Exploring jet properties in magnetohydrodynamics with gravity
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Citation for published version (APA):
Polko, P. (2013). Exploring jet properties in magnetohydrodynamics with gravity
Forged in the cauldron of relativistic gravity, with magnetic fields, highly energetic particles, and photons of all energies as their ingredients, stirred by the accretion disc or space itself, jets are a potent concoction. Accelerating particles to very near the velocity of light, heating the ambient medium to thousands of degrees, pushing it around for thousands of parsecs, they are one of the main sculptors of our Universe. While studied for decades, certain aspects are still a mystery. To gain more insight, we have to bridge the big and the small, the brief and the seemingly endless. So let us start by thinking big.

1.1 Active galactic nuclei

Most galaxies are thought to harbour a supermassive black hole (SMBH) in their centre with a mass between $10^5 - 10^{10} M_\odot$ (Kormendy & Richstone 1995; Magorrian et al. 1998). When there is matter flowing towards this BH, the core of the galaxy can turn into a complex engine that emits copious amounts of radiation, sometimes dominating the combined stellar radiation from the host galaxy, and highly relativistic matter. The core of the galaxy, and by extension the galaxy itself, is then called an Active Galactic Nucleus (AGN). The physical processes liberating this energy is far more efficient than nuclear fusion, ranking AGN among the most efficient engines in the Universe.

The prevailing picture of the physical structure of AGN, called the AGN paradigm, is shown in figure 1.1 (Holt et al. 1992). At the centre is a SMBH, attracting the matter surrounding it. Some distance from the centre, clouds of gas slowly moving in this gravitational potential produce narrow emission lines, forming the narrow-line region (NLR), while clouds close to the BH emit strong Doppler-broadened optical and ul-
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Figure 1.1: Suggested structure of an AGN and the effects of orientation on the AGN class observed. The central SMBH is surrounded by an accretion disc, which in turn is embedded in a torus. The region within the torus, where gas clouds are moving very fast, is called the broad line region. This region can be seen directly only from certain angles. Farther from the centre, where the velocity of the clouds is lower, is the narrow line region, which can be observed from all angles. When we are looking along the axis of symmetry, the jet emission dominates the spectrum. Within the unification scheme radio-loud AGN have jets, while radio-quiet AGN do not. Adapted from figure 1 in Urry & Padovani (1995).

traviolet emission lines, forming the broad-line region (BLR). Surrounding this BLR is a dusty torus, blocking the emission from this region for certain viewing angles. Within this torus, matter is flowing towards the BH, losing its potential gravitational energy, providing enormous amounts of energy, and its angular momentum through viscous or turbulent processes in an accretion disc. Some of the accreted matter is lost to the BH, some may be heated up to be ejected in a disc wind, but another part can be accelerated along helical magnetic field lines produced in the disc or by the spinning BH, forming a relativistic jet. A corona of hot electrons above the accretion disc may form a transitionary region between the disc and the jet, but the exact details of jet formation are still the subject of extensive study and debate.
1.1 Active galactic nuclei

1.1.1 Effect of AGN on galaxy evolution

Due to the enormous energy liberated in the core of the galaxy, an AGN can have a significant impact on the galaxy surrounding it. The jet can impart kinetic energy to the galactic medium, heating it and possibly pushing it out of the galaxy altogether. Since stars form from cold gas, an AGN can significantly reduce the star formation rate and is therefore intimately connected with the evolution of the galaxy. This connection, called AGN feedback, is exemplified by the fact that the central BH mass is tightly related to galactic properties, such as the velocity dispersion of the galaxy’s bulge (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Gültekin et al. 2009), the bulge luminosity (Dressler 1989; Kormendy & Richstone 1995; Gültekin et al. 2009), and the mass of the bulge (Magorrian et al. 1998; Häring & Rix 2004), although the correlation with the velocity dispersion is the tightest (Beifiori et al. 2012). These relations can be explained best by postulating the BH regulates its own growth (e.g., Tabor & Binney 1993; Ciotti & Ostriker 1997; Hopkins et al. 2009). In simulations AGN feedback can explain the old stellar populations in massive elliptical galaxies, which in hierarchical structure formation should still be forming stars (Ferreras & Silk 2000; Trager et al. 2000; Graves et al. 2009), as well as why there are far fewer very bright and very massive galaxies than expected (Croton et al. 2006). In clusters of galaxies, the intracluster gas is expected to radiatively cool and flow towards the central galaxy increasing the mass of the galaxy and enabling star formation (Fabian 1994). Observations show this does not happen, because AGN jets heat the intracluster medium (Mathews & Brighenti 2003) and create giant cavities in the gas, filled with radio emission (Churazov et al. 2000; Giacintucci et al. 2011, e.g.,). Understanding jets thus is essential to galaxy evolution, through the interplay between the galaxy, its BH, and the large scale environment.

1.1.2 AGN classes

Many AGN have been detected and they have been classified according to their observed properties. Although AGN appear in a myriad of classes, two main types of AGN have been distinguished: Type 1 AGN have bright continua and broad emission lines from high-velocity gas in their spectra, while Type 2 AGN have weak continua and only narrow emission lines. In addition there is a small number of AGN with atypical spectral characteristics. Apart from differences in their spectral lines, AGN also cover a range of luminosities, especially in their radio emission. This has led to the adjectives radio-loud, when the ratio of the radio flux at 5 GHz to the optical flux in the B-band $F_{5}/F_{B} \gtrsim 10$, and radio-quiet when this ratio is smaller. Type 1 AGN that are radio-quiet include the low-luminosity Seyfert 1 galaxies with comparatively very bright nuclei, which can only be detected at small cosp-
mological distances. At higher luminosity are the radio-quiet quasars (QSOs; from quasi-stellar objects), which are relatively rare in the local universe, with the most luminous quasars inhabiting the most massive galaxies. Radio-loud AGN of Type 1 are called Broad-Line Radio Galaxies (BLRGs) at low overall luminosities, and radio-loud quasars at higher luminosity.

For the Type 2 AGN the radio-quiet class is called Seyfert 2 or Narrow Emission Line Galaxies (NELGs) and the radio-loud class the Narrow-Line Radio Galaxies (NLRGs). The radio-loud AGN have been divided by Fanaroff & Riley (1974) in two classes with very distinct morphologies. Although the original distinction was made on whether the distance between the regions of highest brightness is less (FR1) or more (FR2) than half of the total extent of the source, in practice FR1 sources have intensities decreasing from the centre, while FR2 sources have two clear hot-spots in the prominent radio lobes surrounding the galaxy.

A minority of AGN have atypical spectra, characterised by rapid variability and no strong emission lines. This group includes the radio-loud blazars, combining the low-luminosity BL Lacertae (BL Lac) objects and the high-luminosity flat-spectrum radio quasars (FSRQ), and optically violent variables (OVVs).

1.1.3 Unification through orientation

In order to reduce this myriad of classes, people have tried to unify them in a single model. One unification scheme based on the orientation of the galaxy with respect to our line of sight, was developed by Urry & Padovani (1995), relating specific spectral properties to different regions of the AGN (see figure 1.1). In this scheme the distinction between the radio-loud and radio-quiet AGN is caused by the presence or lack of a jet, which emits mostly, although not exclusively, in radio.

The distinction between Type 1 and Type 2 AGN is more subtle. The broad lines in the spectrum vary, which suggests that the region emitting this radiation is small. The matter close to the BH rotates very quickly, causing broad lines in the spectrum. These two arguments lead to a proposed small region surrounding the BH that provides the observed broad lines. The narrow lines in the spectrum do not vary significantly, suggesting the emitting region is extended, with the narrow lines advocating a region far away from the BH, where the velocities are lower. If there were an optically thick torus surrounding the broad line region (BLR), for certain viewing angles this BLR would be obscured by the torus. Starting from an edge-on perspective, we would only see narrow lines and radio emission if there were a jet (Seyfert 2 and NLRG). Then as we go towards a face-on view, first the BLR would come into view, dominating the emission from the narrow line region (NLR), changing the perceived AGN to a Seyfert 1 and a BLRG. When the central region of the AGN comes into full view, the luminosity increases and we see either a radio-
quiet or radio-loud QSO. When the viewing angle is smaller than the jet opening angle, we see the quickly varying BL Lac and OVV objects.

1.1.4 Intrinsic differences

While the unification scheme of Urry & Padovani (1995) provides explanations for most observed features of AGN, there are still a few that cannot be explained within this scheme. By comparing BL Lac objects with a model including emission from the jet, host galaxy, and torus Plotkin et al. (2012a) found that, as opposed to FSRQs, by leaving out the torus the BL Lac objects were fitted much better. This result seems to indicate that in these sources the postulated torus is missing, possibly as a result of a lower accretion rate. The presence or absence of a jet may either be caused by the surrounding medium, which could for example explain the differences between FR1 and FR2 sources, or by intrinsic differences such as the accretion rate, the mass, or the spin of the BH, which could have an effect on the power of the jets in AGN (Garofalo et al. 2010).

While there is evidence of intrinsic changes within AGN, unfortunately, due to the enormous masses and length scales involved, these changes can take many thousands to millions of years. Since general relativity predicts that BH physics scales with mass, in order to see these changes on human time scales, we have to go to smaller systems.

1.2 Black hole X-ray binaries

Stellar mass BHs are $\sim 10^4–10^{10}$ times as small as their supermassive counterparts. When accreting from a companion star, they emit large amounts of X-rays. Since they were first noticed in X-ray observations, these systems are called black hole X-ray binaries (BHXRBs). As in AGN, due to angular momentum conservation the accreted material forms an accretion disc, which is heated up and magnifies magnetic fields by viscous processes such as the magnetorotational instability (Balbus & Hawley 1991). These magnetic field lines can guide material from the disc away from the BH, either via a disc wind or a collimated jet (see figure 1.2).

1.2.1 Accretion states

Most BHXRBs are variable, going through spectral changes and eventually returning to its original spectrum in a period of months to a year. These cycles are best seen in a hardness-intensity diagram (HID), which plots the X-ray luminosity versus the slope of the X-ray spectrum (Fender et al. 2004). Figure 1.3 shows the HID for GX 339-4, a galactic BHXRB. Starting from the lower right, after a period of low luminosity,
Figure 1.2: Artist’s impression of an X-ray binary. The blue companion star is donating matter to the orange accretion disc, part of which leaves the system through the purple jet. Credit: NASA/JPL-Caltech/R. Hurt (SSC).

the total X-ray luminosity increases, causing the source to move up. Next the hard X-ray luminosity drops, while the soft X-ray luminosity still increases, leading to a softening of the spectrum, and a shift to the left. After the source spends some time overall X-ray luminosity goes down again, the spectrum returns to its original shape.

These different spectra are thought to be tied to specific configurations of the system, so-called accretion states. Both the mass accretion rate and the geometry of the disc changes as we go up in luminosity. As the mass accretion rate increases, the inner radius of the disc decreases, and from a geometrically thick geometry, the disc becomes geometrically thin. It is believed a thin disc cannot support strong magnetic fields (Meier 2001) and hence the jet and the corresponding radio emission are eventually quenched.
1.3 Mapping of AGN classes onto BHXRB accretion states

But is it really possible to use the knowledge gained from BHXRBs and apply them to SMBHs? There is some evidence this is actually the case. Aside from obvious similarities in the appearance of accreting stellar-mass and supermassive BHs, giving microquasars their name, a correlation has been found between the compact radio luminosity, assumed to be jet emission, the X-ray luminosity, assumed to come from the disc, and BH mass for both stellar mass and SMBHs, called the fundamental plane of black hole accretion/activity (Merloni et al. 2003; Falcke et al. 2004). This correlation is particularly strong when BHXRBs in the jet-dominated hard state are compared with their supermassive counterparts, the low-luminosity AGN (LLAGN). As Merloni et al. (2003) also included BHXRBs in other states and high-luminosity quasars for their analysis, their correlation had more scatter. Recently Plotkin et al. (2012b) were able to derive a more refined relation: \( \log L_X = (1.45 \pm 0.04) \log L_R - (0.88 \pm 0.06) \log M_{BH} - 6.07 \pm 1.10 \). While there is substantial scatter in the relation,
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BHXRBs (10^6 M⊙) Sgr A* (10^9 M⊙) LLAGN (10^7–8 M⊙) FR I (10^8–9 M⊙) SDSS HBLs (10^9–10 M⊙)

Figure 1.4: Edge-on view of the correlation between the compact radio luminosity, the X-ray luminosity, and BH mass for both stellar mass and SMBHs, including high-energy cutoff BL Lacs (HBLs) from the Sloan Digital Sky Survey (SDSS). The solid line shows the best fitting function. Since beaming can have a significant effect on BL Lacs, they have been debeamed with an assumed Doppler factor of 7 (Ghisellini et al. 1993). Figure adapted from Plotkin et al. (2012b).

it does represent a correlation that holds over eight orders of magnitude in mass (see figure 1.4).

So if, as general relativity predicts, there is no fundamental difference between BHs of different masses, it is possible AGN go through the same accretion states as BHXRBs, with radio-loud quasars corresponding to the hard state and radio-quiet to the soft state. As mentioned before, due to the much longer time-scales it is impossible to observe a state change in an AGN on human time-scales, but by looking at the remnants of jet activity it may be possible to say something about the past behaviour of AGN. In clusters of galaxies, when the central AGN jet is active it can blow a bubble in the intracluster gas (see figure 1.5). By making assumptions about the geometry and kinetics of these bubbles, it is possible to estimate the age of the cavities. For Hydra A this analysis gives ages of around 10^8 years for both the duration and the time between cavities Wise et al. (2007). With a central BH mass of 9 × 10^8 M⊙ (Rafferty et al. 2006), these time-scales would be of the order of a year for stellar-mass BHs, corresponding roughly to the observed accretion states cycle in BHXRBs.

Although the mapping is not yet complete, Körding et al. (2006) plotted almost 5000 quasars on disc-fraction/luminosity diagram (DFLD), a generalisation of the HID for BHXRBs. As the frequency of the radiation depends on the mass of the black hole, and the range of black hole masses is rather wide, the DFLD has the disc luminosity plus the power-law component luminosity (L_D + L_{PL}), as a measure of
luminosity, plotted versus the power-law luminosity divided by the sum \([L_{PL}/(L_D + L_{PL})]\), as a measure of hardness. The result has some similarities to the HID for BHXRBs, but only in a statistical sense. The hope is that in the future it may be possible to put an individual AGN on an HID analogue. Despite the fact stellar-mass BH systems appear 10^5 times smaller than AGN\(^1\), they are understood in more detail due to their variability. Extending the knowledge gained from BHXRBs to SMBHs would be a great step towards being able to predict the activity of these active galactic nuclei and their effects on galaxy formation, evolution and ultimately the large-scale structure of the Universe. Conversely, the much higher spatial resolution of AGN gives us information unavailable in BHXRBs, so the combination promises to shed light on jet formation. Since the jet is a fundamental part of the system and contributes significantly to the spectrum, it is vital we understand the effects it has. It

\(^1\)V616 Monocerotis, one of the closest BHXRBs, has a BH mass \(M_{BH} = 6.6 \pm 0.25 \ M_\odot\) and distance \(d = 1.06 \pm 0.12 \ kpc\) (Cantrell et al. 2010) for an angular size of the Schwarzschild radius of \(1.2 \times 10^{-10} \) arcseconds, while for the supermassive BH at the centre of our Galaxy, Sagittarius A* (Sgr A*) with \(M_{BH} = (4.3 \pm 0.38) \times 10^6 \ M_\odot\) and distance \(d = 8.3 \pm 0.35 \ kpc\) (Gillessen et al. 2009) the angular size of the Schwarzschild radius is \(1.0 \times 10^{-5} \) arcseconds.
also seems to regulate other parts of the system, increasing its importance.

1.4 Accretion discs

If we want to be able to explain the observations of BHXRBs, we need to model the hydrodynamics and radiation processes of gas in orbit around the BH. The best-known one is the geometrically thin, optically thick disc model developed by Shakura & Sunyaev (1973). Matter falling towards the BH, either from a companion star, or from the interstellar medium, usually possesses angular momentum with respect to the BH. As it gets closer to the BH the matter starts to rotate around it. The differential rotation due to the Keplerian orbits causes shearing between the different radii. Viscous processes facilitate angular momentum exchange, allowing the matter to spread out in a disc, and also heat up the disc, getting hotter as it moves deeper into the potential well. Due to the temperature of the disc, which can reach $\sim 10^7$ K near the BH, the matter is in a plasma state, radiating as a black body.

It is not clear which physical processes are responsible for the viscosity. One possibility is turbulence, but since hydrodynamic instabilities are not sufficient (Balbus & Hawley 1998), it seems more likely the turbulence is supported by magnetic fields (McKinney & Gammie 2002) via the magnetorotational instability (Balbus & Hawley 1991). When a field line threading the disc develops a small radial kink, the field line will be stretched due to the differential rotation. This causes the inner material to slow down, falling to a lower orbit, while the outer material is sped up, reaching a higher orbit. In this way angular momentum is exchanged between different annuli. Only if angular momentum can be transported outwards, can matter eventually fall into the BH.

The origin of the magnetic fields is a puzzle. Since BH do not have a material surface, they cannot support a magnetic field. While in theory a charged BH could solve this problem, the electric force would dominate the gravitational force, and they would preferentially accrete matter with opposite charge, becoming effectively neutral within a few light-crossing times. There are several other methods by which magnetic fields can appear in the disc. The accreting matter can drag weak magnetic fields with it into a smaller volume, which would increase the field strength. This initial magnetic field could be stretched azimuthally by the MRI (Balbus & Hawley 1991). Since the disc gas and the magnetic field remain in pressure balance, a strong magnetic field has a corresponding lower matter density, making it rise buoyantly (Parker 1966). This vertical movement strengthens the vertical field, which can then feed into the MRI (Tout & Pringle 1992). Yet by ignoring vertical gravity, Hawley et al. (1995) also found some dynamo effects, without the Parker instability. While progress is being made (Johansen & Levin 2008), it is clear that exactly how magnetic
fields are generated is still one of the main issues in accretion physics.

Close to the BH there are no stable orbits, so the thin disc has to terminate. This happens at the innermost stable circular orbit (ISCO), which is located at $r_{\text{ISCO}} = 6 \, r_g$ for a Schwarzschild BH with an event horizon $r_S = 2 \, r_g$, and coincides with the event horizon of a maximally-rotating (or extreme) Kerr BH $r_{\text{ISCO}} = r_K = r_g$. When the matter reaches the ISCO, it will have radiated $0.057 \, mc^2$ for a Schwarzschild BH and $0.42 \, mc^2$ for an extreme Kerr BH. The potential energy liberated by viscous processes is radiated locally as a black body, but since the temperature of the plasma increases as the matter gets closer to the BH, instead of a single black body spectrum, the disc radiates as a superposition of many black bodies of different temperature. The standard multi-colour disc (MCD) model used for this does not take the torque-free boundary at the ISCO into account and therefore emits too much radiation there (Gierliński et al. 1999). Magnetic fields can couple the disc to a Kerr BH, extracting rotational energy, which can also significantly change the spectrum of the inner accretion disc (Wilms et al. 2001).

The above is a description of the high/soft state, which has a dominant thermal component in its spectrum believed to come from the disc, and occurs at high sub-Eddington accretion rates. In contrast, the low/hard state occurs at lower accretion rates, and is dominated by a non-thermal power-law component. One possible source for this component is the inverse Compton process. Low-energy seed photons, either from the disc or the jet, can gain energy from collisions with hot electrons in a corona surrounding the disc. This process causes a hump at higher energies, which can resemble a power law. Another source could be emission from the jet.

For sources at very low accretion rates, the accretion rate determined from the spectrum by assuming an MCD is much lower for the inner disc than the outer disc (McClintock et al. 1995). While originally explained by matter piling up due to a disc instability, later it was noticed a more realistic solution was supposing the thin disc is truncated before the ISCO (Narayan et al. 1996), with the interior being filled by an advection-dominated accretion flow or ADAF (Narayan & Yi 1994, 1995b). This ADAF radiates away only a fraction of the available gravitational energy, with the remainder being advected into the BH, alleviating the very strict upper limits on the accretion rate from the spectrum. Since the flow is not cooled radiatively, the electron temperature can reach $10^9 \text{--} 10^{10} \, K$, which causes a puffed up, possibly nearly spherical, flow geometry (Narayan & Yi 1995a). ADAFs have been used to fit both stellar mass BHs (Narayan et al. 1996) and LLAGN (Narayan et al. 1995; Lasota et al. 1996).

Extensions to the original ADAF model include the advection-dominated inflow-outflow solutions (ADIOS), where the energy stored in the flow is used to drive away part of the accreting matter in the form of a wind (Blandford & Begelman 1999),
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Quiescent State
Low State
Intermediate State
High State
Very High State

Figure 1.6: Schematic of the thin disc (horizontal bars) and ADAF (dots) in different accretion states as a function of the Eddington-scaled mass accretion rate \( \dot{m} \). Although the very high state is shown, it is not part of the unification scheme (Esin et al. 1997).

the convection-dominated accretion flow (CDAF), where the flow becomes convectively unstable due to a low viscosity (Igumenshchev & Abramowicz 1999; Narayan et al. 2000; Quataert & Gruzinov 2000), and the magnetically-dominated accretion flow (MDAF), which is situated within an ADAF and is supported by well-ordered magnetic field (Meier 2005). Collectively these models are known as radiatively inefficient accretion flows (RIAFs).

One possible picture of how the disc relates to the accretion states has been sketched by Esin et al. (1997, see figure 1.6). At very low accretion rates, the disc is truncated at a large radius and the ADAF has a low density. As the accretion rate increases, the density of the ADAF first increases as well, but then, as the disc starts to move inwards to the ISCO, decreases again. While successful in describing the spectral evolution of BHXRBs, the model does not unify the very high state, explain flaring events, or describe in detail the transition from a cold disc to a hot ADAF. It is also clear the different accretion states depend on more parameters than only the
accretion rate.

It is possible to avoid the requirement of RIAFs altogether. Merloni & Fabian (2001) showed that the corona has to be strongly magnetised in order to explain the observed hard X-ray, and acts as a magnetic reservoir intimately connected to the accretion disc. This reservoir contains enough energy to power the high-energy emission. This hot, magnetically-dominated corona is an ideal site for launching jets, which, if radiatively inefficient, would make the source overall radiatively inefficient, without the need for a RIAF (Merloni & Fabian 2002).

1.5 Jets

Astrophysical jets are collimated outflows with a roughly helical magnetic field structure. These jets have been observed around as varied objects as young stellar objects, white dwarfs, neutron stars, and black holes (BHs), and they are thought to play a key role in the most energetic events of our Universe, the gamma-ray bursts. While formed in very different environments, it is believed jets need three basic ingredients: a source of power (either matter accreting onto a compact object, or the spinning object itself), rotation, and magnetic fields. Because they transfer matter from close to the BH to potentially large radii, jets can be an efficient method of transporting angular momentum, diminishing the need for viscous processes in the accretion disc. They also deposit a large amount of energy and momentum in the ambient medium, heating and displacing it. In the case of AGN, this can affect the evolution of their host galaxy (e.g. Best et al. 2006).

The matter content of jets is still mostly unknown. It is possible they consist of electron/positron pairs, a proton/electron mix, or a combination of the two. It seems clear, however, that the electrons (and possibly positrons) are responsible for most of the radiation, through the synchrotron process, where relativistic electrons circle around field lines emitting polarised radiation, and the inverse-Compton process, where photons gain energy through elastic collisions with high-energy electrons.

1.5.1 Observations of jets

Regardless of the size of the compact object, many jets can accelerate particles to highly relativistic speeds. The Lorentz factors of AGN jets are found to be usually $\lesssim 10$, although some rare sources may go up to 50 (Lister et al. 2009). For BHXRBs the typical jet Lorentz factors are $\lesssim 2$, with GRS 1915+105 seemingly occasionally reaching up to 5 (Mirabel & Rodríguez 1999).

It is not yet clear whether the spin of the BH has an effect on the jet power. For AGN it is a theoretical possibility with some observational justification (Garofalo et al. 2010). For BHXRBs the observational evidence is far less certain. Fender et al.
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(2010) posit no clear relation between these two quantities exists, while Narayan & McClintock (2012) claim there is one. The latter authors argue that in the hard state the steady jet is produced sufficiently far away from the BH that its spin has no appreciable effect. Conversely, during the transition from the hard to the soft state the inner edge of the accretion disc reaches the ISCO, resulting in a shock or other instability intermittently launching blobs of plasma at higher relativistic velocities (Fender et al. 2004). Since the radius of the ISCO depends on the spin of the BH, this would explain a correlation between spin and jet power. However, with the current issues of reliably determining the spin, the lack of a consistent definition of the jet power, and only four objects plus one lower limit, it seems too early to assert its validity. But if the relation is confirmed, it would provide a valuable method to ascertain one of the most difficult parameters from the broadband spectrum.

The observational characteristic of jets is the synchrotron emission, observed in both AGN (Marscher & Gear 1985) and BHXRBs (Fender 2002). This emission is produced by relativistic electrons rotating around the magnetic field lines. The emission we observe is usually appreciably polarised, suggesting the magnetic field lines are well-ordered. The resulting spectrum depends on the underlying electron energy distribution. For a thermal distribution, expected at the base of the jet, the spectrum has an exponential cutoff at high frequencies. A flat or slightly inverted radio spectrum is seen in the hard state in BHXRBs (Fender 2001), as well as in LLAGN (Ho 1999). This can be interpreted as a superposition of synchrotron spectra from a population of electron with a power-law energy distribution \( dn = N_0 E^{-\gamma} dE \) (Blandford & Konigl 1979). With this distribution the spectrum at a location in the jet with a certain density is \( F_\nu \propto \nu^{5/2} \) for frequencies \( \nu \) where the jet is optically thick, and \( F_\nu \propto \nu^{-(p-1)/2} \) for frequencies where the jet is optically thin. Since the density and magnetic field strength of the jet decrease outwards, also the peak of the spectrum and the total power decrease. All these synchrotron components along the jet add up to a nearly flat radio spectrum (see figure 1.7).

This flat spectrum extends to the frequency corresponding to the peak of the population of electrons with a power-law energy distribution closest to the BH. Beyond this frequency the spectrum falls as the above mentioned \( F_\nu \propto \nu^{-(p-1)/2} \). In AGN jets this break typically occurs in the GHz range (Ho 1999), and for BHXRBs this break is predicted to occur in the infrared (Markoff et al. 2001, 2003; Heinz & Sunyaev 2003). The observed slope of the optically thin component corresponds to a power-law index \( p \sim 2 \)–\( 2.6 \), which means, depending on the exact break frequency, the optically thin tail of this component can extend well into the X-rays. If the acceleration region is located rather close to the BH, the optically thin tail can be the dominant contribution in the X-ray, diminishing or removing the need for an inverse-Compton, or disc component. Determining the break frequency can thus tell us which process provides
Figure 1.7: Schematic synchrotron spectrum. The synchrotron components (green) add up to a flat spectrum with a high-energy turnover (red). The slopes of the synchrotron components are also indicated.

the X-ray flux, and consequently what the conditions in the jet and corona are. A picture is evolving that in the hard state, at low accretion rates, the X-ray emission is predominantly optically thin synchrotron from the jet, while at higher accretion rates, in the soft state, emission from the inner accretion disc is the main contributor. However, this view has to be corroborated by different approaches.

Although for BHXRBs the band where the break occurs, is usually dominated by the spectrum of a stellar companion or the accretion disc, the break has been observed in GX 339-4 during the hard state (see figure 1.8; Corbel & Fender 2002; Gandhi et al. 2011). It corresponds to the region in the jet where electrons first get accelerated from a thermal into a power-law energy distribution, with a higher break frequency indicating a region closer to the BH. From fitting multiple spectra of BHBs and AGN this region seems to be offset from the BH, with the height in the range of $\sim 10-1000 r_g$, where $r_g$ is the gravitational radius, $GM/c^2$, with $G$ the gravitational constant, $M$ the mass of the BH, and $c$ the velocity of light (Markoff et al. 2001, 2003, 2005; Migliari et al. 2007; Gallo et al. 2007; Markoff et al. 2008; Maitra et al. 2009a).

This height should also cause the synchrotron radio core to be offset from the BH in direct imaging. Although the required spatial resolution is very high, for nearby
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Figure 1.8: Broadband radio–X-ray spectrum of two hard states in GX 339-4 observed in 1981 (filled symbols) and 1997 (open symbols). The long-dashed and short-dashed lines correspond to the optically-thick and optically thin regime, respectively, with spectral indices $+0.15$ and $-0.6$ for 1981 and $+0.08$ and $-0.65$ for 1997. Since an extrapolation of the X-rays intersects the near-infrared data with a slope compatible with optically thin synchrotron, it is very possible the X-rays are emitted by the jet. This interpretation is corroborated by the fact the whole spectrum is lower by a factor of four in the 1997 data, suggesting a common physical origin for all three bands. The optical data of 1981 are consistent with thermal emission, presumably from an accretion disc. Taken from Corbel & Fender (2002).

This would be possible. Indeed in M87, an AGN with a large angular diameter at a distance of $17.0 \pm 0.3$ Mpc (Tonry et al. 2001) with a large SMBH of $6.4 \pm 0.5 \times 10^9 M_\odot$ (Gebhardt & Thomas 2009, although note this value is twice the mass found in previous studies), the offset seems to be $\sim 100 r_g$ (Junor et al. 1999; Walker et al. 2008), in line with the values found for other sources. The offset of the radio core with respect to the BH has been extremely stable over the last years (Asada et al. 2011).

1.5.2 Theoretical models of jets

Since the exact formation of jets is still unclear, several models have been proposed that provide the energy in different ways. The Blandford-Znajek model (Blandford
& Znajek 1977) describes field lines threading a spinning BH, extracting rotational energy to power a magnetically dominated jet populated with pair-produced electrons and positrons. The Blandford-Payne model (Blandford & Payne 1982) on the other hand, has the jet anchored in the accretion disc, with the rotation providing a centrifugal force accelerating the matter along the field lines. A later extension to the Blandford-Payne model describes a relativistic jet where the initial acceleration is provided by the thermal energy of the matter, which is later taken over by magnetic acceleration (Vlahakis & Königl 2003a). It is possible both types exist simultaneously in the same source, with the Blandford-Znajek jet forming the spine, and a Blandford-Payne jet surrounding it as a sheath. For an overview of the development of jet models, we refer the reader to chapter 2.

The fundamental plane of black hole accretion, mentioned above, is a natural consequence if accretion processes and jets scale with the gravitational radius, the fundamental length in the system (Falcke & Biermann 1995; Markoff et al. 2003; Heinz & Sunyaev 2003). Here we will summarise the derivation of this relation given by Heinz & Sunyaev (2003). If jet and accretion processes are indeed scale free, we can separate variables in mass and radius and write all dynamically relevant quantities as

\[ f(M, \dot{m}, a, r) = \phi_f(M, \dot{m}, a) \psi_f(r/r_g, \dot{m}, a), \]

where \( \dot{m} \) is the Eddington-scaled accretion rate, and \( a \) is the spin of the BH. We observe jets in the hard state, which is well described by a Shakura-Sunyaev disc, with \( B \propto M^{-1/2} \). The jet emits synchrotron radiation from a power-law distribution of electrons: \( dN \propto N_0 E^{-p} dE \), with \( p \) the power-law index, which observations tell us is close to \( p = 2 \). Assuming equipartition gives us \( N_0 \propto B^2 \propto M^{-1} \). As there is not too much difference between the Lorentz factors of BHXRBs and AGN, we assume there is no mass dependence, which allows us to combine the dependence on viewing angle due to Doppler beaming and optical depth effects into a function \( \zeta(\theta) \) independent of mass. Next we calculate the surface integral over the jet surface brightness \( S_\nu \sim \zeta(\theta) j_\nu (1 - e^{-\tau_\nu})/\alpha_\nu \), where \( j_\nu \) is the synchrotron emissivity, \( \tau_\nu \) is the optical depth, and \( \alpha_\nu \) is the synchrotron self-absorption coefficient. We define the spectral index \( \alpha \equiv -\partial \log(F_\nu)/\partial \log(\nu) \). Now we can obtain an expression for

\[ \frac{\partial \log(F_\nu)}{\partial \log(M)} \equiv \xi_M \]

by substituting in \( \alpha \) and using the dependencies of \( B \) and \( N_0 \) on \( M \):

\[ \xi_M = \frac{2p + 13 + 2\alpha}{p + 4} + \frac{\partial \log(\phi_B)}{\partial \log(M)} \left( \frac{2p + 3 + \alpha(p + 2)}{p + 4} \right) \]

\[ + \frac{\partial \log(N_0)}{\partial \log(M)} \left( \frac{5 + 2\alpha}{p + 4} \right) \approx \frac{17}{12} - \frac{\alpha}{3}, \]

for our assumed values. This equation represents the exponent of the relation between the jet radio emission and the BH mass. Following the same steps, we can derive
an equation for the exponent of the relation between the jet radio emission and the accretion rate:

$$\xi_m = \frac{\partial \log(\phi_B)}{\partial \log(\dot{m})} \left[ \frac{2p + 3 + \alpha(p + 2)}{p + 4} \right] + \frac{\partial \log(\phi_{N_0})}{\partial \log(\dot{m})} \left( \frac{5 + 2\alpha}{p + 4} \right) \approx \frac{17}{12} - \frac{\alpha}{3}, \quad (1.2)$$

for ADAF-type accretion with $N_0 \propto B^2 \propto \dot{m}$. Now following Markoff et al. (2003), we can use the equations:

$$\log L_R = \xi_M \log M + \xi_m \log \dot{m} + K_1, \quad (1.3)$$

$$\log L_X = \log M + q \log \dot{m} + K_2, \quad (1.4)$$

to cast everything into the form:

$$\log L_R = \xi_{RX} \log L_R + \xi_{RM} \log M_{BH} + b_R, \quad (1.5)$$

$$\log L_X = \xi_{XR} \log L_R + \xi_{XM} \log M_{BH} + b_X. \quad (1.6)$$

If we assume a flat radio spectrum ($\alpha = 0$), and $q \approx 2$, close to an ADAF, we obtain:

$$\xi_{RX} = \frac{\xi_m}{q} \approx 0.71, \quad (1.7)$$

$$\xi_{RM} = \xi_M - \frac{\xi_m}{q} \approx 0.71, \quad (1.8)$$

$$\xi_{XR} = \frac{\xi}{\xi_m} \approx 1.4, \quad (1.9)$$

$$\xi_{XM} = 1 - \frac{q}{\xi_m} \xi_M \approx -1. \quad (1.10)$$

not too far off the observed values. The strength of this analysis is that it is independent of the assumed jet model. By observing the different sources, we can determine the exponents of the fundamental plane correlation, as well as $\alpha$ and $p$, and in turn determine the dependence of the magnetic field and power-law distribution on the mass and accretion rate, and by constraining $q$, whether it is radiation or gas pressure supporting the disc, or if it is actually an ADAF. In this way the fundamental plane provides a very strong check on the origin of the radiation.

### 1.6 Spectral fitting

A spectral fitting code was developed to test the hypothesis that the hot magnetised corona could be the base of the jet, also called the jet-disc symbiosis. This program describes a standard thin, optically thick accretion disc (Shakura & Sunyaev 1973), that truncates at a certain radius and turns into a hot, radiative-inefficient accretion
1.6 Spectral fitting

flow (e.g., Esin et al. 1997). The disc radiates as a multi-temperature black body, contributing to the infrared through ultraviolet, depending on the size and temperature of the disc. A certain fraction of the accretion energy is powering the jet, shared between the magnetic field and the bulk kinetic energy of the particles with a certain ratio, with the protons carrying the kinetic energy and the electrons causing thermal synchrotron and inverse Comptonisation of disc and jet photons. The jet then exits a nozzle with the proper sound speed \( \gamma_\beta c \approx 0.4c \) for a hot electron/proton plasma and expands at the same rate. As the jet expands, it cools adiabatically, causing a thermal pressure, which accelerates the jet. This weak acceleration provides the only collimation. At a certain height, the particles, which are assumed to have a quasi-thermal distribution, are accelerated into a power-law distribution, changing the local synchrotron spectrum. These synchrotron components add up along the jet to form a flat (Blandford & Königl 1979), or slightly inverted spectrum, covering the radio to possibly the X-ray, depending on the height of the acceleration region. The particles have to be continuously accelerated beyond the start of the acceleration region, since otherwise the radiative losses would quickly cool down the electrons again, contrary to observation. For an XRB there can be an additional companion star radiating as a black body, while for an AGN there can be an additional iron line. The total spectrum is thus built up from a multi-temperature black body, a pre-shock and post-shock synchrotron component, an inverse Compton component and an optional black body. An irradiated disc component has also been added (Maitra et al. 2009a). By fitting the spectrum of an observed source, parameters such as the inner radius and temperature of the accretion disc can be determined.

This code has been expanded and refined over the years (Falcke & Biermann 1995; Falcke 1996; Falcke & Markoff 2000; Markoff et al. 2001, 2003, 2005, 2008; Maitra et al. 2009a), and has been used to model both AGN (Falcke 1996; Falcke & Markoff 2000; Markoff et al. 2008; Maitra et al. 2009b, 2011) and XRBs (Markoff et al. 2001, 2003, 2005; Maitra et al. 2009a). With the exception of Sgr A*, in all these sources there is a remarkable similarity in fitted parameters, with for example the height of the acceleration region lying in the narrow range of \( 10r_g - 400r_g \) (Markoff et al. 2008; Maitra et al. 2011).

However, since it is built upon an HD model (Falcke & Biermann 1995; Falcke & Markoff 2000), the magnetic field simply enters as a global parameter, serving to guide the flow and enable synchrotron radiation, but not to accelerate and collimate the material. Due to its HD nature, the model has merely weak longitudinal acceleration due to thermal pressure and can therefore only describe systems where the jets are neither highly accelerated, nor highly collimated.

Incorporating an MHD model has several advantages. First, the model will treat the magnetic fields in a self-consistent way, with the fields providing the acceleration
and geometry of the jet. Second, the model will be suited to a wide range of environments, where either the velocity, the magnetic field, the gravitational potential, or all can attain relativistic energies. This inclusion will therefore allow the code to be applied to an even greater variety of sources of both mass scales, and help shed light on the mapping of the BHXRB states to the AGN classes. Since discs provide the boundary conditions for a jet, and our model relates those conditions near the BH to those far away in the jet, by observing the properties of jets in actual BHXRBs, we will be able to constrain certain disc models. Third, it will allow us to independently calculate the power of the jets, which is an essential parameter for AGN feedback models. Fourth, the height of the acceleration region becomes a derived quantity and is removed as a free parameter.

A natural way to accelerate particles into a power-law distribution is via diffusive shock acceleration (e.g. Bell 1978; Drury 1983). Since the highly energetic electrons cool very fast via radiative losses, this shock acceleration must happen everywhere beyond this acceleration point, since we do not observe a decaying power-law distribution anywhere along the jets (e.g. Jester et al. 2001). Since the particles should be accelerated continuously, this shock should be a steady feature within the jet.

Since the height where acceleration starts seems to be relatively similar in several systems, it may be possible to identify this location with a critical point in a magnetohydrodynamical (MHD) flow, especially the magnetosonic modified fast point (MFP) (Blandford & Payne 1982). At the MFP the jet begins to overcollimate, meaning the jet radius decreases again, which could cause recollimation shocks. Another feature of the MFP is that it is the place where the outward flowing jet becomes causally disconnected from the upstream flow, so shocks can occur without disrupting the flow upstream. Such shocks thus could be a stable feature in the jet, continuously accelerating the particles into a power-law distribution. Since the shock is tied to the location of the MFP, we will identify the MFP as the start of the particle acceleration region.

1.7 This thesis

The goal of the research in this thesis is to develop a relativistic jet acceleration model that includes gravity. This jet model can then be used to determine the location of the start of the acceleration region, identified with the height of the MFP, and relate this height to the conditions close to the BH. We want to cross all three singular points in order to have the most reliable physical link between the observed regions and the jet region near the BH. This jet model can then be used to determine physical parameters of black hole systems, based on their broadband spectra.

In the next chapter we give a historical introduction to the field of outflow models, explain the nomenclature used throughout this thesis, as well as an overview of the
steps taken to derive the jet model.

In chapter 3 we present, for the first time, solutions to the relativistic MHD equations that cross the MFP.

In chapter 4 we describe how we include the gravitational force due to kinetic inertia of the plasma into the model. This addition allowed us to find solutions crossing all three singular points. We also show how the properties of the solutions depend on the parameters chosen.

Chapter 5 gives the extension of the model including the gravitational force due to the full relativistic inertia (kinetic, thermal, and electromagnetic), as well as a parameter study of the models.

In chapter 6 we will discuss our results and present our conclusions.