E2. Background

Accretion is the process by which cosmic matter falls into a gravitational potential field, unlocking potential energy stored in the gravitating system. The basic physical principle is that angular momentum is removed from the gas by viscous or magnetic turbulence, and transported outwards: this allows matter to fall inwards. At the same time, the related turbulent dissipation produces heat, which may be radiated, or carried towards (or into) the central object, depending on the inflow timescale. This mechanism provides the main source of power in a wide range of astrophysical objects: from protostars to compact remnants (white dwarfs, neutron stars and stellar black holes), from active galactic nuclei to galaxy clusters (Frank et al. 2002 for a review). This process has been used to probe the strong gravity field of black holes (BHs), the growth of collapsed objects, and the dynamics of matter flows in their surroundings. But only recently was it realized that accretion processes have played a crucial role in shaping the present-day baryonic universe. A substantial amount of that energy is returned into the surrounding medium (BH feedback), in the form of large-scale bulk flows, microscopic gas kinematic motions, relativistic particles, turbulence and electromagnetic radiation. This re-injection of energy may substantially modify structure formation and chemical enrichment in galaxies and even clusters of galaxies.

BH accretion can extract more than 10 per cent of the rest-mass energy of the infalling gas: it is an order of magnitude more efficient that nuclear fusion. BHs can be fed by many sources of gas: the hot or warm interstellar medium, a companion star, molecular clouds, or galactic-scale inflows. Some of the inflowing gas plunges through the event horizon — making the BH grow — and is forever removed from the environment; but a considerable fraction of the inflow does not end up into the BH. There are various processes that may enable most of the infalling matter and energy to escape. When the gas approaches the BH, it emits radiation, which pushes outwards the surrounding gas. The luminosity at which the outward force exerted by the radiation balances the inward gravitational force is known as "Eddington limit" (Frank et al. 2002). The mass accretion rate at which such limit is reached depends on the radiative efficiency and the geometry (spherically symmetric or disk-like) of the inflow. Large-scale magnetic fields may also stop and accelerate outwards (along their field lines) some of the accreting gas. Energy can escape directly as radiation, or as kinetic or thermal energy carried by the ejected gas, either via a fast, light jet or a slow, mass-loaded wind. Collimated, relativistic outflows may carry out most of the gravitational energy, but only a small fraction of the inflowing mass. Thermal or radiation-driven outflows may re-eject a large fraction of the mass, at comparatively lower speed.

The emitted radiation has a thermal component, which peaks in the soft X-ray band (for stellar-mass BHs) or UV band (for supermassive BHs), and a non-thermal component, which may dominate the hard X-ray band up to energies of a few hundred keV. The thermal component comes primarily from the energy dissipated in the turbulent *accretion disk*; the non-thermal component may come from synchrotron emission or inverse-Compton scattering in a hot *corona* or at the base of the *jet* (Fig. 1). Each BH may go through cycles of activity dominated at various stages by thermal or non-thermal radiative emission, or outflows, or energy advection into the BH.

My proposed research investigates how much mass/energy is falling into a BH, and how much is re-injected into the environment. I will use the information from X-ray, optical and radio data — both from the point-like central source and from its surroundings — to determine the mechanisms that control the *distribution of power between advection, radiation and outflows*. I will quantify the

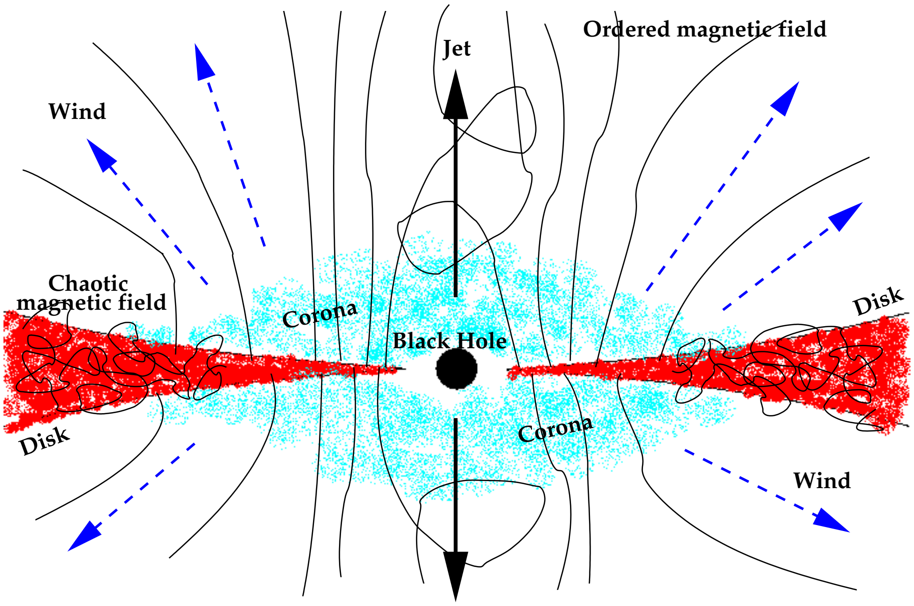

Figure 1: Schematic illustrations of the main physical components in an accreting black hole system: a thin disk threaded by tangled magnetic fields, open field lines enabling a wind and a relativistic jet, a hot corona. The challenge is to disentangle the physical properties, geometry and relative contribution of these components in different accretion states, from the observational appearance in various energy bands.

activity and variability of BHs in different mass ranges, identify observational signatures of the jet, wind and radiation components, and study the effects they have on the surrounding environment.

E3. Aims and Approach

I propose to study the energy budget and environmental impact of accretion onto BHs in stellar and galactic systems. My objectives are to determine:

- **what regulates the distribution of power** between the inflowing matter/energy component advected into the BH, the outflowing component carried by winds and jets, and the emerging radiation, for BH systems of various scales and accretion rates;
- **how radiation and outflows from an accreting BH alter its environment**, affecting the surrounding gas distribution, and enhancing or quenching star formation.

Energy channels: inflows, outflows and radiation.
One of the hallmarks of BH accretion is a pattern of phenomenological *accretion states*, characterized by different luminosity, spectral and time-variability properties (Remillard & McClintock 2006). Different states correspond to different geometrical and physical structures of the flow, and a different redistribution of the accretion power between various channels. For example, some BH systems are found in a luminous state dominated by thermal UV/soft X-ray emission (high/soft state); in this state, jets are quenched and most of the accretion power is efficiently radiated by an optically-thick, geometrically-thin disk. Other systems have a spectrum dominated by power-law radio and X-ray emission extending to a few hundred keV. In this radiatively-inefficient non-thermal state, a jet may carry out most of the power; the X-ray emission spectrum is interpreted as inverse-Compton scattering of soft seed photons in a hot corona or jet, or as synchrotron emission.

Other possible states correspond to advective flows, when the infall timescale is so short that most the energy is carried into the BH, because of radiation trapping or inefficient radiative cooling.

The time evolution of accreting BHs is often described as empirical tracks in a hardness–luminosity or temperature–luminosity diagram (Fender et al. 2004). The limitation of such approach is that it is based on observational quantities defined in specific bandpasses of certain detectors. The relation between empirical quantities (for example, the observed soft X-ray flux) and the underlying physical parameters (for example, the mass accretion rate) is very model-dependent and still not well quantified. The objective of my research is to explain the apparently large and confusing phenomenology of accretion states and state transitions as the effect of few fundamental physical parameters. This will allow a more predictive modelling of BH accretion/outflow processes, of their mechanical and radiative efficiency, and the relative importance of various mass-energy channels.

Earlier models of BH accretion states have described the observed luminosity and spectral evolution primarily as a function of one physical parameter: the *mass accretion rate* normalized by the BH mass (Esin et al. 1997). This approach does not reproduce the complexity of the observations. It has now become clear that the mass inflow rate at the outer boundary of the BH sphere of influence can be much larger than the actual accretion rate across the BH horizon. In addition, the outer-boundary conditions of the inflowing gas (in particular, specific angular momentum and temperature) may determine the energy channels. In stellar-mass BHs, such parameters depend on the mechanism of mass transfer from the donor star. In supermassive BHs, they depend on the relative distribution of hot, warm and cold gas in the host galaxy, and how these components are channelled towards the central region. In both classes of BHs, the outer-boundary conditions are affected by BH feedback (X-ray photons, winds).

More recently, it was proposed that the magnetic energy density in the inflow may be a fundamental parameter, and that **changes in the magnetic field topology may determine state changes** (Kuncic & Bicknell 2007). Turbulent magnetic fields may drive accretion, remove angular momentum, heat the gas in the accretion disk, and transfer part of the energy to a corona. On the other hand, ordered magnetic fields, anchored on the disk, may launch a collimated jet or winds. Topological rearrangements of the magnetic field may create a locally-ordered field from an initially stochastic field. This would cause a switch from a radiatively-efficient thermal state to a jet-dominated state. I will formulate observational predictions to test and improve this model, and look for the effects that the presence of a jet has on the emission properties of the underlying disk.

A specific objective of my project is to understand the nature of **ultraluminous X-ray sources** (ULXs), by modelling their accretion states and variability. ULXs are the most luminous class of non-nuclear BHs, with apparent X-ray luminosities up to 50 times higher than the most luminous stellar-mass BHs in our Galaxy. Many competing models have been proposed to explain such luminosities (Roberts 2007). ULXs could be the long-sought *intermediate mass BHs*; or they could be stellar-mass BHs accreting well above the Eddington limit, with some degree of collimation. I will combine phenomenological modelling and multiband observational studies to constrain the BH mass in ULXs, determine the flow structure and radiative efficiency of their accretion states, and make quantitative comparisons with accretion states in stellar-mass and supermassive BHs. An intriguing problem I want to solve is *whether ULXs have a jet*, and indeed whether or when the jet may dominate their power output. If ULXs are accreting well above their Eddington limit, they would be local-Universe analogs of early quasars in their most rapid phase of growth. Therefore, understanding the thermal and mechanical power distribution in ULXs may give us clues on the co-evolution of supermassive BHs and galaxies in the first 500 million years of the universe.

BH feedback on the environment

BH feedback (e.g., Springel et al. 2005) takes many forms. On stellar scales, BH jets and high-energy radiation may ionize and disperse the interstellar medium, creating bright radio and optical nebulae. At the same time, ionization fronts may compress cold gas and trigger sequential star formation around an active BH. In active galaxies, matter and energy are transported and redistributed by radio jets and lobes. Smaller galaxies may lose their gas because of the outflows. Gas-rich galaxies may go through cycles of activity dominated alternately by large-scale inflows towards the nuclear region and outflows driven by the nuclear BH. On even larger scales, cooling flows in galaxy clusters can be quenched by the energy re-injected by the supermassive BH in the central galaxy. The observed relation between the masses of nuclear BHs and those of their host galactic bulges (Ferrarese et al. 2006) is an example of how BH feedback regulates star formation.

A key question I will address is how much gas inflow is needed to make a quiescent nuclear BH switch to an active state, and conversely, what feedback is needed to push the gas away and self-regulate the level of activity. By comparing stellar-mass BHs in X-ray binaries, ULXs, and supermassive BHs in galactic nuclei, I will study why transient BHs switch back to a quiescent state: whether that happens because the inflowing gas has been pushed away by radiation and outflows, or because the gas supply is exhausted, or because the BH has switched to a radiatively-inefficient state. Another key problem I will investigate is what happens at very high inflow rates, tens or hundreds of times above the Eddington limit, as may be the case for ULXs (in the local Universe) and early quasars (at redshift ~ 6). It was suggested that such sources cannot be in a radiatively-efficient thermal state, because a standard disk (Shakura & Sunyaev 1973) cannot be stable at such inflow rates. We do not yet know whether they can be in a non-thermal, less radiatively-efficient, jet-dominated state. My research will determine whether most of the inflowing matter is ejected (strong feedback) or accreted (fast BH growth) but perhaps with low radiative efficiency.

Strategy and techniques

I want to quantify how the accretion power is distributed between jet, wind, advected and radiative components, how much mass enters the BH, and how much the BH feedback affects its environment. I will focus in particular on *two very different regimes: very high (super-Eddington) and very low accretion rates*. For each of the two regimes, I will study similarities and differences across the BH mass range, from stellar-mass to supermassive systems.

For the high-accretion case, I will primarily study ULXs and relate their accretion states with those seen in stellar-mass BHs, certain types of active galaxies (narrow-line Seyfert 1s), and quasars. To do so, I will model X-ray spectral and timing observations, determine the variability associated to each component, and estimate the size of the thermal-emitting region. Using long-term X-ray lightcurves, I will investigate the tell-tale signatures that a source is approaching or exceeding the super-Eddington, radiation-trapping regime. I will further test disk/wind models by searching for variable absorption and optical/UV emission lines, which I will use to probe the irradiation on the outer disk, optical depth, gas velocity and density in the outflow.

For the low-accretion case, I will continue and complete my studies of gas-starved nuclear BHs in quiescent, nearby galaxies (Soria et al. 2006a,b). I will extend a *Chandra* and *XMM-Newton* imaging survey of normal galaxies to determine *the X-ray luminosity distribution of low-state nuclear BHs*, and how that is related to the stellar population, gas density, Hubble type of the host galaxy. By studying the statistical distribution of the neutral absorption, I will probe the presence of a nuclear torus in low-luminosity AGN and normal galaxies, and quantify the threshold between the two classes. Using X-ray, optical/UV and radio data, I will determine to what extent nuclear star clusters coexist with nuclear BHs. Such study will help test and extend the relation between the sizes of galactic bulges, of nuclear star clusters and of nuclear BHs.

A key aspect of my project is to test the recently proposed scenario that explains BH state transitions in terms of topological rearrangements of the magnetic field in the accretion flow. To this purpose, I will contribute to develop a new theoretical model of coupled, magnetized disk/winds, in collaboration with Z. Kuncic at the University of Sydney and G. Bicknell at the Australian National University. This project will include for the first time fully 3-dimensional magnetohydrodynamic simulations with the FLASH code, combined with analytical modelling and comparison with the observations. Existing numerical simulations predict that an accretion disk almost always develops a jet; however, the coexistence between the two energy channels has not yet been unequivocally observed. To prove the link between disk and jet, I will quantify the effect that a jet has on the observable properties of the inner disk (compared with standard disk models without jets). For example, a jet will cool the disk by extracting energy through a non-thermal channel (Kuncic & Bicknell 2007); BH systems where the inner disk is faint or not visible in the X-ray band may be examples of jet cooling. I will compare the observational predictions of our jet-cooling model with those expected from a truncated disk. In the case of ULXs, I will look for radio counterparts, and constrain the integrated power of the jet over the source lifetime, by modelling the optical and radio emission from the surrounding nebulae (Soria et al. 2006c).

Impact on other fields of astrophysics.
My research will have a significant impact on several different areas of astrophysics.
—Much of the fundamental physics used to describe BH accretion also applies to low-magnetic-field neutron stars. The crucial difference, predicted by general relativity, is the presence of an event horizon in BHs, and of a hard surface in neutron stars. Therefore, quantifying the differences between BH and neutron star accretion processes provides observational tests on the existence of a horizon. The Monash astrophysics group is internationally recognized for their expertise in *neutron-star astrophysics*. My BH-focused research will suitably complement the research area of Dr. D. Galloway and collaborators, with great mutual benefits.
—The formation of massive spheroidal galaxies at high redshift is characterized by intense star formation in parallel with a rapid growth of the central BH, in < 500 Myr. Determining the exact start and duration of the two processes, and why they ended, is crucial for our understanding of galactic morphology today. If the accretion was radiatively efficient, the rate of growth would be limited by the Eddington luminosity. Instead, if the accretion was radiatively inefficient (for example due to photon trapping), the BH could have grown in a shorter time. I will test the suggestion that ULXs could be *local-Universe analogs of early quasars*, accreting above the Eddington limit.
—Determining the *BH mass function in the universe* is a fundamental problem still unsolved. So far, only stellar BHs with masses ~ 5–$30 M_{\odot}$, and nuclear BHs between $\sim 10^6$–$10^9 M_{\odot}$ have been discovered. We still do not know how large the gap is between the two classes. Studying accretion onto the nuclear BH of small disk galaxies and in ULXs will constrain such gap.

E4. Significance and National Research priority

Scientific outcome: this project will significantly improve our understanding of the way in which gravitational power is converted to mechanical power and radiation in the proximity of a black hole. More specifically, I will test between different models for ultraluminous X-ray sources, I will achieve a better understanding of accretion states (particularly at very high mass-inflow rates), and investigate the fundamental similarities between stellar-mass and supermassive black holes.

Benefit to Australian astronomy: a central theme of my research is the study of X-ray emission from black holes. Australian astronomy has traditionally been based on optical and radio studies. However, a physical understanding of accretion and ejection processes can only be obtained by combining data from high-energy bands with radio and optical data. A strong high-energy astrophysics community will greatly enhance the scope of radio, optical and theoretical research in Australia. Monash University is one of the leading institutions in the development of high-energy astrophysics in Australia, thanks to a group of young, motivated researchers with overseas experience and collaborations. I am keen to join their group and contribute to this development.

National Research Priorities: My project is aligned with two of the priority goals for Frontier Technologies for Building and Transforming Australian Industries: *Breakthrough science* and *Promoting an innovation culture and economy*. Investigating the mass and energy distribution in accreting black holes, and the conditions for the formation of jets and outflows, will create the conditions for significant breakthroughs in this fundamental science field. Participation in this area of research will enable Australian researchers to be more competitive when applying for international grants, and benefit more fully from international collaborations. Moreover, high-energy astrophysics is space-based: strengthening this research line may lead to a stronger participation of Australian industry and technology in future astrophysical space missions. Developing and fostering human talent, by training a motivated group of young students and researchers, will be one of the outcomes of my proposed research. Exciting astronomical discoveries also provide a great motivation for secondary-school students to get interested in science and maths. The urgent need to boost secondary-school science participation in Australia was expressed in a recent ACER report.

E5. Collaboration

At the national level, my project will strengthen a collaboration between Monash University, the Australian National University (through Prof. G. Bicknell and collaborators at the Research School of Astronomy and Astrophysics) and the University of Sydney (through Dr. Z. Kuncic at the School of Physics), based on the development of three-dimensional magnetohydrodynamical simulations of magnetic fields threading an accretion disk. A significant part of my project is based on data from NASA's *Chandra X-ray Observatory* and ESA's *XMM-Newton* X-ray telescope. This will strengthen my ongoing, fruitful collaborations with colleagues at the Harvard-Smithsonian Center for Astrophysics (Prof. G. Fabbiano) and University College London (Prof. K. Wu, Dr. M. Page). For the multiband study and theoretical interpretation of ultraluminous X-ray sources, I will continue my collaboration with colleagues at the Strasbourg Observatory (Prof. M. Pakull), Tsinghua University in Beijing (Prof. S.-N. Zhang) and NASA/Marshall Space Flight Center (Prof. D. Swartz). For combined radio/X-ray studies of accreting black holes, I will continue to collaborate with Dr. R. Fender at the University of Southampton and Dr. R. Perna at JILA/University of Colorado.

E6. Communication of Results

Results will be communicated through: publications in high-impact, refereed astronomy journals (e.g., The Astrophysical Journal, Monthly Notices of the Royal Astronomical Society); invited or contributed presentations at major international conferences and workshops; press releases and articles on popular science magazines. I will also contribute to outreach activities, such as Open Day presentations and talks for schools and amateur astronomical societies.

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