Relativistic jets from stellar black holes

Gallo, E.

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CHAPTER 1

BLACK HOLES IN THE GALAXY

1.1 Gravity and black holes

The gravity of a celestial body is essentially a measure of how fast a rocket must be fired in order to escape the body’s attraction. Nowhere gravity is stronger than near the objects we call ‘black holes’: regions in space where the pull of gravity is so strong, that not even light can escape. Therefore, a black hole can never be observed directly; rather, its presence can be inferred by the effects of its gravitational field on nearby objects, during the collapse while it was forming, or by the light emitted by rapidly swirling matter being pulled into the black hole.

1.1.1 Conceiving black holes

The concept of a body so massive that not even light could escape from it is more than 200 years old; it was first put forward by the English geologist J. Michell, in 1783. He computed that a body 500 times the radius of the Sun and of the same density would have at its surface an escape velocity equal to the speed of light. In 1915 Einstein developed the theory of general relativity; whereas Newton described gravity as a force transmitted between bodies, Einstein postulated that gravitational fields are manifestations of the curvature of ‘space-time’ itself. Masses do not ‘exert’ gravitational pull; rather, their presence distorts space and time around them. A few months later K. Schwarzschild gave the solution for the gravitational field of a point mass, showing that something we now call a black hole could theoretically exist. The Schwarzschild radius is now known to be the characteristic horizon radius (see below) of a non-rotating black hole. In the 1920s, Chandrasekhar argued that special relativity demonstrated that a non-radiating body above a certain mass, now known as the Chandrasekhar limit, would collapse since there would be nothing that could stop the collapse. Black holes could in principle be formed in nature. Such objects for a while were called frozen stars since the collapse would be observed to rapidly slow down and become heavily red-shifted near the Schwarzschild radius. However,
these hypothetical objects were not the topic of much theoretical interest until the 1960s, thanks to the discovery of quasars and of the first pulsar. Shortly thereafter, the expression ‘black hole’ was coined by theoretical physicist J. Wheeler.

General relativity not only says that black holes can exist, but does predict that they will be formed whenever a sufficient amount of mass gets packed in a given region of space, for instance through gravitational collapse. As the mass inside that region increases, its gravity becomes stronger, the space around it becomes increasingly deformed. When the escape velocity at a certain distance from the centre reaches the speed of light, an ‘event horizon’ is formed within which matter must inevitably collapse onto a single point, forming a singularity. A quantitative analysis of this idea led to the prediction that a star remaining about three times the mass of the Sun at the end of its evolution, will almost inevitably shrink to the critical size needed to undergo a gravitational collapse. Once it starts, the collapse cannot be stopped by any physical force, and a black hole is formed. Smaller black holes can only be created if the matter is subjected to sufficient pressure from some source other than self-gravitation. Such enormous pressures are thought to have existed in the very early stages of the universe, possibly creating primordial black holes with masses smaller than that of the Sun.

According to theory, the event horizon of a black hole that is not spinning is spherical; if the black hole carries angular momentum (‘Kerr black hole’), it begins to drag space-time surrounding the event horizon. Objects can exist within this spinning ‘ergosphere’ without inevitably falling into the hole. However, because space-time itself is moving in the ergosphere, it is impossible for objects to remain in a fixed position with respect to distant flat space time. Objects grazing the ergosphere could even be ejected outwards extracting energy and angular momentum from the black hole. Supermassive black holes containing millions to billions of solar masses could also form wherever a large number of stars are packed in a relatively small region of space, or by large amounts of mass falling into a ‘seed’ black hole, or by repeated fusion of smaller black holes. The necessary conditions are believed to exist in the centres of some – probably all – galaxies. Sagittarius A* is now agreed to be the most plausible candidate for the location of a supermassive black hole at the centre of our own Galaxy, with a mass of about 3 million of solar masses.

Figure 1.1: Artistic impression of a black hole X-ray binary system undergoing Roche lobe overflow. The Roche lobe is the region around a star in a binary system within which orbiting material is gravitationally bound to that star. If the star expands past its Roche lobe, then the material outside of the lobe will fall into the other star. Thus an accretion stream is created for significant mass to flow out toward the black hole for accretion. In the case of Roche-lobe overflow, the angular momentum of the accreting material will cause it to form a differentially rotating disc. Due to friction the material in this accretion disc then spirals towards the gravitational well of the black hole, heating up the inner disc to temperatures over $10^6$ K (more precisely the inner disc temperature depends upon the black hole mass and the rate at which the matter accretes).

1.1.2 Observing black holes

Black holes can be inferred by observations of phenomena occurring near them. Probably the most prolific effect is that of accretion, i.e. the extraction of gravitational potential energy of the matter falling into the event horizon. The importance of accretion as a source of power was first recognized in the study of Galactic X-ray binary systems: a subclass of binary star systems made up of a normal star and a collapsed object, a black hole in the case of black hole X-ray binaries (BHXBs hereafter).

At some stage of their evolutionary lifetime, binary systems may start to
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transfer matter under two main circumstances: i) one of the stars can increase its radius, or the binary separation shrinks, to the point where the gravitational pull of the companion can remove outer layers of its envelope; ii) at some phase one of the stars may eject much of its mass in the form of a wind, some of which will be captured gravitationally by the companion. The former case is known as Roche lobe overflow (depicted in Figure 1.1), the latter as stellar wind accretion (see Tauris & van den Heuvel, 2005, for a review on formation and evolution of stellar X-ray sources).

In the case of BHXBs, when matter starts to be transferred from the evolved star which filled its Roche lobe towards the black hole, it has rather high specific angular momentum and can not accrete directly. A continuous stream of gas tends to the orbit of lowest energy for a given angular momentum, i.e. a circular orbit. In order to fall into the gravitational potential well, such ring of gas has to loose angular momentum. Dissipative processes must be taking place (shocks, viscous dissipation, collisions etc.), which will convert some of the kinetic energy of the bulk orbital motion into internal energy, i.e. heat. Eventually, some of this energy is radiated and thus lost to the gas. As a consequence, the gas sinks deeper into the gravitational potential of the black hole, orbiting more closely. Material flowing from the companion star piles up in a dense disc orbiting the black hole: an accretion disc is formed (see Frank, King & Raine 2002 and references therein).

Until the early ‘90s, there was no clear candidate for the actual angular momentum transport mechanism in accretion discs, since e.g. normal atomic viscosity turns out to be orders of magnitude too small to drive the accretion-powered X-ray emission. Balbus & Hawley (1991; 1998) showed that the combination of a weak magnetic field and outwardly decreasing differential rotation rapidly generates magneto-hydrodynamic (MHD) turbulence via a linear instability. The result is a greatly enhanced effective viscosity. It is now widely accepted that this instability, known as the magneto-rotational instability (MRI), is responsible for the angular momentum transport in the inner regions of accretion discs.

For accretion-powered sources with a hard surface (as neutron stars) all the kinetic energy of the infalling matter is converted into radiation at the stellar surface. The maximum Newtonian value of the accretion luminosity of a body of mass $M$ and radius $R_*$ that accretes mass at a rate $\dot{M}$ is given by: $L = G M \dot{M} / R_*$ (where $G$ is the gravitational constant). For the case of accretion on to a black hole, with no hard surface, much of the accretion energy could disappear into the horizon, simply adding to its mass, rather than being radiated. This uncertainty can be parametrized by an efficiency $\eta$, such that the accretion luminos-
ity of a black hole can be expressed as $L_{\text{acc}} = \eta M c^2$, substituting $2GM/c^2$ (the Schwarzschild radius) for $R_s$. In principle, accretion on to a black hole can be extremely efficient, converting up to 40 per cent of the mass energy of the infalling matter into radiation ($\eta \approx 0.42$ for a maximally rotating Kerr black hole). For comparison, $\eta = 0.007$ for nuclear burning. As noted by Frank, King & Raine (2002): ‘For the nineteenth century physicists, gravity was the only conceivable source of energy in celestial bodies, but gravity was inadequate to power the Sun for its known lifetime. In contrast, at the beginning of the twenty-first century it is to gravity that we look at to power the most luminous objects in the Universe, for which the nuclear sources of the stars are wholly inadequate.’

For radiatively efficient accretion discs, the luminosity is characterized – and in general limited – by the so-called Eddington luminosity: the luminosity at which the radiative momentum flux from a spherically symmetric source is balanced by the gravitational force of the accreting object: $L_{\text{Edd}} \approx 1.38 \times 10^{38}$ erg s$^{-1}$ per solar mass of the accretor. Correspondingly, the Eddington mass accretion rate can be defined as: $\dot{m}_{\text{Edd}} = L_{\text{Edd}}/c^2$.

In order to estimate the characteristic temperature of the radiated energy, we can define a blackbody temperature $T_b$ as the temperature an accretion-powered source would have if it radiated the given power as a black-body spectrum, and a thermal temperature $T_{\text{th}}$ that the accreted material would reach if its gravitational potential energy were converted entirely into heat. In general the radiation temperature $T_{\text{rad}}$ can be expected to vary in the range $T_b \lesssim T_{\text{rad}} \lesssim T_{\text{th}}$. As a result of accretion on to stellar mass black holes the upper limit gives $T_{\text{th}} \approx 5 \times 10^{11}$ K, or, in terms of energies, $kT_{\text{th}} \approx 50$ MeV (being $k$ the Boltzmann constant). The lower limit (only weakly dependent upon $L_{\text{acc}}$) gives $T_b \approx 10^7$ K, or $kT_b \approx 1$ keV. Thus accreting stellar black holes are expected to be medium to hard X-ray emitters (and possibly $\gamma$-ray sources). Such compact X-ray sources were indeed discovered by the first satellite X-ray experiments, and added to by subsequent investigations.

At the time of writing, 18 black hole X-ray binaries have been identified in the Local Group (Milky Way and Magellanic Clouds), and 22 black hole candidates – for which the nature of the accretor is still uncertain – are awaiting confirmation (McClintock & Remillard 2005). These black holes are the most visible representatives of an estimated 300 million stellar mass black holes that are believed to exist in our own galaxy (van den Heuvel 1992; Brown & Bethe 1994; Timmes et al. 1996; Agol et al. 2002). Thus the mass of this particular form of collapsed matter is about 5 per cent of the total baryonic mass of the Milky Way (Bahcall 1986; Bronfman et al. 1988).
1.2 X-ray states of black hole X-ray binaries

The spectral-energy distribution (SED) of the gravitational power released as electromagnetic radiation when matter accretes onto a black hole is far from universal. Different accretion modes are possible, and often the same initial conditions at the outer boundaries admit more than one stationary solution for the accretion flow configuration at the inner boundary, with often very different radiative properties. The main goal of accretion flow theory is to understand and distinguish all the possible different modes of accretion, and classify the different observations in terms of such modes.

The energy spectra of BHXBs at energies greater than 10 keV are roughly described by a power law, which may or may not have a detectable high-energy cutoff. The slope of this power-law is characterized by the photon index, $\Gamma$, where the photon number flux per unit energy (photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) is $F_N(E) \propto E^{-\Gamma}$, where $E$ is the photon energy. The Fourier power spectra of the X-ray light curves provide an estimate of the variance as a function of Fourier frequency $\nu$ (typically in the range mHz-kHz) in terms of the power density $P_\nu(\nu)$ (see van der Klis 2005 and references therein). Broad – and hence aperiodic – structures in the power spectra are referred to as ‘noise’ while narrow features are called ‘quasi-periodic oscillations’ (QPOs).

Different X-ray states are distinguished based upon the properties of the power (strength of the noise, presence or absence of peculiar QPOs) and energy spectra (broadband luminosity, relative contribution to the X-ray luminosity of the hard power-law component with respect to a 'soft', quasi-thermal component which peaks around 1 keV). At luminosities close to the Eddington one, BHXBs are often in the very high state, where both of the two components contribute substantially to the SED. At slightly-lower luminosities, the quasi-thermal component dominates and the power-law is usually steeper ($\Gamma > 2$) and extended to the $\gamma$-ray band. This state is traditionally termed high/soft. At even lower luminosities the spectra are completely dominated by a hard power-law component (with $\Gamma \approx 1.7$), with the quasi-thermal component extremely weak or even absent: these are the so-called low/hard states. Sometimes, at luminosities intermediate between those of the soft and the hard states, an intermediate state is observed, with properties similar to those of the very high state. Below a few $10^{-5}$ Eddington, a quiescent state is identified, with properties similar to the low/hard state. In terms of power spectra, the low/hard, intermediate and very high state are generally characterized by the presence of strong band-limited noise (i.e. that steepens towards higher frequencies) and a hard power-law component in the power spectra, whereas the high/soft state is characterized by these features.
Figure 1.2: X-ray states of black hole X-ray binaries: broadly speaking, different X-ray states are distinguished based upon the integrated X-ray luminosity, the relative contribution of a ‘soft’, quasi-thermal and a ‘hard’, power-law-like spectral component, and timing properties. It is often the case that the same source, either persistent or transient, undergoes a transition between spectral states, and therefore between accretion modes. This is the case for the black hole binary XTE J1550-564 shown in this plot, where we can distinguish a low/hard state, peaking at 100 keV, and a variety of high mass accretion rate spectra, all of which peak around 1 keV: there a high/soft state (disc sharply peaking at 1 keV), an ‘ultra-soft’ high/soft state (disc showing a rounded peak at 1 keV) and two very high states (strongly Comptonized disc, giving a smooth, steep spectrum). From Done (2002).

It is often the case that the same source, either persistent or transient, undergoes a transition between spectral states, and therefore between accretion modes (see Figure 1.2). There are a number of reviews (with author-dependent jargon) describing in detail the properties of X-ray states of BHXBs. We refer to the reader to: Esin, McClintock & Narayan (1997); Done (2002); Homan et al. (2001); McClintock & Remillard (2005); Homan & Belloni (2005). In particular, McClintock & Remillard (2005) have recently introduced a new clas-
Figure 1.3: Sketch representing possible different accretion flow geometries over the different X-ray states (from Esin et al. 1997). It was generally believed that the main parameter driving the transition between states is disc accretion rate $\dot{m}$, here indicated in units of Eddington, even though it has been suggested that a second parameter may play a role (Miyamoto et al. 1995; Homan et al. 2001).

It is generally believed that the main parameter driving the transition between states is the instantaneous accretion rate $\dot{m}$ (see Figure 1.3) even though a second parameter may play a role (Miyamoto et al. 1995; Homan et al. 2001).
1.3 Accretion modes

The majority of spectral studies of BHXBs in the X-ray band suggest that the power-law continua of these sources are produced by thermal Comptonization (Shapiro et al. 1976; Sunyaev & Titarchuk 1980; Zdziarski 1999) in a hot, rarified electron corona, which probably resides where most of the accretion energy is released, namely in the inner part of the flow. Furthermore, there is evidence that this hot, Comptonizing medium strongly interacts with the colder thermal component: such an interaction is not only required to explain the ubiquitous reflection features in the X-ray spectra (Lightman & White 1988; Matt, Perola & Piro 1991; Fabian et al. 2000), but could also provide the feedback mechanism that forces the observed values of coronal temperature and optical depth to lie in very narrow range for all the different observed sources (Haardt & Maraschi 1991). The soft quasi-thermal component is instead associated with a geometrically thin, optically thick multi-temperature accretion disc (Shakura & Sunyaev 1973; Novikov & Thorne 1973; Lynden-Bell & Pringle 1974; Pringle 1981).

It is worth mentioning that the observed hard-X-ray power laws represent a signature of a physical process, more than of specific accretion dynamics. This is why, if there is little doubt that the standard thin accretion disc model accounts for the basic physical properties of black holes in their soft states, the accretion mode responsible for the low-luminosity hard/quiescent states is still a matter of debate. Radiatively inefficient accretion can take place at low accretion rates if the density of the accreting gas is low enough to inhibit the energy coupling between protons and electrons.

Since their rediscovery in recent years (Narayan & Yi 1994, 1995; Narayan, Mahadevan & Quataert 1998), radiatively inefficient accretion flows (RIAFs hereafter; Ichimaru 1977; Rees et al. 1982) have been regarded as natural solutions. The key feature of RIAF solutions is that the radiative efficiency of the accreting gas is low, so that the bulk of the viscously dissipated energy is stored in the protons as thermal energy. Low-density RIAFs only exist below a critical accretion rate (which scales as the second power of the viscosity parameter). Typically, $\dot{m}_{\text{crit}} < 10^{-2} - 10^{-1} \dot{m}_{\text{Edd}}$. The optically thin gas in the flow radiates with a spectrum that is very different from the blackbody-like spectrum of a thin disc; the electrons cool via synchrotron, bremsstrahlung, and inverse Compton processes, which are responsible for producing the entire spectrum, from the radio to hard X-rays.

More importantly, the luminosity of such flows has a steep dependence on the accretion rate. The efficiency with which thermal energy is transferred from ions to electrons (to be subsequently radiated) is proportional to $\dot{m}/\dot{m}_{\text{Edd}}$, and
\( L \propto (\dot{m}/\dot{m}_{\text{Edd}})^2 \). In contrast, the luminosity of a Shakura-Sunyaev disc varies as \( L \propto \dot{m}/\dot{m}_{\text{Edd}} \). The key difference is that whereas in a thin disc a large fraction of the released energy is radiated, in a RIAF nearly all the energy remains locked up in the gas as thermal energy. Advection dominated accretion flows (ADAFs) are popular analytical models for the dynamics of RIAFs. The structure of an ADAF is somewhat similar to the spherical Bondi accretion, despite the fact that angular momentum and viscosity are still important. ADAF solutions predict that a significant fraction of the energy stored in the protons is advected inward, and, in case of a black hole accretor, ‘disappears’ into the horizon. When tested against the best data for hard state BHXBs, though, as in the case of XTE J1118+480 (Esin et al. 2001) or Cygnus X-1 (Esin et al. 1998), ADAF models alone cannot work. A transition between an inner ADAF and an outer Shakura-Sunyaev disc is needed, as can also be inferred from studies of X-ray reflection components (Esin, McClintock & Narayan 1997; Done 2001).

There are concerns with the theoretical aspects of the aforementioned solutions, the main one being that part of the accreting gas is generically unbound and can escape freely to infinity. The reason is that the gas is likely to be supplied with sufficient angular momentum to orbit the hole and its inflow is controlled by the rate at which angular momentum is transported outward. This angular momentum transport is necessarily associated with a transport of energy. If one attempts to conserve mass, angular momentum and energy in the flow, it is found that the energy that the gas would have if it were allowed to expand adiabatically to infinity is twice the local kinetic energy.

Alternative models for the dynamics of RIAFs include e.g. convection dominated accretion flows (CDAFs, e.g. Quataert & Gruzinov 2000) and magnetically-dominated accretion flows (MDAFs; e.g. Meier 2004). In CDAFs, a significant fraction of binding energy, most of which is released in the innermost region of accretion flows, is transported outward by convection motions, whereas in MDAFs well-ordered magnetic fields play a more important role than weak, turbulent fields in the inner regions of the inflow.

Blandford & Begelman (1999) have proposed an alternative solution called adiabatic inflow outflow solution (ADIOS). Here the key notion is that the excess energy and angular momentum is lost to a wind at all radii. This mass loss makes the accretion rate on to the black hole much smaller than the rate at which mass is supplied at the outer radius. In this model the radial energy transport drives an outflow that carries away mass, angular momentum and energy, allowing the disc to remain bound to the hole. The final accretion rate into the hole may be only a tiny fraction (in extreme cases \(10^{-5}\)) of the mass supply at large radius. This leads to a much smaller luminosity than would be observed from a standard
accretion flow.

Another possible scenario for low-luminosity black holes is that proposed by Merloni & Fabian (2002), where strong, unbound, magnetic coronae are powered by thin discs at low accretion rates. These coronal-outflow-dominated solutions are both thermally and viscously stable, as in general are all standard Shakura-Sunyaev accretion disc solutions in the gas pressure dominated regime. However, rapid and dramatic variability in the observed high-energy flux is expected, as X-rays are produced by coronal structures that are the eventual outcome of the turbulent magnetic field generation inside the disc. The geometry of these structures (open vs. closed field lines, for example) plays a very important role and may be such that, at times, parts of the corona become temporarily radiatively efficient.

Radiatively inefficient accretion can also take place at very high accretion rates, comparable to those needed to produce super-Eddington luminosities. In this case, due to the high density, the dynamical timescale of the inflow becomes shorter than the radiative timescale, causing the photons to be trapped in the accretion flow (e.g. Begelman 1979). The inability of such discs to radiate the gravitational potential energy, together with the viscous transport of energy and strong radiation pressure, is likely to drive strong outflows. The appearance of such discs is highly uncertain – it is unclear whether an X-ray emitting corona forms, and whether the atmosphere of such a disc may be capable of producing X-ray reflection spectral signatures.

It remains to be seen which, if any, of these models comes closest to reproducing the observational characteristics of accretion on to black holes at different accretion rates.

1.4 Relativistic jets

Somewhat surprisingly, part of the matter which spirals in towards the black hole can be turned around and propelled outward, in the form of narrow bipolar streams of energy and particles flowing out of the system with relativistic velocities. The origin of these relativistic jets remains an unsolved astrophysical problem. The effects of relativistic aberration and beaming modify their observed appearance, particularly for jets directed along our line of sight, whose emission is greatly amplified. As jets travel away from the black hole, they may decelerate and form more extended structures or lobes. Jets and lobes contain ultra-relativistic electrons and magnetic field, and thus emit synchrotron and inverse Compton radiation. They are typically visible at radio wavelengths, but in some cases the spectrum of the emission extends into the
optical, X-ray and even $\gamma$-ray bands. Although there is a general consensus that the formation and initial collimation of jets requires magnetic fields, we still do not fully understand why certain sub-classes of object produce powerful jets whilst others do not. The composition of jets is also uncertain: relativistic electrons and magnetic field must be present, but it is unclear whether the positively-charged particles are protons or positrons; the composition may also evolve as jets propagate. The parameters which characterize the jet flows such as velocity, density, pressure and magnetic-field structure have proved to be difficult to determine. We refer the reader to e.g. Hughes (1991) and Guthmann et al. (2002) for reviews of astrophysical jets.

Several mechanisms for producing bipolar outflows have been suggested but none of these seems to be able to produce outflows approaching the highly-relativistic speeds inferred for the fastest jet sources. The currently-favoured mechanism is a magneto-hydrodynamical one, somewhat similar to terrestrial accelerators of particle beams. MHD jet production was first suggested in 1976 (Blandford 1976; Lovelace 1976) and has been applied to magnetized accretion discs and rotating black holes, as outlined in the following.

The Blandford-Payne model (BP; Blandford & Payne 1982) relies on extraction of angular momentum and rotational energy from an accretion disc, by magnetic field lines that leave the disc surface (magneto-centrifugal acceleration). A centrifugally driven outflow of matter is possible if the poloidal component of the magnetic field makes an angle of less than $60^\circ$ with the disc surface. At large distances from the disc, the toroidal component of the magnetic field collimates the outflow.

An outflow could also be extracted from the black hole magnetosphere through the Blandford-Znajek (BZ; Blandford & Znajek 1977) mechanism. First, the rotational energy of the black hole is extracted by large scale magnetic field lines which thread the horizon, and angular momentum is transferred along those field lines to the external plasma via magnetic tension. Such energy is then converted into Poynting flux and finally to relativistic electron/positron pairs.

Another type of (indirect) magnetic coupling is possible. This mechanism, suggested by Punsly & Coroniti (PC; 1990), has the same effect as the BZ mechanism but the field lines do not have to thread the horizon itself. Instead, they are anchored in the accreting plasma. When this plasma sinks into the ergosphere near the black hole, frame dragging causes the plasma to rotate with respect to the exterior, twisting up the field lines in a manner similar to the situation when the field is anchored in a disc.
The most important ingredient in the MHD mechanism is a magnetic field that is anchored in a rotating object and extends to large distances where the rotational speed of the field is considerably slower (see e.g. Meier, Koide & Uchida 2001; Koide et al. 2002 for reviews on MHD simulations of jet formation). Plasma trapped in the magnetic field lines is subject to the Lorentz ($\mathbf{J} \times \mathbf{B}$) force, which, under conditions of high conductivity (the MHD assumption), splits into two components: a magnetic pressure gradient ($-\nabla B^2/8\pi$) and a magnetic tension ($\mathbf{B} \cdot \nabla \mathbf{B}/4\pi$). Differential rotation between the inner and outer regions winds up the field, creating a strong toroidal component. The magnetic pressure gradient up the rotation axis accelerates plasma up and out of the system while the magnetic tension, or ‘hoop’ stress, pinches and collimates the outflow into a jet along the rotation axis (see Figure 1.4). This basic configuration of differential rotation and twisted magnetic field accelerating a collimated wind are thought to be achieved in relativistic jet sources.

**Figure 1.4:** An MHD simulation of a thick magnetized disc surrounding a black hole. (A) Initial state showing the disc in rotational equilibrium with an axial magnetic field. (B) As the simulation begins, the differentially rotating torus drags the field lines in the azimuthal direction, creating a braking force that allows the material to accrete inward and gain additional rotational energy. The effect of this process is to produce a torque on the external magnetic field, generating a spinning plasma jet that carries away matter, angular momentum, and energy from the system. From Meier et al. (2001).
Alternatively, outflows can be radiatively driven. For instance, the electron/positron pairs in the corona could be accelerated by the annihilation radiation, in the so called ‘Compton rocket’ scenario (O’Dell 1981). Radiatively driven disc winds, made of electrons and protons, have been proposed with a radiative pressure due to line emission or dust (Proga, Stone & Kallman 2000). The terminal velocities of such winds do not exceed $v \approx 0.5c$ though (Icke, 1977), thus such mechanisms are unable to explain the highest velocities, but may still be operating in mildly relativistic jet sources.

The other alternative to magnetic acceleration is thermal driving, as it is the case in the solar wind. In this case, the presence of a hot corona above the disc and/or the magnetosphere is essential for the acceleration, which is proportional to the sound speed, i.e. to the square root of the coronal temperature. A corona with a temperature of $10^9$ K for both the ions and the electrons could result in terminal speed of 10000 km s$^{-1}$; however, if $10^9$ K is the electron temperature, while the protons are at $10^{12}$ K, a wind results with a terminal speed close to the speed of light. Thus thermal acceleration is likely to be as efficient as magnetic processes (and in fact it has been suggested that both may be at work in disc winds) for electron/protons plasmas, while the electron/positron pairs would be more likely magnetically driven from a black hole magnetosphere.

It is important to stress that there are reasons to believe that more than one jet launching mechanism may be at work in accreting black holes, and that there are definite candidates in the different cases. The following identifications are suggested by Meier (2003a; 2003b): BP-type outflows may be responsible for the lower velocity ($\sim 0.1c$) outflows, while the PC/BP mechanism inside the ergosphere may be responsible for most jets we see in active nuclei and stellar black holes. Lorentz factors $\Gamma \approx 3$ have been achieved in simulations of this process (Koide et al. 2000; Meier et al. 2001). Finally, very high Lorentz factor ($\Gamma \gtrsim 50$, inferred e.g. for the central engine of $\gamma$-ray bursts) might be identified with the BZ mechanism that couples to the black hole horizon itself.

Finally, the extreme possibility has been suggested that all types of ultra-relativistic outflows are pure electromagnetic phenomena, rather than gas dynamical (see Blandford 2002 and references therein). Electromagnetic outflows are naturally anisotropic and self-collimating; the observed jet-like emission would trace out regions of high current densities where global instabilities drive a turbulence spectrum that is responsible for the particle acceleration and the observed synchrotron and/or inverse Compton emission.
Figure 1.5: Spectral energy distribution of the prototypical 10 solar mass black hole in the high mass X-ray binary system Cygnus X-1. In the hard X-ray state the system is radio active, powering a steady jet which is resolved on VLBA scales (Stirling et al. 2001). When the system moves to higher accretion rates/X-ray luminosities, the thermal emission from the disc dominates the power output while the radio emission is quenched by a factor up to 50 with respect to the hard state. Adapted from Tigelaar et al. (2004).

1.5 Radio emission from black hole X-ray binaries

Historically, the key observational aspect of X-ray binary jets lies in their synchrotron radio emission (see Hjellming & Han 1995; Mirabel & Rodríguez 1999; Fender 2005 for reviews). The synchrotron nature of the radio emission from X-ray binaries in general is inferred by the high brightness temperatures, high degree of polarization and non-thermal spectra. The outflow nature of this relativistic (as it emits synchrotron radiation) plasma is inferred by brightness temperature arguments, leading to minimum linear sizes for the emitting region that often exceed the typical orbital separations, making it unconfinable by any known
Different jet properties are associated with different X-ray spectral states of BHXBs. This is illustrated schematically in Figure 1.5, which shows the spectral energy distribution, from radio to γ-ray wavelengths, of the (prototypical) stellar mass black hole in Cygnus X-1 over different accretion regimes.

1.5.1 Steady jets

BHXBs in hard states display persistent radio emission with flat radio-mm spectrum. Since we are in presence of a relativistic plasma, which is inevitably subject to expansion losses, the persistence of the emission implies the presence of a continuously replenished relativistic plasma. The flat spectral indices can only be produced by inhomogeneous sources, with a range of optical depths and apparent surface brightness, and therefore are generally interpreted in terms of synchrotron emission from a partially self-absorbed, steady jet which becomes progressively more transparent at lower frequencies as the particles travel away from the launching site (Blandford & Königl 1979; Hjellming & Johnston 1988; Falcke & Biermann 1996). We shall refer to them as steady jets. The observed time delays between different frequencies (e.g. in GRS 1915+105, Pooley & Fender 1997; Mirabel et al. 1998) rule out models in which the flat/inverted radio-mm spectrum is due to optically thin synchrotron emission from a very hard energy distribution of electrons (e.g. Wang et al. 1997). Confirmations of the collimated nature of these hard state outflows come from Very Long Baseline Array (VLBA) observations of Cyg X-1 (Stirling et al. 2001; Figure 1.6) and GRS 1915+105 (Dhawan et al. 2000; Fuchs et al. 2003), showing milliarcsec-scale (tens of A.U.) collimated jets.

Some authors propose a jet interpretation (rather than the standard Comptonizing corona) for the X-ray power-law which dominates the spectrum of BHXBs in the hard/quiescent state (Markoff, Falcke & Fender 2001; Markoff et al. 2003). In this model, depending on the location of the frequency above which the jet synchrotron emission becomes optically thin to self-absorption and the distribution of the emitting particles, a significant fraction – if not the whole – of the hard X-ray photons would be produced in the inner regions of the steady jet, by means of optically thin synchrotron and synchrotron self-Compton emission.

No core radio emission is detected while in the soft state: the radio fluxes are ‘quenched’ by a factor up to about 50 with respect to the hard X-ray state (Fender et al. 1999; Corbel et al. 2001), probably corresponding to the physical disappearance of the steady jet. This has been taken as strong evidence in
Figure 1.6: A milliarcsec scale steady jet in the hard state of Cygnus X-1. This high spatial resolution radio observations (with the Very Long Baseline Array) have confirmed the jet interpretation of the flat-spectrum radio emission in the hard state of BHXBs. From Stirling et al. (2001).

favour of MHD jet formation (Meier 2001; Meier, Koide & Uchida 2001): in this framework the jet power is proportional to the second power of the poloidal component of magnetic field, which in turn would scale as the accretion flow scale-height. Thus the steady jet would be naturally suppressed in soft state, where a geometrically thin accretion disc accounts for the observed spectrum.
Figure 1.7: Radio observations (with the MERLIN array) of the BHXB GRS 1915+105, the first Galactic superluminal source discovered. This sequence of maps shows multiple-epoch arcsec-scale ejections of radio plasmons moving away from the binary core with highly relativistic velocities: a typical example of transient jets. From Fender et al. (1999).
1.5.2 Transient jets

Radio observations of apparent superluminal motions from GRS 1915+105, performed with the Very Large Array (VLA) back in 1994, demonstrated unequivocally that BHXBs could produce highly relativistic jets (Mirabel & Rodríguez 1994). These kind of events – after which the popular name microquasars was coined – have proved to be rather common among BHXBs. X-ray state transitions appear to be associated with arcsec-scale (thousands of A.U.) synchrotron-emitting plasmons moving away from the binary core with highly relativistic velocities (Mirabel & Rodríguez 1999; Fender et al. 1999; Fender 2005 and references therein). We shall refer to them as transient jets. Unlike milliarcsec-scale steady jets, such discrete ejection events display optically thin synchrotron spectra above some frequency, from which the underlying electron population can be derived. If the underlying electron distribution is a power law of the form $N(E)dE \propto E^{-p}dE$, then observations of the spectral index ($\alpha = \Delta \log S_\nu/\Delta \log \nu$, i.e. $S_\nu \propto \nu^{\alpha}$) in the optically thin part of the synchrotron spectrum can directly reveal the form of this electron distribution: $p = 1 - 2\alpha$. Observed optically thin spectral indices ($-0.4 \geq \alpha \geq -0.8$), indicate $1.8 \leq p \leq 2.6$. This is the same range derived for the majority of extragalactic jets powered by super-massive black holes and also for synchrotron emission observed in other astrophysical scenarios e.g. supernova remnants, and is consistent with an origin for the electron distribution in shock acceleration (e.g. Longair 1994). The monotonic flux decay observed after a few days in these transient radio ejections seems to be primarily due to adiabatic expansion losses, as the decay rate is the same at all frequencies. Significant loss of energy through the synchrotron emission process itself, or via inverse Compton scattering, would result in a more rapid decay at higher frequencies. The fact that adiabatic losses dominate indicates that the synchrotron radiation observed from such events is only a small fraction of the total energy originally input.

Association of a given synchrotron luminosity with a given volume (either by direct radio imaging or by measurement of an associated variability timescale) allows estimation of the minimum energy associated with the synchrotron-emitting plasma – for a given jet composition and filling factor – at a corresponding ‘equipartition’ magnetic field (equipartition is the condition at which the energy is nearly equally shared by the relativistic particles and the magnetic field; see Burbidge 1959).
1.6 Aims of this thesis

The largest body of observational data that pertain to relativistic jets is undoubtedly associated with active galactic nuclei. There is evidence that in some sources the jet power is a sizable fraction of the bolometric power of the accreting gas (e.g. Celotti & Fabian 1993; Di Matteo et al. 2003; Pellegrini et al. 2003) and, in general, the jet phenomenon has to be seen, on energetic grounds, as an intrinsic part of the accretion process.

Nevertheless there is still no agreement about the fundamentals of the inflow and outflow of mass around black holes; part of the problem is that there are interactions between all pairs of elements – the hole, the disc, the corona, and the jet – and most of the controversy comes about in assessing the character and strength of these interactions. Here is where stellar mass black holes may play a major role: in spite of the poorer statistics with respect to extragalactic jet sources, they are well worth studying because the duty cycles, which are thought to be set by the accretor size, and hence mass, are $10^5$ up to $10^8$ times shorter, and thus give far better sampled datasets for exploring time-variable accretion processes and related phenomena.

The main aim of this thesis is to provide a quantitative description of the jet-accretion coupling in black hole X-ray binary systems, and to assess the jet importance with respect to the overall accretion process in terms of energetics, and as a source of energy for the ambient interstellar medium.

In Chapter 2 evidence is presented for a quantitative scaling between the jet and the accretion power in the low/hard state of BHXBs; Chapter 3 discusses the consequences of such a correlation, extending the case to X-ray binary systems hosting neutron stars accretors, with relevant implications for the modelling of accretion flow at low luminosities. In Chapter 4 the study is extended to supermassive black holes; a possible correspondence begins to emerge between the different X-ray states and radio behaviour of BHXBs and active galactic nuclei as a function of $L/L_{\text{Edd}}$. Chapter 5 describes the formation and evolution of a large-scale transient radio jet from a prototypical BHXB following a major X-ray outburst. Chapter 6 discusses the nature of radio emission from BHXBs at low X-ray luminosities, in the ‘quiescent’ X-ray state. These results have contributed to the formulation of the first unified model for BHXBs jets, which is presented in Chapter 7. Chapter 8 concerns the discovery of a remarkable ring of radio emission around the ‘classical’ black hole in Cygnus X-1, and the consequences of this finding for low-luminosity black holes in general. The summary, final remarks and future prospects of this work are left to Chapter 9.
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