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**Memorie** della

# Galactic black holes

## Accretion and feedback

R. Fender

Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
e-mail: `r.fender@soton.ac.uk`

**Abstract.** In this brief review I will discuss, primarily in the context of black hole X-ray binaries, the current state of our understanding of the evolution between different modes of accretion during an outburst, and the connection between those modes and kinetic feedback in the form of relativistic jets and winds. I will briefly discuss how some of this phenomenology may be applicable to other types of system, and outline what I think are the key recent discoveries and most likely next big things.

**Key words.** black holes, X-rays, radio, accretion

### 1. Introduction

Astrophysical black holes have affected their environment in many ways, on many scales, over the age of the universe. Accretion onto the first generation of black holes, within a billion years of the big bang, would have been a key component of the ionizing flux which heralded the end of the dark ages. Kinetic feedback from the supermassive black holes that these objects grew into appears to have helped to regulate the growth of their host galaxies. Black hole binaries (BHXB) in the Milky Way and other nearby galaxies allow us to study on humanly-accessible timescales the kind of large changes in accretion rate, and modes and rates of kinetic feedback, which the supermassive black holes in Active Galactic Nuclei (AGN) underwent on timescales of millions of years. Studying these objects, and comparing their behaviour with the demographics of AGN as a function of redshift, is our best hope of understanding how black holes shaped galaxy growth.

### 2. Stellar mass black holes

It is estimated that $\sim 10^8$ stellar mass black holes exist in our galaxy as a direct result of the collapse of the corresponding number of very massive stars over the age of the Milky Way. A small fraction of these (perhaps a few 1000) are in close enough binary systems that mass transfer and subsequent accretion at high rates can occur: these are the X-ray binaries, which I will discuss in more detail in the following pages. It is interesting to note that if the rest of the population, the ‘isolated’ black holes, have the same mean mass as estimated for the black holes in BHXBs, of 7–8 $M_{\odot}$, then the total mass in isolated black holes in our galaxy is 100–1000 times that in Sgr A* (and that notwithstanding any black hole mass which may be in, for example, intermediate mass black holes in globular clusters).

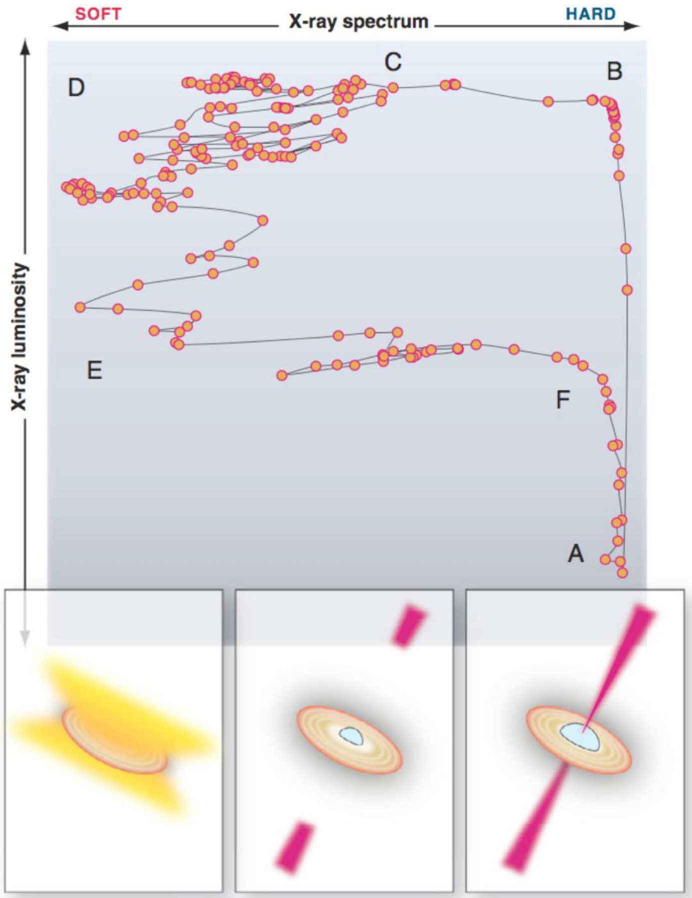


**Fig. 1.** The evolution of the outburst of a black hole X-ray binary in the hardness-intensity diagram (HID). The x-axis corresponds to X-ray spectral state (right is 'hard', left is 'soft') and the y-axis to X-ray luminosity. A loop A-through-F is typically followed by a system in outburst over a timescale of months–years. There is a clear match between location in the diagram and mode and strength of kinetic feedback. In the hard state (right side) we see steady (on short timescales) radio emission almost certainly associated with a compact core jet. During the transition B→C→D bright radio flaring is observed which can sometimes be spatially resolved in to relativistic ejecta. In the soft state (left side) the radio emission drops and a strong accretion disc wind is observed. From Fender & Belloni (2012).

As well as being the best test beds for understanding black hole feedback, and therefore gaining insight into how AGN regulated the growth of their host galaxies, stellar mass black holes are also the best places in the universe for testing general relativity. Although the potential at the horizon is the same for any black hole, the curvature is much stronger for the stellar-mass variety (which is why only the stellar-mass black holes would 'spaghettify' an astronaut, and why you won't get the tidal disruption of a main sequence star around a $10^9$ solar mass black hole). This means that stellar mass black holes are also the best places to test deviations from classical GR, as discussed in detail in Psaltis (2008).

### 2.1. Patterns of accretion and feedback

The following section is punctuated by references to Fig 1, e.g. (A→B), which is reproduced from Fender & Belloni (2012), wherein the reader can find a detailed description of the evolution of a source through the key stages of an outburst. The temporal evolution of these states and the feedback modes is illustrated in Fig 2. The story is as follows.

In Fender et al. (1999) it was observed that when the BHXB entered the soft X-ray state (B→D) the radio emission which had until that point, in the hard state, (A→B), tracked the X-ray flux (Hannikainen et al. 1998), suddenly dropped below detectable levels, alongside the hard X-ray flux. When the source re-entered the hard X-ray state (E→F), the radio emission recovered back to more or less the same correlation it had displayed before it disappeared in the soft state. It was subsequently established (Fender 2001) that all BHXB showed more or less steady radio emission while in the hard state, and that this radio emission correlates in a very neat and non-linear way with the total X-ray flux while in the hard state but was generally strongly suppressed in soft states (Corbel et al. 2003; Gallo, Fender & Pooley 2003); note that more recently a less radio-loud but similar track has been found below the main correlation – see e.g. Coriat et al. (2011); Gallo, Miller & Fender (2012) and references therein). Around the same time studies of the high accretion rate BHXB GRS 1915+105, which has been in outburst since the early 1990s, revealed that each transition from a hard to a soft spectral state was associated with exactly one radio flare (e.g. Klein-Wolt et al. 2002). This all led to a phenomenological model which was presented in Fender, Belloni & Gallo (2004) (hereafter FBG04; see also Corbel et al. 2004) and tested and refined in Fender, Homan & Belloni (2009).

Does this model apply to AGN? Some of the first hints that there may be similarities came from monitoring studies of blazars, in which the powerful AGN jet is aligned very close to the line of sight. Marscher et al. (2002) first reported connections between spectral changes and resolved (with VLBI) ejections in the blazar 3C120, which they compared directly to the behaviour in GRS 1915+105. Then, around the turn of 2003/2004, two papers arrived very close together in time which made a breakthrough in our understanding of the quantitative connections between stellar-mass and supermassive black holes. Merloni, Heinz & di Matteo (2003), and Falcke, Körding & Markoff (2004), each found – albeit in slightly different ways and with different samples – that a three-dimensional plane ($L_X$, $L_R$, $M$) could fit black holes of all masses.

Shortly thereafter, and motivated by the model of FBG04, Körding, Jester & Fender (2006) made the first attempt to compare the distribution of accretion states and related radio (jet) luminosities for AGN with the pattern we'd learned from BHXBs. The results were encouraging, and have fed into models of kinetic feedback from AGN over cosmological time (e.g. Körding, Jester & Fender 2008). However, it was clear for some time that if a good connection to AGN was to be made, then we had to understand what phases of a BHXB outburst might be associated with the strong winds observed in AGN (in particular BAL QSOs). Or perhaps that was a mode which simply had no analogue in BHXBs? Again a breakthrough was observationally driven, when Neilsen & Lee (2009) realised that in GRS 1915+105 (again) strong absorption features indicative of a wind were seen only in softer X-ray states, the opposite of what was true for the radio emission which traced the jet. Taking all existing high-resolution X-ray spectra, Ponti et al. (2012) took this idea and tested it against the ensemble of BHXBs and found a striking result: X-ray winds were always seen from BHXB when they were (i) in a soft state, and (ii) viewed close to edge on (as is GRS 1915+105). This led to the conclusion that soft states always produce winds, but that they are equatorially flattened.

This discovery of a kinetic outflow component may have completed the top-level phenomenology of combined kinetic/radiative feedback in black hole outbursts[1].

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[1] I have no doubt this statement will appear hilariously naïve within a decade

## 3. Outstanding questions and the Next Big Things

In this section I briefly highlight some recent discoveries, current controversies, and future prospects. This viewpoint is, inevitably, extremely subjective.

### 3.1. It depends how you look at it

In Fig 2 of Ponti et al. (2012), BHXBs are separated into those believed to be viewed at relatively high (disc close to edge on) and low (disc close to face on) inclination. As discussed above, this analysis clearly revealed that disc winds were only observed (at least in absorption) in high inclination systems. However, inspection of the background HIDs suggested that the overall pattern of X-ray behaviour was different for the two groups. Mũnoz-Darias et al. (2013) took this apparent effect and investigated it in detail, finding a clear difference in observed HID shapes and – more fundamentally – measured accretion disc temperatures, between the two groups. Accretion discs viewed close to edge-on appeared to be systematically hotter than those observed close to face on. The origin of this effect probably lies in a combination of special- and general-relativistic effects which occur in the X-ray emitting gas close to a black hole, as originally predicted decades ago by Cunnningham (1975) and revived by Zhang, Cui & Chen (1997). The result is interesting because it suggests that study of the HID alone can reveal a BHXB's inclination and possibly even spin, it is surprising in a sense because the effects were long predicted and the HIDs had been in the public domain for over a decade before the inclination-dependent differences were noted.

### 3.2. Spin spin

It has long been suggested that black hole spin might, to some extent, power the relativistic radio jets observed from supermassive black holes in AGN. Blandford & Znajek (1977) demonstrated that this process was indeed theoretically feasible but, despite a long debate in the literature, the 'smoking gun' of this effect has yet to be unambiguously demonstrated (at least in this author's opinion). Much of this work has been driven by an apparent radio loud:radio quiet bimodality in AGN which has been attributed to an underlying bimodality in the spin of the central supermassive black hole (e.g. Sikora, Stawarz & Lasota (2007), references therein and citations thereafter).

A current very hot topic of research is whether or not the smoking gun for spin-powering of black hole jets can be found in the BHXBs. In these systems estimates of the black hole spin can be made via X-ray spectroscopy of the 'reflection' region around the iron line (approximately 5–10 keV; e.g. Fabian & Ross 2010) or the accretion disc continuum (below 5 keV e.g. Shafee et al. 2006). By the late-2000s, there were enough radio data and reported spin measurements from X-ray spectroscopy to make a direct comparison. In Fender, Gallo & Russell (2010) we reported our analysis of these data, finding no correlation between reported spins and any measure of radio jet power (or speed), with the strongest constraints associated with the 'steady' jets observed in the hard X-ray state. However, subsequently, Narayan & McClintock (2012) reported a correlation between spins measured from the disc continuum method and the peak radio luminosity of the brightest flares observed from a system. One suggestion (already made in e.g. Meier 2001; Fender, Belloni & Gallo 2004) is that the hard state jet, perhaps being associated with a recessed disc, does not connect to the black hole spin, whereas the brighter flares are associated with brief periods of tapping the spin. The debate in this area continues (e.g. Steiner, McClintock & Narayan 2013; Russell, Gallo & Fender 2013) but in the absence of a killer case either way there are still some important discussion points to consider, for example:

(i) Considering that the hard state and transient jets might be powered by two different mechanisms, it is not completely clear which jet actually dominates the integrated kinetic power output over the course of an outburst (see again Fig 2).

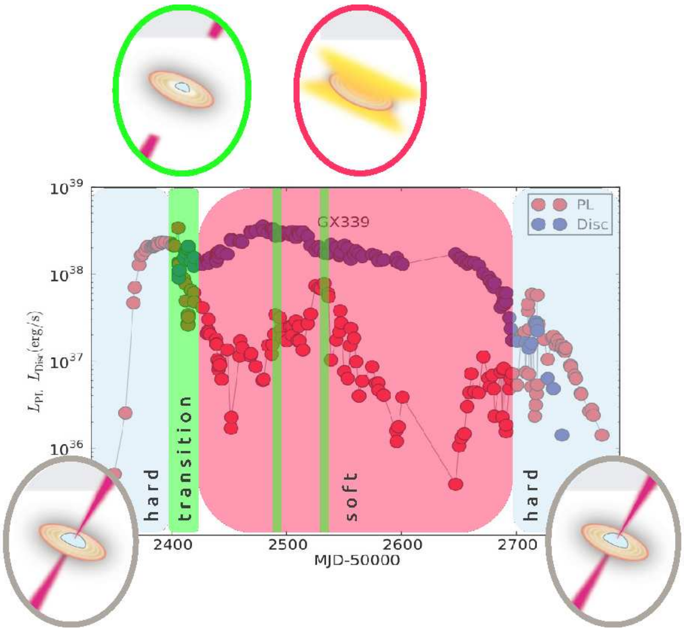


**Fig. 2.** The evolution of a black hole outburst in time. An outburst of the same source is mapped into the HID in Fig 1. The hard and soft spectral states can be clearly seen in the relative ratios of the power-law ('PL') and disc components of the X-ray spectrum. For a typical source in outburst, the longest phase at very high accretion rates (above a few % of Eddington in terms of X-ray luminosity) is typically in the soft state. The hard state however can extend for many years before and after the outburst (under the assumption that 'quiescence' is just a very low hard state). The state transitions, where the resolved relativistic ejections occur, is by far the shortest phase of the outburst. The light curve here is from Dunn et al. (2008).

(ii) However, the recent measurement with the Event Horizon Telescope of a very small (less than 5.5 gravitational radii) radio component at the base of the jet of M87 (Doeleman et al. 2012), which is currently accreting orders of magnitude below the Eddington rate, suggests that maybe even in 'hard' states the jet is launched from very close to the black hole and should be affected by spin.

Both of the above are very relevant when it comes to considering how the cosmic evolution of black hole spin may have affected kinetic feedback from AGN and in turn the growth of galaxies.

## 3.3. Further afield

There are strong reasons to expect accretion onto neutron stars to be similar in many ways to that onto black holes. They are, after all, very similar in their ratio of mass to radius. On the other hand, of course, the neutron stars have a surface while the black holes do not. There is already some evidence (e.g. Migliari & Fender 2006) that jets from neutron stars are similar in many ways to those from black holes, although there may be some differences. Pushing on this area, in particular using the neutron stars as a control-sample-with-a-surface to compare to the black holes, is a very good way to test what is special about accretion onto black holes.

Moving futher afield, it may be that systems in completely different regimes also behave similarly, prompting us to consider what exactly it is that determines patterns of accretion and ejection behaviour. Körding et al. (2008) showed that the nearby Cataclysmic Variable (white dwarf accretor) SS Cyg also seems to show similar patterns, despite being a far less relativistic object than black holes or neutron stars. Open questions include whether or not these patterns could also be applied perhaps to other accreting objects, e.g. GRBs or even YSOs. Furthermore, Tidal Disruption Events appear to be the best chance to see in AGN the outbursting behaviour we see in BHXBs when the accretion rate varies by several orders of magnitude on a very short timescale. The detection of radio emission, probably from jets, from some of these objects is a very exciting development (Zauderer et al. 2011; see also discussion in van Velzen, Körding & Falcke 2011, amongst others).

## 4. Conclusions

In this paper I have attempted to summarize, in a very broad brush manner, the current state of our understanding of the phenomenology of disc-jet coupling in stellar mass black holes in binary systems. I have also highlighted a small subset of areas where surprising, exciting and sometimes contentious research is being carried out at present. These systems remain the among the best sites in the universe in which to study highly relativistic phenomena, and are still our best sample for trying to understand black hole feedback over cosmological timescales.

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