc orbital frequency and disc density (also mean density within event horizon) with black hole mass, for black holes accreting radiatively efficiently at the same Eddington ratio (the combination of which requirements probably means an Eddington ratio ≥ 0.01) and with the same spin. Also indicated are the ionisation potentials for H and both HeI and HeII, based on a temperature of 1 keV for an Eddington rate $10_{\odot}$ black hole (i.e. the temperature scale is the actual temperature in keV).

How the energy density and organisation of the magnetic field in the accretion flow, which are likely to be important both for effective viscosity and jet formation, vary with black hole mass, is less well understood.

2 Observations of black hole X-ray binaries

More than 20 objects consistent with black holes of mass $\sim 10 M_\odot$ have been identified in X-ray binary systems within our galaxy (e.g. [55]). This population may be the tip of an iceberg of $\sim 10^8$ stellar-mass black holes within our galaxy (i.e. a far larger total black hole mass than that associated with the $\sim 10^6 M_\odot$ black hole, Sgr A*, at our galactic centre). These binary systems show semi-regular outbursts in which they temporarily brighten across the electromagnetic spectrum by many orders of magnitude. The origin of these outbursts is believed to be a disc instability driven by the ionization of hydrogen above a given temperature (e.g. [22]). However while describing general outburst trends, there are many difficulties in explaining all the observational characteristics. When comparing to AGN, we imagine that X-ray binaries near the peaks of their outbursts correspond to the high Eddington-ratio systems such as Quasars, and that when in quiescence (the most common phase for most systems) they correspond to low luminosity AGN (LLAGN) such as Sgr A* at the centre of our own galaxy.

The evolution of two outbursts from the binary GX 339-4 are illustrated in Fig. 4. In very brief summary, most black hole X-ray binaries spend most of their time in a 'quiescent' state with X-ray luminosities as low as $\sim 10^{30}$ erg s^{-1} ($\leq 10^{-9} L_{\rm Edd}$; e.g. [29]). Mass transfer from the companion star, usually via Roche Lobe overflow, progresses at a higher rate than that at which matter is centrally accreted onto the black hole (or neutron star), and so the mass (and temperature) of the disc increase. At some point the effective viscosity of the disc increases, perhaps due to the hydrogen ionization instability mentioned above, and the matter in the disc rapidly drains towards the central accretor. During this phase the central accretion rate is much higher than the time-averaged mass accretion rate from the companion star, and the source becomes very luminous, often approaching the Eddington luminosity [2].

An early stage in the outburst the source X-ray spectrum begins to soften (motion to the left in the HIDs in Fig. 3). Within a few weeks or months, when some significant fraction of the disc mass has been accreted, the disc cools, and the source returns towards quiescence [3] In doing so it makes the X-ray spectral transition away from the soft state at a lower luminosity than that at which it entered the state. This results in a hysteretical track in the HID. For more details on black hole outbursts see Chaps. 3,4 and 6 in this volume.

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[2] The *E*ddington Luminosity corresponds to the luminosity at which the outwards radiation force from accretion balances the inward force of gravity. For spherical accretion of hydrogen it is approximately $L_{\rm Edd} \sim 1.4 \times 10^{38} (M/M_\odot)$ erg s^{-1}

[3] It is worth bearing in mind that two of the sources we use most in our studies of black hole binaries do not really fit this pattern: GX 339-4 doesn't ever really settle into extended quiescent periods (see Fig. 4), and Cyg X-1 is not accreting via simple Roche lobe overflow.
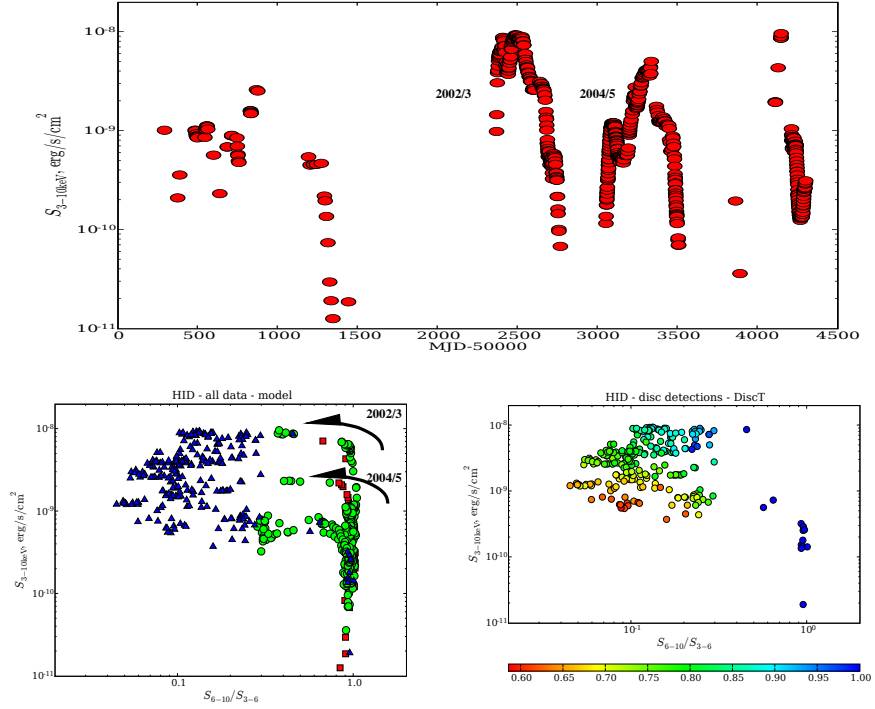
Fig. 4. Outbursts of the black hole binary GX 339-4. **Top panel:** the X-ray light curve of GX 339-4 as measured with the PCA instrument onboard the RXTE satellite. Gaps in the data coverage between major outbursts usually indicate low / quiescent flux levels. The outbursts in 2002/3 and 2004/5 are covered in the greatest detail and a represented in Hardness-Intensity Diagrams (HIDs) in the lower panels. In these HIDs the abscissae (x-axes) indicate x-ray 'colour' or hardness ratio, whereas the ordinates (y-axes) indicate luminosity. In the **left panel** the time evolution of the two separate outbursts are indicated; triangles indicate those spectra where a strong accretion disc (black body-like) component was required in the spectral fit. Two different outbursts are overplotted – both show hysteretical patterns of behaviour, in that the transition from hard → soft states occurs at higher luminosities than the soft → hard transition, but they also clearly differ in that the earlier outburst reached higher a higher luminosity in the initial stages. The **right panel** indicates the variation of fitted accretion disc temperature (colour scale) in the soft X-ray state, decreasing with luminosity. Adapted from[9].

2.1 Relations between accretion 'state' and radio emission

Most of our insight into the relation between modes/rates of accretion and the type and power of any associated feedback (also known as the 'disc–jet' coupling [4]) come from (near-)simultaneous radio (also sometimes infrared) and X-ray observations of rapidly varying systems. The radio (and, often, infrared) emission is assumed to arise via synchrotron emission in a jet-like outflow, and the X-ray emission to be a tracer of the accretion flow (rate, geometry, temperature, even composition). It has also been suggested that a significant fraction of the X-ray emission in some states may arise in the jet (see Chap. 6).

A good example of coupling between X-ray state and radio emission is given in Fig. 5. In this figure several hours of overlapping radio and X-ray observations of the powerful jet source and black hole binary GRS 1915+105 are presented (from [43]). The radio emission shows clear phases of oscillatory behaviour during periods of strong dips in the hard X-ray light curve, and far less activity when the X-rays, although at the same luminosity, are not showing the long hard state dips. Similar, maybe identical, patterns are observed at widely separated epochs, demonstrating a clear and repeating pattern of accretion:outflow coupling.

2.2 Towards unified models for accretion:ejection coupling

Based on more than a decade of X-ray and radio observations, attempts were made in the past few years to find simple and unified patterns for the accretion – outflow ('disc–jet') coupling in black hole X-ray binaries. Our analysis is heavily based upon the assumption that radio emission is associated with jet-like outflows, something argued in more detail in e.g. [18] and by many other authors. In terms of relations to X-ray states, [14] demonstrated that during the high/soft X-ray state of the binary GX 339-4 the radio emission was suppressed with respect to the hard state at comparable luminosities. In fact this phenomena had been observed more than two decades earlier by [89] in the case of Cygnus X-1. Around the same time, [31, 7, 8] demonstrated that while in the hard X-ray state (right hand side of the the HID) the same binary, GX 339-4, repeatedly displayed a correlation of the form

$$L_{\mathrm{GHzradio}} \propto L_{\mathrm{softX-ray}}^{b}$$

where $b = 0.7 \pm 0.1$. [15] demonstrated that steady, flat-spectrum radio emission (spectral index $\alpha = \Delta \log S_\nu / \Delta \log \nu \sim 0$) such as observed from GX 339-4 in the hard X-ray state, was observed from *a*ll hard state black hole binaries (this characteristic post-outburst radio behaviour had been noted by e.g. [34] but not clearly associated with X-ray state).

In a wider-ranging study, [25] found that another binary V404 Cyg (GS 2023+338) displayed the same correlation ($b \sim 0.7$) *a*nd the same normalisation, within uncertainties. Radio and X-ray measurements for several other black hole binaries in the hard state were also consistent with the same 'universal' relation, and repeated suppression of the radio emission in softer X-ray states of Cygnus X-1 was reconfirmed.

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[4] This expression now has confusing connotations because people sometimes take the word 'disc' in this context to mean only the geometrically thin, optically thick component of the accretion flow
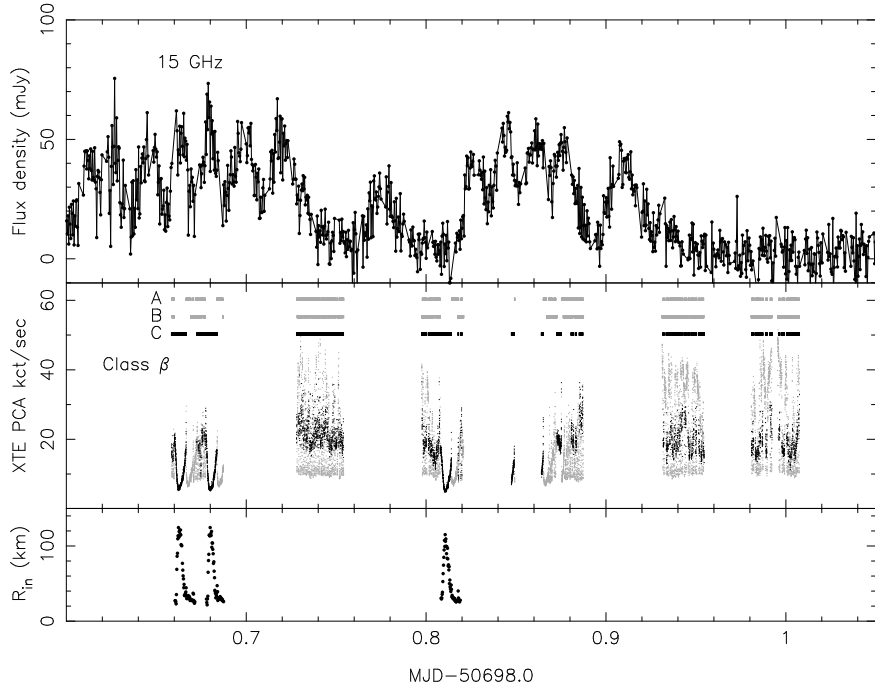
Fig. 5. Radio–X-ray coupling in the binary black hole system GRS 1915+105. The **top panel** shows radio monitoring at 15 GHz from the Ryle Telescope, the **middle panel** shows the X-ray flux as measured by RXTE, with the light curve subdivided into 'soft' (A and B) and 'hard' (C) X-ray states. The radio oscillation events, which we think are associated with individual relativistic ejection events, only occur when long hard (state C) dips are followed by rapid transitions to soft states (e.g. the first and third phases of X-ray coverage) and not when more rapid fluctuations occur, albeit at the same luminosity. While GRS 1915+105 is a complex case, the general pattern of behaviour – major ejection events during state transitions – is consistent with other accreting black hole binaries. From [43].

More recently however, several hard state black hole binaries have been discovered which are underluminous in the radio band (see [23], and Chap. 4 in this volume for more discussion).

These hard-state, flat-spectrum jets are in fact very powerful, and not just an interesting sideshow to the main event of X-ray production [15]. In fact the combination of two non-linear couplings, $L_{\mathrm{radio}} \propto L_{\mathrm{X}}^{0.7}$ (observed) and $L_{\mathrm{radio}} \propto P_{\mathrm{jet}}^{1.4}$ (theoretical, where P_{jet} is total jet power, but also observed in [46], implies that $P_{\mathrm{jet}} \propto L_{\mathrm{X}}^{0.5}$, and that as the X-ray luminosity of a source declines the jet may come to dominate over radiation in terms of feedback from the accretion process [16]. The key goal then was to determine the normalization for the jet power, which a variety of methods has established as being comparable to the X-rays luminosity at high Eddington ratios, dominating at lower Eddington ratios (e.g. [27, 32]). The current consensus is therefore that *in* the hard X-ray state black hole binaries pro-

duce powerful, flat-spectrum relatively steady jets, whose strength correlates in a (near-)universal way with the X-ray luminosity.

However, really spectacular radio ejection events, during which relativistic, sometimes apparently superluminal radio components were observed to propagate away from the binary, were also known (e.g. [77, 35]). These jets also carry away a large amount of power (see [17] and references therein). How did these relate to the steady radio emission in the hard state, and the apparently suppressed radio emission in the soft state ?

Careful examination of X-ray data compared to radio monitoring and imaging observations revealed the answer: such bright ejection events occurred during the transition from hard to soft X-ray states. Combining our knowledge of the hysteretical outburst behaviour of black hole binaries (see Chap. 3) with these insights into the coupling to radio emission, allowed a first attempt at a 'unified model' for the disc–jet coupling, which was put forward by [17], see Fig. 6.

Since this model was first proposed, nearly five years ago, we have repeatedly attempted to test whether or not any of the basic empirical relations was wrong. In particular, we have sought to confirm that the major radio outbursts always occur during the hard $\rightarrow$ soft transitions (i.e. left to right motion at the top of the HID). In a study of over 16 black hole outbursts (compared to four in [17]) we ([19]) have found no clear exceptions to this. In fact in revisiting the case of the black hole transient XTE J1859+226 we find strong evidence that all of five recorded radio flare events (which we associate with an ejection) occurred at $\sim$ same X-ray hardness (Fig. 7).

While [17] attempted to provide a simple physical interpretation of the empirical relations, several more detailed theoretical models have arisen based upon the emerging phenomenology (e.g. [21, 65]; see also Chap. 9). A very interesting combined observational / theoretical result was also presented by [66] who analysed optical and X-ray observations of the hard state black hole XTE J1118+480. What they found (see also [40, 37]) was that the very rapid correlated optical and X-ray variability in this source could be explained by a strong synchrotron component in the optical, which arose in a jet / coronal outflow which dominated the feedback or accretion energy in this state – the same conclusion as reached from radio studies (see above).

[17] only really connected the X-ray spectral properties and long-term (i.e. hours and longer) evolution to the state of the jet. Since then several groups have been trying to see if the moment of ejection may be better determined by examining the timing properties, as measured by X-ray power spectra (see also Chap. 3). Certainly the hard to soft transition at the top of the HID is both the time when the major ejections occur, and the region when dramatic changes in the power spectra, including the strongest QPOs, are observed (see [42]). In Fig. 8 we plot X-ray r.m.s. variability as a function of X-ray colour for three sources in outburst. We indicate the moments of bright radio flares (probably associated with relativistic ejection events). Dips in the r.m.s.–colour relation, roughly indicated in the figures, have been associated with the sharpest changes in the X-ray timing properties, so are they related directly to the ejections ? The result of the comparison is tantalising: in the case of XTE J1550-564 the bright radio flare occurred between the low-r.m.s. 'zone' and an earlier very sharp dip, and in the case of XTE J1859+226 the five radio flares all occurred around the 'zone'. However, in GX 339-4, the radio flare
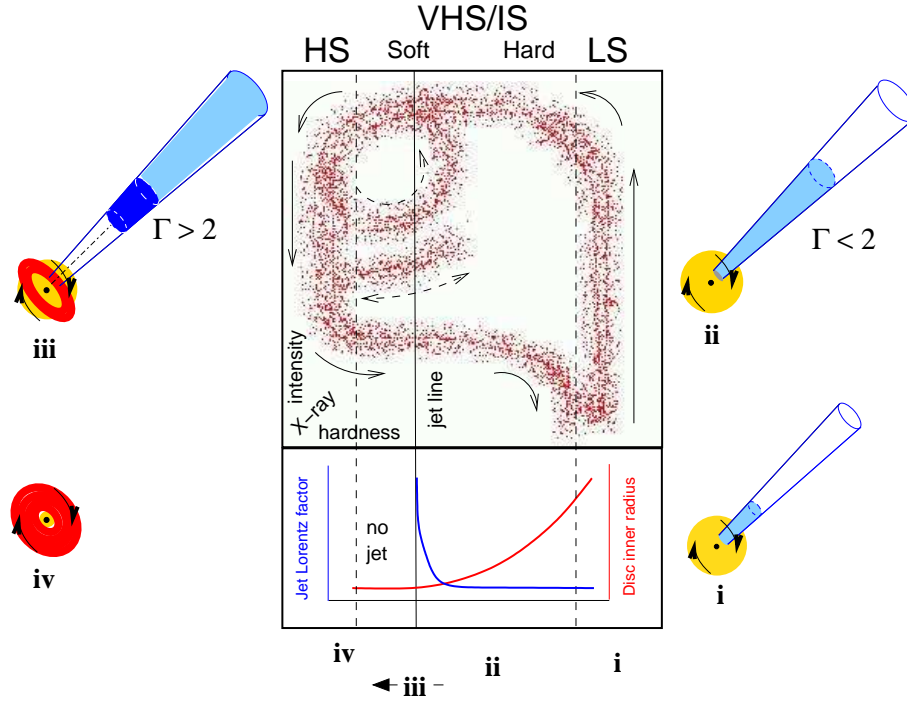
Fig. 6. A schematic of the simplified model for the jet-disc coupling in black hole binaries presented by [17]. The **central box panel** represents an X-ray hardness-intensity diagram (HID); 'HS' indicates the 'high/soft state', 'VHS/IS' indicates the 'very high/intermediate state' and 'LS' the 'low/hard state'. In this diagram, X-ray hardness increases to the right and intensity upwards. The **lower panel** indicates the variation of the bulk Lorentz factor of the outflow with hardness – in the LS and hard-VHS/IS the jet is steady with an almost constant bulk Lorentz factor $\Gamma < 2$, progressing from state **i** to state **ii** as the luminosity increases. At some point – usually corresponding to the peak of the VHS/IS – Γ increases rapidly producing an internal shock in the outflow (**iii**) followed in general by cessation of jet production in a disc-dominated HS (**iv**). At this stage fading optically thin radio emission is only associated with a jet/shock which is now physically decoupled from the central engine. As a result the solid arrows indicate the track of a simple X-ray transient outburst with a single optically thin jet production episode. The dashed loop and dotted track indicate the paths that GRS 1915+105 and some other transients take in repeatedly hardening and then crossing zone **iii** – the 'jet line' – from left to right, producing further optically thin radio outbursts. Sketches around the outside illustrate our concept of the relative contributions of jet (blue), 'corona' (yellow) and accretion disc (red) at these different stages.
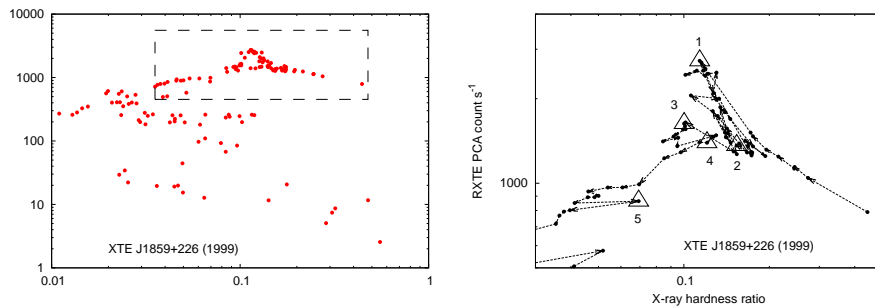
Fig. 7. Moments of five radio flare ejection events from the black hole binary XTE J1859+226 (from [5]) as a function of position in the HID. The **left** panel indicates the overall HID for the source which travelled in a generally anti-clockwise direction in the figure, typical for such outbursts. In the **right** panel we focus on the region (indicated by a box in the left panel) around the time of the radio ejections. Triangles indicate the estimated moments of ejection, and arrows indicate the temporal evolution in the HID. It is clear that all five radio ejection events took place at approximately the same hardness. Most notable is the last event, number 5, which is associated with a brief excursion back to harder states even as the source is in a softening trend. These date support the idea of a near-constant jet line on the upper branch of the HID, at least within one outburst loop. From [19].

reported by [26] occurred days *b*efore the 'zone'. Currently therefore the relation of major ejections to source timing properties remains unclear.

3 Connections to Active Galactic Nuclei

As the wealth of data on the coupling between accretion and ejection in black hole X-ray binaries grew, more serious attempts were made to scale physical properties up to the AGN. The binary studies had made it clear that there was a strong dependence on accretion rate for a given black hole (not surprisingly), and of course a strong dependence of a variety of properties with black hole mass was also expected (e.g. Fig. 2). Therefore some of the first attempts to quantitatively scale properties between black hole binaries and AGN involved black hole mass M, accretion rate $\dot{m}$ (or some proxy for it) and some other property (namely radio luminosity or power spectral break frequency).

3.1 Luminosity scalings

As noted above, Corbel et al. and Gallo et al. reported a non-linear correlation between radio and X-ray luminosities in a number of hard state black hole binaries. Shortly afterwards two groups ([70, 13]) independently established the existence of a plane linking these binaries with a large population of active galactic nuclei (AGN) hosting supermassive black holes. The plane is based upon the relation of the radio luminosity L_{radio}, the X-ray luminosity L_X and the black hole mass. This should be
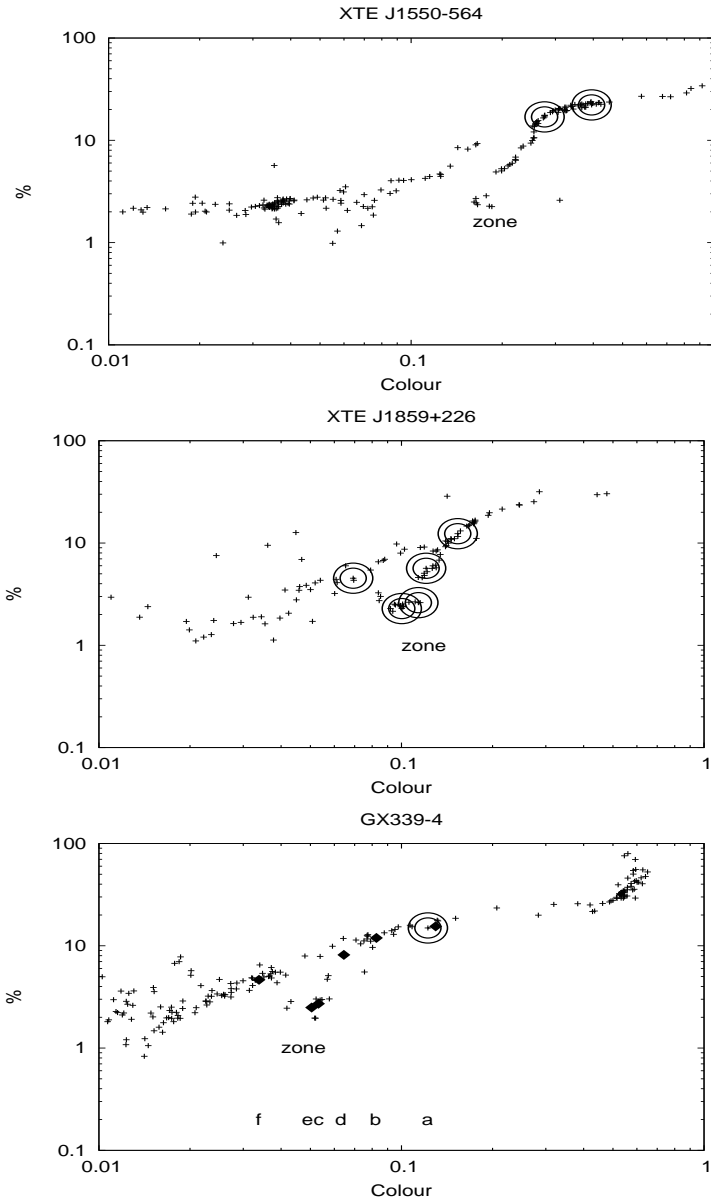
Fig. 8. Location of observed radio flare events (probably connected with relativistic ejections) in the hardness-r.m.s. diagram (which does not show the same hysteresis as the HID). Dramatic drops in X-ray r.m.s. are associated in many cases with the sharpest changes in X-ray power spectra during the overall hard → soft state transition, and have been speculatively linked with the relativistic ejections. In the case of XTE J1550-564 (**top panel**) the ejection appears to occur at the beginning of the drop to the low-r.m.s. 'zone', and in XTE J1859+226 (**middle panel**) the sequence of five ejection events all happen close to the 'zone'. However in the case of GX 339-4 (**bottom panel**), a major radio flare event was observed to occur several days *b*efore the r.m.s. drop, casting into doubt any direct causal connection between them. From [19].

considered one of the major steps in the unification of black hole accretion on all mass scales.

In the Merloni et al. formalism, the fundamental plane can be represented as:

$$L_{\mathrm{radio}} \propto L_X^{0.6} M^{0.8}$$

where the power-law indices are fitted values to a large sample of XRBs and AGN.

The most recent refinements of the plane are presented in [28, 45]. Criticisms of the plane have been rebuked by a consortium of all the original discovery authors, in [71].

Of the three parameters of the fundamental plane, one is genuinely fundamental (M), and one is a good indication of the total radiative output of the system and is therefore pretty fundamental (L_X). However, the third parameter, L_{radio} is merely a tiny tracer of the enormous power carried by the jets from these systems. The fact that it seems to correlate so perfectly with L_X is itself quite amazing and indicates a remarkable stability and regularity in the jet formation process. For example, for a X-ray binary in a bright hard state, the radio emission can be estimated to constitute about 10^{-7} of the total jet power, and yet over long timescales, including phase of jet disruption and reformation, the correlation between radio and X-ray luminosities holds very well (albeit not perfectly – S. Corbel, private communication).

Returning to the plane, it might be a more useful indicator of physical quantities and the flow of matter and power around the black hole if L_{radio} could be replaced with, say, the total jet power L_J or the mass accretion rate $\dot{m}$. In fact we can do both, based upon the relations established in [46] (hereafter KFM03; see also e.g. [32, 33]. In Fig. 9 we use the relations from this paper to 'calibrate' the plane, by replacing the axes of Merloni et al. with the physical quantities of jet power (left) and accretion rate (right).

3.2 Variability scaling

AGN X-ray timing studies started in the 1980s with the launch of EXOSAT, which probed AGN X-ray variability on time-scales up to a few days. It was soon established that on these time-scales AGN showed red-noise (i.e. "1/f") variability with steep unbroken PSDs ([54, 58]). However, McHardy (1988) noted using sparse long-term archival data that the PSDs appeared to flatten or break on longer time-scales, similar to the PSD shapes seen in BH XRBs. The launch of RXTE in 1995 allowed long-term light curves to be obtained with extremely good sampling and categorically proved the existence of PSD breaks on time-scales close to those expected by scaling the BH XRB break time-scales up by the AGN BH mass (e.g. [93, 69, 59]), although with some considerable scatter in the mass-time-scale relation.

Recently, [74] established that for a small sample of X-ray binaries there was a positive correlation between radio luminosity and the frequencies of timing features. This was to be expected, since we are confident that on the whole both timing frequencies and radio luminosity are increasing functions of accretion rate (although we also know there are other, state-related, dependencies at high accretion rates).

[60] have now fitted a plane which relates mass and accretion rate to the break frequency in X-ray power spectra, such that
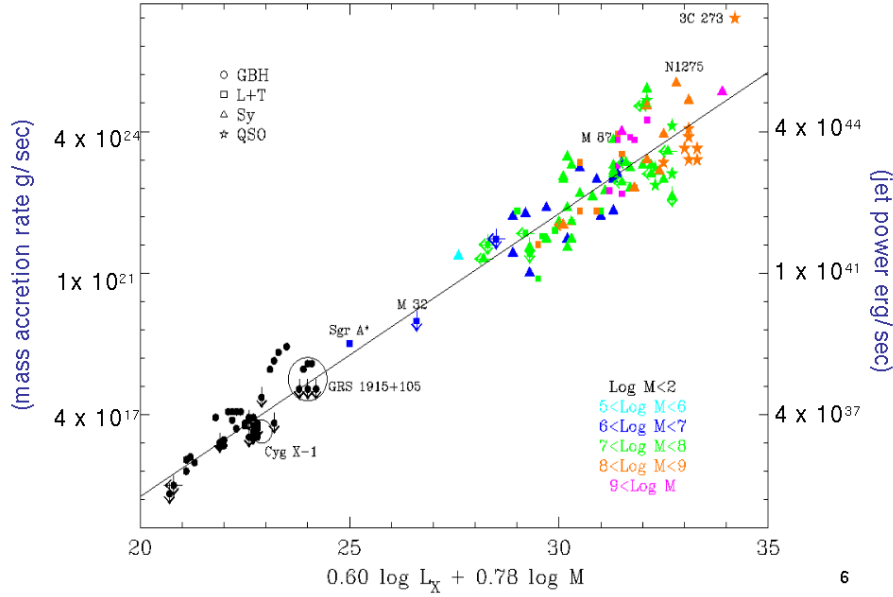
Fig. 9. The 'fundamental plane' of black hole activity as presented originally in [70], but in which their ordinate (y-axis) of radio luminosity has been replaced by the jet power and mass accretion rate (which scale linearly with each other) as estimated by [49].

$$T_{\mathrm{break}} \propto M^{-2.1} L_{\mathrm{bol}}^{-1}$$

Where T_{break} is the break timescale, reciprocal of the break frequency, M is black hole mass and L_{bol} is bolometric luminosity (Fig 10). All of the sources used in the correlation are believed to be in radiatively efficient states and so L_{bol} is used as a proxy for accretion rate. Using this substitution converted to accretion rate and integer power-law indices (i.e. $2 \sim 2.1$), we arrive at

$$T_{\mathrm{break}} \propto M/(\dot{m}/\dot{m}_{\mathrm{Edd}})$$

revealing the expected linear correlation of break timescales with black hole mass, albeit for a fixed Eddington ratio of accretion rate.

[49] have extended and refined this variability plane to include lower-luminosity black hole binaries and neutron star binaries (and even considers white dwarf accretors in cataclysmic variable binaries). Fig. 11 plots the extended plane; note that the two lines indicate that a further parameter, related to X-ray state, should be required to fit all sources (as we see in X-ray binaries that timing frequencies can vary at the same X-ray luminosity, if the spectral state is changing).
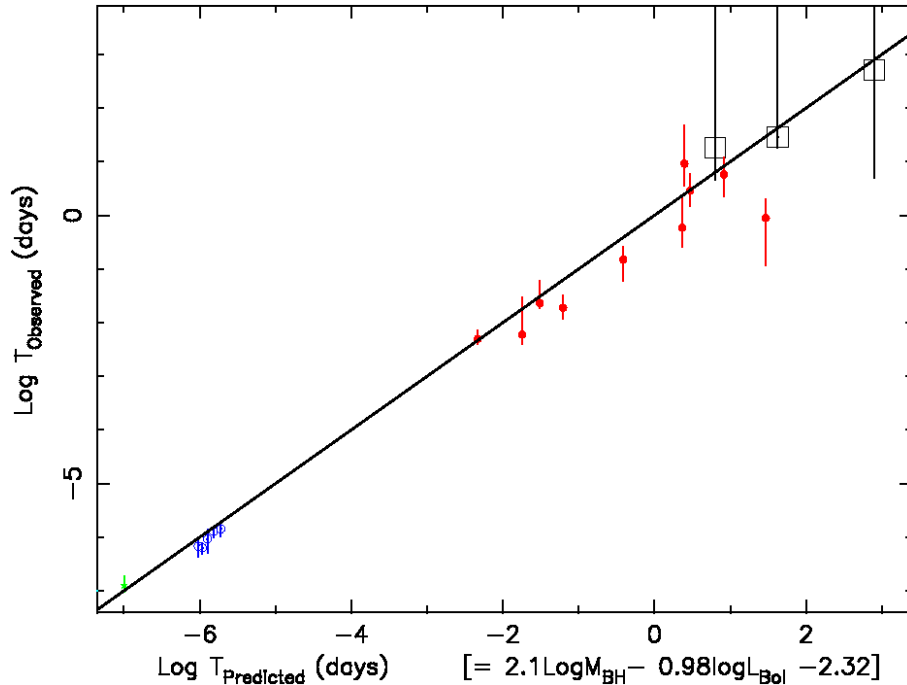
Fig. 10. A second fundamental plane, essentially relating characteristic timescales to mass and accretion rate, from [60]. More recently [49] have shown this to extend 'hard state' black hole X-ray binaries and neutron star systems.

3.3 Further similarities

As noted earlier, black hole X-ray binaries seem to (nearly) always follow a pattern of behaviour in outburst similar to that sketched in [17, 36] (see Fig. 6). However, it is clear that between different outbursts of the same source, or outbursts of different sources, the luminosities at which the hard → soft and soft → hard state transitions may occur can vary quite significantly (e.g. Fig. 4; [2, 42]). As a result, an ensemble of X-ray binaries would present a pattern in the hardness:luminosity diagram with a long handle and a filled-in head. Such an ensemble is obviously what we're going to have to deal with if we want to be able to compare patterns of disc:jet coupling in XRBs with those in AGN.

In [47] we have attempted to do this. First we constructed the Disc Fraction - Luminosity Diagram, in which hardness is replaced by the ratio of power law to total luminosity, a number which approaches zero for disc dominated soft states, and unity for hard states. This is necessary for a physical comparison, since the accretion discs temperature is a decreasing function of black hole mass, and for AGN does not contribute significantly in the X-ray band. We then simulated an ensemble of BHXRBs, based upon [17] and the slight refinement (suggested in [2]) that the 'jet line' might be diagonal in such a diagram. This was then compared to a sample of AGN from the SDSS DR5 for which there were X-ray detections and either radio
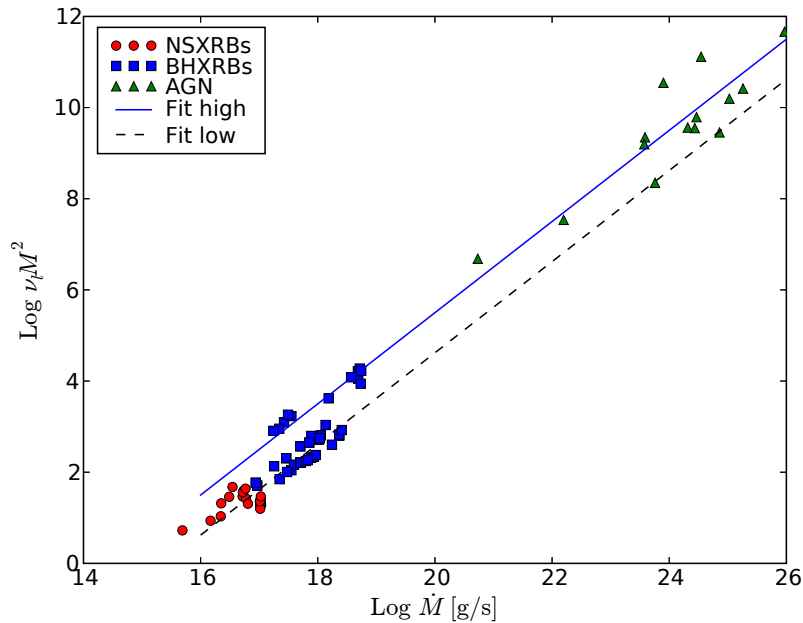
Fig. 11. The black hole timing plane extended to lower luminosity black holes *a*nd neutron stars. From [49]. The two lines hint at a further parameter, related to X-ray state, which may be required to fully fit all sources.

detections or limits, *p*lus a sample of low-luminosity AGN (LLAGN). The similarity was striking (see Fig. 12) and suggests that *t*he radio loudness is determined by the combination of 'state' and luminosity in a similar way for accreting black holes of all masses. Note that, while it is tempting to consider, the diagram does *n*ot indicate that AGN necessarily follow the same anti-clockwise loop in the diagram as XRBs: the motion in such loops could possibly be dominated by disc instabilities which may not apply to AGN (although in the Fender, Belloni & Gallo interpretation, major radio flares would require right → left transitions in order to produce the internal shocks). What it does indicate is that when an AGN finds itself in a particular accretion 'state', whether disc or corona dominated or some mix of the two, the jet it produces will be comparable to that which a XRB would make in the same state. [39] further discuss possible similarities and differences between feeding cycles in AGN and X-ray binaries.

It is worth noting that although the DFLD was chosen to both provide easy and understandable comparison with the HID *a*nd to provide a clear method of physical comparison with accretion states in AGN, it does show some differences with the HID even for X-ray binaries.

Firstly, the work of [9] who have produced the first real DFLDs for an X-ray binary (GX 339-4) shows that the hysteretical zone of the HID becomes rather less square in shape when transferred to the DFLD. This seems to be because as the disc
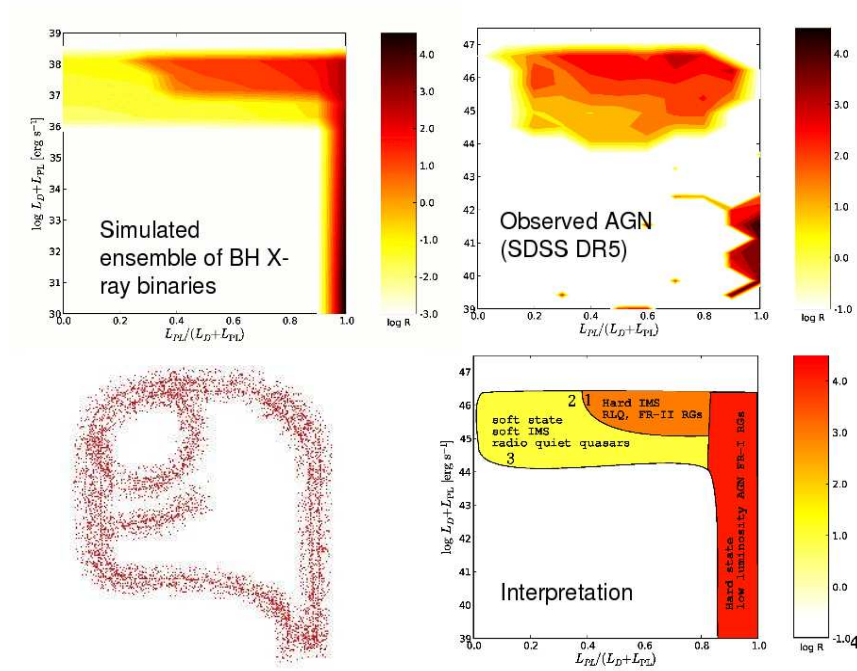
Fig. 12. A comparison of the disc:jet coupling in X-ray binaries with that in AGN, based upon the Disc Fraction Luminosity Diagram (DFLD; see [47]). Based upon the disc:jet model for black hole X-ray binaries presented in [17], an example track for which is shown in the **lower left panel**, a simulated ensemble of X-ray binaries was produced (**upper left panel**). This was compared with a sample of SDSS quasars and low luminosity AGN (**upper right panel**) and a striking similarity revealed. The lower right panel offers an explanation for the similarities between the different classes of object.

cools on the soft branch, the disc fraction is dropping (not as obvious as it sounds – it depends upon how fast the hard component is also dropping). Secondly, the work of [56, 57] has demonstrated that by the time sources are in quiescence, the radiative luminosity of the disc is one to two orders of magnitude *g*reater than the X-ray luminosity – i.e. at the lowest accretion rates discs are once more dominant in terms of the radiation. Of course at these low accretion rates we still estimate that the kinetic power of the jet dominates over both of these terms. Fig. 13 presents the DFLD for a set of black hole binaries for which the disc component strength has been (relatively) well measured either in the soft X-ray, ultraviolet or optical bands (from [6]). The (designed) similarity with the HID at high luminosities is apparent, but interestingly the path of a source loops back to the disc-dominated state in quiescence. It is not clear that we would expect to see this lower disc-dominated branch in AGN since it rather reflects the conditions of the outer accretion flow.
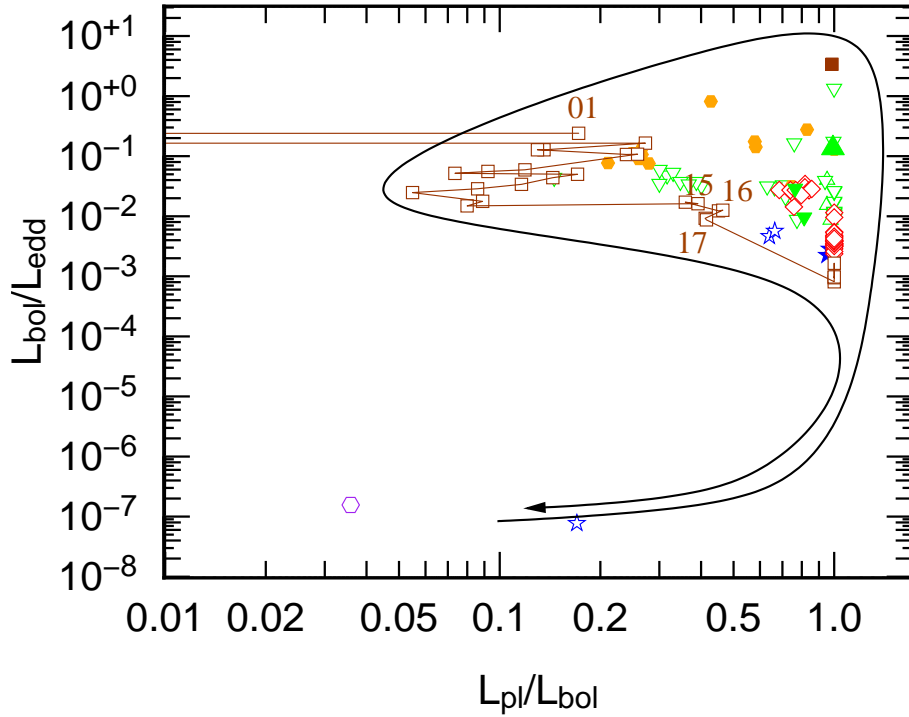
Fig. 13. The disc-fraction luminosity diagram (DFLD) for black hole X-ray binary systems where the disc component is well measured in the X-ray band (*S*wift or SAX) or optical bands. The connected brown points correspond to the *S*wift observations of XTE J1817-330. The black line with arrowhead indicates a possible path of a transient black hole from quiescence to outburst and back again. It is well established, but not widely appreciated, that as well as in soft X-ray states, in quiescence systems are also completely dominated in their radiative output by the accretion disc (see [57]). From [6]; all X-ray data have been independently reanalysed, while optical fluxes are from the literature.

Further similarities in patterns of behaviour have been noted in the past. In Fig. 14 patterns of X-ray temporal and spectral behaviour are related to directly imaged relativistic ejection events in the AGN 3C 120 ([67]; see also Chap. 7).

3.4 Differences

Despite the clear similarities, there are clear differences, both expected and observed, between X-ray binaries and AGN. Some of these result from the fact that these systems are more than just the central black hole. In particular the *e*nvironment may play a role in

1. supplying matter with varying distributions of angular momentum, possibly even changing direction of rotation, depending on the merger history of the
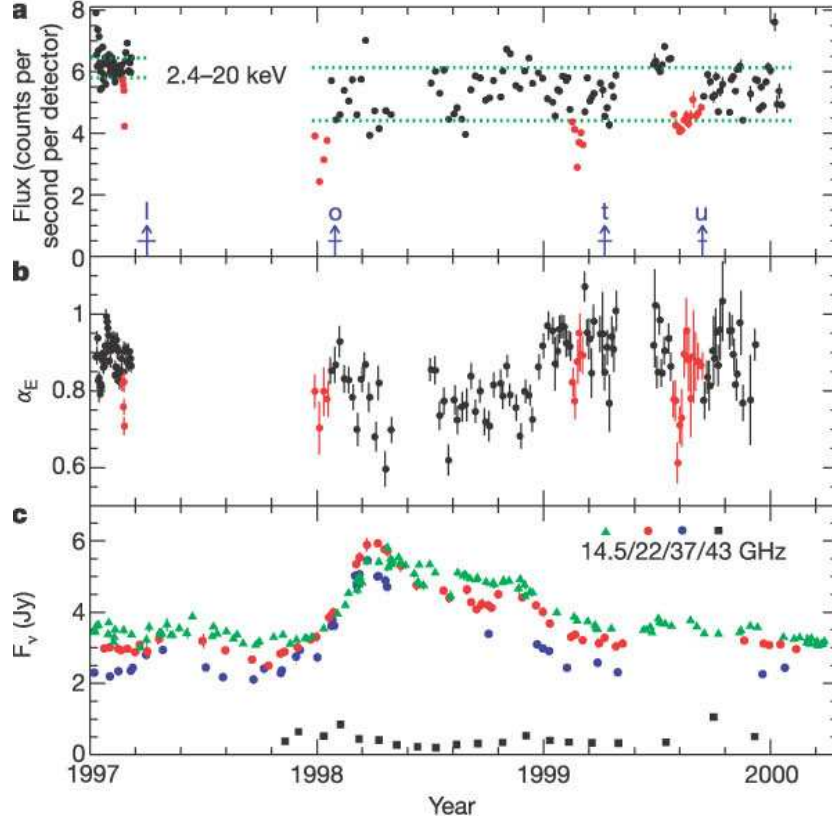
Fig. 14. Possible disc-jet coupling in the AGN 3C 120, from [67]. **Top panel:** X-ray light curve in photon counts per second per detector; for many data points, the error bars are smaller than the symbols. Times of ejections of superluminal radio knots, as resolved with the VLBA, are indicated by upward blue arrows, with the horizontal crossbar giving the uncertainty. **Middle panel** X-ray hardness; lower value is harder.**Lower panel** Radio light curves at 14.5 GHz (green triangles); 22 GHz (red circles) and 37 GHz (blue circles); and 43 GHz (core only, black squares).

host galaxy and the path taken by the gas in reaching the region of the black hole (e.g. [11] and references therein). This clearly does not occur in Roche-lobe overflow binary systems, in which mass and angular momentum transfer takes place at a more or less constant rate.

2. Obscuration and inclination play major roles in the appearance of AGN (e.g. [92]; however these authors do not really consider the relation of appearance to accretion rate / state). There may be some parallels with this in the case of some X-ray binaries, but in the majority it is not the case.

3. Jets from AGN in dense environments will probably dissipate their energy on smaller physical scales as they inflate the medium around them. There may be some parallel here between e.g. GHz-peaked AGN (e.g. [82]) and the interaction

of powerful jets and strong stellar winds in the systems like Cygnus X-3 and SS 433.

In addition to environmental effects, there is (at least) one key region in the geometry of AGN which appears simply not to be present in X-ray binary systems: the Broad Line Region (BLR). The broad emission lines in AGN have been shown by reverberation mapping techniques to arise within typically a few days of the central black hole ([84] and references therein). The precise velocity field of the BLR is however uncertain. [10] presents a clear case for a BLR that originates in a relatively thin conical outflow which has its origin in the accretion disc, but whose major component of motion is away from the disc. However, [83] argue that the variable components to BLR emission lines show the expected virial relation between velocity V and radius r, $V \propto r^{-1/2}$, implying that the motions of the line-emitting regions are dominated by the gravity of the central black hole. This facilitates the use of reverberation mapping techniques to estimate central black hole masses ([84] and references therein, but see [53] for a critique of the method). Other works, e.g. [95], also conclude that the motion in the BLR is primarily circular/orbital. [78, 79, 80] have studied in detail the appearance of emission lines from combined accretion disc plus wind systems, with application to both binary systems (cataclysmic variables) and AGN, and have shown that single-peaked lines can arise from rotating flows. Why then is there no clear evidence for an outflowing BLR in black hole X-ray binaries, when there are so many other apparently scale-free similarities in black hole accretion and jet formation ?

Firstly, [85] have already demonstrated, on the basis of detailed calculations, a strong line-driven wind is unlikely in the case of accretion discs around X-ray binaries. The problem is essentially that the central X-ray source is too strong a source of ionising radiation, which strongly inhibits line-driving. In AGN, in contrast, the cooler central disc is a UV source which is suitable for driving such winds. What if there are significant winds driven off by other means such as large-scale magnetic fields (e.g. [4, 76] or thermal expansion [1]? In this case we can ignore the line-driving requirement. Nevertheless, the strongly ionising X-ray source still prevents line emission from the inner, fast moving, regions of this wind. For example, the BLR for a 10^8 M$_\odot$ black hole in an AGN, accreting at close to the Eddington limit is typically estimated to be at a distance of several tens of light days (10^{16} cm $\leq R_{\mathrm{BLR}} \leq 10^{17}$ cm), or 300–3000 gravitational radii [84]. The line-emitting region of the disc is fairly close to this [99]. On the other hand, X-ray to optical delays in BHXBs accreting at comparable Eddington ratios (e.g. [38]) indicate lags of order seconds, or $> 10^4$ gravitational radii. The difference in the radii of the line-emitting regions of the accretion discs is due, once again, to the much hotter environments around stellar-mass black holes in BHXBs ($T \propto M^{-1/4}$ at the same Eddington ratio, and for a radiatively efficient flow). Therefore it seems likely, albeit in this case without detailed calculations, that even if a strong wind could be launched without line-driving, if it were launched from close to the black hole then the gas would be too highly ionised to produce BLR-like lines.

3.5 What about spin ?

There has been much speculation over the past few decades about the possible role of black hole spin in jet formation (e.g. [97, 51]) and any relation it might have

to the apparent radio loud:radio quiet dichotomy in AGN (listed as one of the ten major questions for the field by [92]). There have, more recently, been strong claims for clear measurements of black hole spin in AGN (e.g. [96]) and X-ray binaries (e.g. [75]). It is this authors view that to date there is no clear evidence either way for the role of spin-powering of jets in black hole X-ray binaries (contrary to the view put forward in e.g. [98]). Some points to consider, however, are

- In black hole binaries both 'radio loud' and 'radio quiet' states are observed from the same source, repeatedly, and are related to the accretion state, not spin changes
- In AGN there may be a larger range of black hole spins, relating to the merger history, whereas all black holes in binary systems have (presumably) formed from the collapse of a massive star and will have some intermediate value of spin

4 Using, testing and exploring

Now that we have established the first good quantitative scalings, as well as a new set of qualitative similarities, between black holes on all mass scales, what do we use them for ? The goal expressed by many for several years was to use the insights we gain from the disc–jet coupling in stellar-mass black holes to understand better the process of accretion and feedback in AGN. The importance of this connection has been greatly strengthened in recent years by the discovery that feedback from black holes is likely to be directly linked to both the formation of galaxy bulges [30, 20], and to the heating of the inner regions of cooling flows (e.g. [3, 94]).

An obvious and important place to start is therefore with the kinetic feedback of AGN, or kinetic luminosity function. [72] and, more directly, [48] have estimated the kinetic luminosity function of AGN based upon both power and spectral state scalings from black hole binaries. Both groups conclude that kinetic feedback into the IGM is actually likely to be dominated by supermassive black holes accreting at relatively low Eddington ratios. Future studies need a better regulated sample with mass measurements and more precise measurements of core coronal, disc and jet components.

Another example relates to the argument originally noted by [87] (see also e.g. [12] and references therein), that the local mass density of black holes is consistent with the growth of black holes via *radiatively efficient* accretion (current limits place a factor of a few on this consistency). However, as is clearly the case for binary black holes, radiatively efficient accretion above $\sim 1\%$ Eddington, can occur with powerful jets (hard and hard intermediate states) or without a jet (soft state). Taking extremes, if most of the X-ray background results from accretion in hard or hard intermediate states, then $\sim 10^{67}$ erg Gpc^{-3} may have been injected into the ambient medium in the form of kinetic energy over the lifetime of black hole growth. If most of the X-ray background results from accretion in jet-free *s*oft X-ray states then the figure will be much smaller, probably by a factor of a hundred or more.

4.1 Somewhere in the middle: using radio emission to look for intermediate mass black holes

The publication of the fundamental planes of black hole activity by [70] and [13] coincided with a period of greatly renewed interest in 'ultraluminous' X-ray sources

(ULXs) and the suggestion that some of these object could be 'intermediate mass' black holes ($10^2 M_\odot \leq M \leq 10^4 M_\odot$). These ULXs were not located at the dynamical centres of their host galaxies, and could sometimes produce X-ray luminosities in excess of 10^{41} erg s^{-1}, or the Eddington limit for a $\geq 70 M_\odot$ black hole, *if* the X-ray emission was isotropic. Alternatives based upon anisotropy of the emission, whether intrinsic or associated with relativistic aberration, have been put forward (e.g. [41]; [44].).

The fundamental planes immediately implied two things which were potentially good for this field:

1. If you could measure the X-ray and radio luminosities of a ULX, you could infer its mass
2. Radio observations were the best way to find intermediate mass black holes accreting at low rates from the ambient medium

Point [1.] has had mixed success. Several ULXs do appear to have radio counterparts, and simply plugging these radio luminosities into the fundamental plane implies large black hole masses, $>> 100 M_\odot$. However, in most cases this radio emission is in fact resolved and looks like a large scale nebula (e.g. [81, 88]), and no very compact and variable radio counterparts have yet been found.

Point [2.] has been explored in some detail by [62] and [64] (see also[63]). Put simply, black holes accreting at low rates should be easier to find in the radio band. This situation is enhanced the greater the mass of the black hole, as the radiative efficiency seems to fall off with Eddington ratioed accretion rate. Recent confirmation of this approach may have come in the form of the detection of a radio source at the centre of the globular cluster G1 by [91], which is consistent with a black hole of mass $\geq 100 M_\odot$.

4.2 Comparison with neutron stars and white dwarfs

A control sample exists which allows us to test whether properties unique to black holes, such as the presence of an event horizon, are in any way essential for any of the observed phenomena. Neutron stars are collapsed stellar remnants with masses $1 M_\odot \leq M_{NS} \leq 2 M_\odot$ and sizes only a factor of 2–3 larger than their Schwarzschild radii (see Fig. 2). Squeeze them to make them half as large as they are and they would collapse to form black holes. The gravitational potential energy released per unit mass of matter accreted onto a neutron star is therefore very similar to that of a black hole. In addition, we find them in X-ray binary systems with very similar patterns of accretion, including outbursts and extended periods of quiescence, to the black hole binaries. A full review of the properties of jets from neutron star binaries is beyond the scope of this paper, but the key points from the comparison are

1. Neutron stars seem to produce both steady and transient jets, just like black holes, with a similar relation to hard states and outbursts (although poorly sampled to date)
2. The radio to X-ray ratio is in general lower for neutron star binaries
3. Neutron star jets are less 'quenched' in soft states than black hole jets
4. Neutron star jets may be just as, or even more, relativistic (in terms of bulk velocity) than black hole binary jets

5. The radio:X-ray correlation, although much less well measured, appears to be steeper than that for black holes by a factor of two or more, i.e. $L_{\mathrm{radio,NS}} \propto L_{\mathrm{X,NS}}^{\geq 1.4}$ compared to $L_{\mathrm{radio,BH}} \propto L_{\mathrm{X,BH}}^{\sim 0.7}$

6. Two neutron star jet systems (Sco X-1, Cir X-1; possibly also the 'odd' system SS 433) appear to show unseen but highly relativistic flows which energise slower-moving bulk flows further out.

[73] present the most comprehensive review to date of the properties of jets from neutron star binaries (see also [46] and Chap. 4 in this volume, and references therein).

Several of the points listed above strongly imply that the basics of relativistic jet formation do not require any unique property of black holes, such as an event horizon. However, as discussed earlier (and illustrated in Fig. 2), in terms of gravitational potential, neutron stars are almost black holes, and so perhaps the similarities are not so surprising. However, there is another major class of accreting binary systems, which contain accreting objects which are very different: Cataclysmic Variables (CVs). In these systems a white dwarf, with a M/R ratio about a thousand times smaller than for a black hole or neutron star, accretes matter from a companion (white dwarf accretion is less efficient than nuclear fusion).

However, [50] have recently shown that there may even be direct similarities between accretion state changes at high luminosity in disc-accreting CVs and black holes and neutron stars. Fig. 15 presents HIDs or equivalent for the black hole binary GX 339-4, the neutron star binary Aql X-1 and the disc-accreting CV SS Cyg. The similarity is striking, but what is key is that observations with the VLA have revealed radio flaring at around the point of the high luminosity state transition in SS Cyg, just as seen in GX 339-4 and other black hole binaries. This strongly suggests the transient formation of a jet during this phase, further suggesting that $p$atterns of disc:jet coupling relate solely to the behaviour of the disc and not the central accretor (which may, however, affect e.g. jet velocity).

To conclude, there are clear similarities, both quantitative and qualitative, between accretion (luminosity, state) and jets (formation, steady or transient) in black holes of all masses. These links provide us with tools to understand feedback from AGN and its role in the formation of galaxies and evolution of clusters, and with insight into the process of relativistic jet formation. However, we should be cautious about drawing wide-ranging conclusions about the effect of black hole properties, e.g. spin, on jet formation, when we find comparable patterns of behaviour in related (neutron star) and also very different (white dwarf) classes of object.

4.3 Further reading

This review has necessarily been both brief and biased, and the literature associated with this area of research is vast and ever-expanding. In particular, I have approached the area of disc–jet coupling from the realm of X-ray binaries, looking for scalings and comparisons with AGN, and have not even scratched the surface of the wide phenomenology associated with accreting supermassive black holes.

For a broader introduction to AGN, I would recommend [52] and references therein. For a more AGN-centric view of the disc-jet coupling around accreting black holes, see papers by Marscher, e.g. [68]. For an up-to-date reference list of all things related to black holes, see [24].
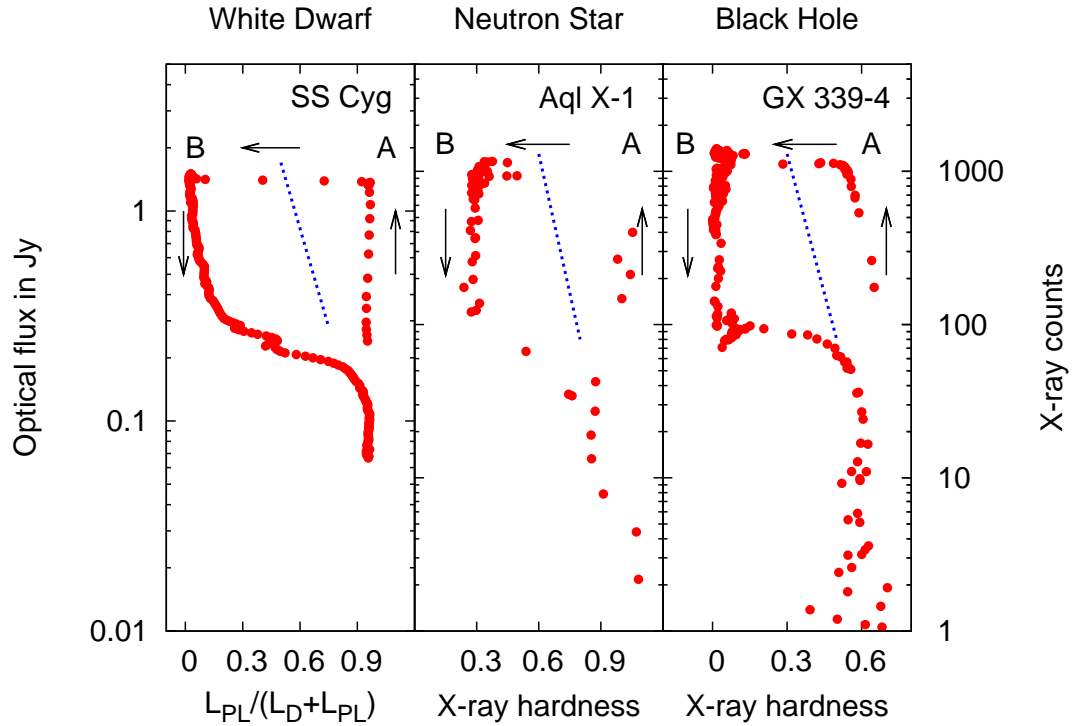
Fig. 15. HID for a black hole, a neutron star, and the disc-accreting CV SS Cyg. The arrows indicate the temporal evolution of an outburst. The dotted lines indicate the jet line observed in black hole and neutron star XRBs: On its right side, one generally observes a compact jet; the crossing of this line usually coincides with a radio flare. For SS Cyg, we show a disc-fraction luminosity diagram. We plotted optical flux against the power-law fraction measuring the prominence of the "power-law component" in the hard X-ray emission in relation to the boundary layer/accretion disk luminosity. This power-law fraction has similar properties to the X-ray hardness used for XRBs. Radio flaring has been observed during the high luminosity state transition in SS Cyg just like in black hole systems.

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