Truncated accretion discs around stellar mass objects

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Chapter 1

Introduction

1.1 Overview

This thesis explores dynamical and radiative processes that occur in accretion flows around various stellar-mass objects. The work is divided into two separate themes: the interaction between strong stellar magnetic fields and accretion flows (chapters 2, 3, and 4) and radiative processes and accretion flow geometry in black holes at low luminosity (chapter 5).

1.2 Accretion Processes Around Stars

Accretion in astrophysics is defined as the process in which gas falls into a gravitational potential well (such as a star or a black hole), which converts its gravitational energy into kinetic, thermal or radiative energy. Typically a large fraction of the gravitational potential energy is released as radiation, making accretion-powered stars much brighter than their non-accreting counterparts. The amount of energy released will depend on the depth of the accreting object’s potential well. This is often expressed as the compactness of an object, $M_*/R_*$, or the ratio of the object’s mass to radius (in a black hole, the radius is given by the event horizon). The more compact a star, the deeper its potential well. Both neutron stars and black holes are so compact that the fraction of energy released (compared to the rest mass energy of the accreted matter) is considerably larger than in nuclear fusion. Unsurprisingly, accretion-powered objects are some of the brightest, highest-energy observable sources in the Universe.

The luminosity of an accreting object is frequently characterized by its Eddington luminosity. This is defined as the luminosity at which the radiation pressure from accretion equals the gravitational potential, which then slows accretion (thus decreasing the luminosity, which is derived from accretion energy). The Eddington luminosity thus acts to set a rough upper boundary on the luminosity of a source. If the accretion is spherically symmetric and electron scattering is the dominant form of radiation pressure (assuming the gas is entirely hydrogen), the Eddington luminosity will be given by:

$$L_{\text{Edd}} = \frac{4\pi GM_* m_p c}{\sigma_T},$$  \hspace{1cm} (1.1)
where $\sigma_T$ is the Thomson cross-section of the electron, and $m_p$ is the proton mass (Frank et al. 2002). The Eddington luminosity will have a corresponding accretion rate, $\dot{M}_{\text{Edd}}$, which will depend on the efficiency at which gravitational potential energy is converted to radiation, and the depth of the potential well. For comparison, in a solar-mass star, $L_{\text{Edd}} \sim 10^{38} \text{ergs}^{-1}$, or roughly $25\,000 \,L_{\odot}$, while both accreting neutron stars and black holes show maximum luminosities $\sim L_{\text{Edd}}$.

A number of objects in our galaxy primarily radiate due to accretion. These generally fall into two categories: binaries and single stars. In the first category, compact stars accrete from a binary companion, which donates mass either via Roche lobe overflow or by a stellar wind. The second process arises in the late stages of star formation, after the protostar has formed out of a collapsed molecular cloud but matter continues to fall inwards. The accretion processes are similar in both, although accreting compact stars radiate at much higher energies and generally evolve on much shorter timescales. Most significantly, the gas accreted in both cases will have a large amount of angular momentum, which the gas must shed in order to move inwards.

The initial angular momentum of the accreting gas slows the rate of accretion onto the star. Unless the accretion time is very short compared with the cooling time of the gas, the gas will rapidly cool as it orbits around the star. Since the accretion flow is pressure-supported, the gas will fall into an axisymmetric disc in orbit around the star, with a pressure scale-height $H/r < 1$. Except in unusual cases (such as an ADAF, described in 1.5.2), this condition will generally hold, and accretion will proceed from an accretion disc. Gas will thus rotate in the disc in nearly Keplerian orbits, slowly accreting inwards.

In order to accrete onto the star, the angular momentum must be transported outwards in the disc, which requires that gas in adjacent orbits interacts viscously. The magnitude of viscosity needed to power observed accreting sources is much larger than the molecular viscosity of the gas and is generally attributed to some form of turbulence generated by instabilities in the disc, which act over some radial extent and produce an effective viscosity in the disc. Discovering likely instability candidates for viscosity has been a major area of research in accretion physics. Currently the leading viscosity candidate is the Magneto-Rotational Instability (MRI; Balbus & Hawley 1991), which is produced by weak magnetic fields being sheared by the relative rotation in the disc. Questions such as the magnitude of instability (Fromang & Papaloizou 2007), or whether it can account for accretion in weakly ionized young star discs (Gammie 1996) remain unanswered, however.

Even without knowing the exact source of the effective viscosity in an accretion disc, researchers have still been able to make tremendous progress in understanding accretion physics. One of the most fruitful achievements in 20th-century astrophysics was an estimate for the effective viscosity in an accretion disc by Shakura & Sunyaev (1973). They speculated that some (unknown) source of turbulence was responsible for the viscosity in the disc, which would then have some characteristic lengthscale and speed. They assumed $H$, the pressure scale height in the disc, to be the characteristic length scale for the turbulent eddies, and $c_s$, the sound speed in the disc, to be a characteristic speed. This allowed them to write
down a definition for viscosity:

$$\nu \simeq \alpha c_s H,$$

(1.2)
in which $\alpha \leq 1$ is a dimensionless number that parameterizes the uncertainty in the viscosity. The magnitude of $\alpha$ and its functional dependence on other parameters remains unknown, but this description of the viscosity has allowed for considerable progress.

1.2.1 Thin accretion discs

Using (1.2) for the viscosity, and defining an inner boundary condition for the disc (where material deviates from Keplerian orbits to crash onto the star), Shakura & Sunyaev (1973) constructed a solution for the density and temperature structure of a thin, diffusive accretion disc with a fixed accretion rate ($\dot{M}$). Assuming that the disc is optically thick, their results predict a disc radiating thermally with a maximum temperature that depends on the compactness of the accreting object and the accretion rate. In a neutron star or black hole accreting at a moderately high rate, the thermal peak will be in the soft X-ray band, corresponding well with observed luminosities and X-ray spectra. This early accreting disc model has provided the basis for accretion physics.

1.3 Accreting stars with strong magnetic fields

Many accreting stars (X-ray pulsars, Intermediate Polars, T Tauri stars) have large organized magnetic fields that govern the gas dynamics in the inner regions of the accreting flow, disrupting the disc and channelling material along field lines onto the surface of star. The point where the disc will be disrupted is usually called the magnetospheric radius or Alfvèn radius, which we here define as the inner edge of the disc, $r_{\text{in}}$. It can be (somewhat crudely) estimated as the location where the magnetic pressure, $B^2/4\pi$, is equal to the ram pressure of the infalling gas, $\dot{M}v_r$ (Pringle & Rees 1972).

We assume for simplicity that the magnetic field is a dipole aligned with the star’s spin axis and the disc (so that the problem is axisymmetric). Adopting cylindrical coordinates $[r,\phi,z]$ with the $z$-axis aligned with the star’s spin axis, the magnitude of the field in the plane of the disc is $B_z = B_S \left(\frac{R_*}{r}\right)^3$ (where $B_S$ is the field at the stellar surface, and $R_*$ is the star’s radius). If the radial velocity of the gas is of order to the Keplerian velocity so that $v_r \sim (GM_*/r)^{1/2}$, the magnetospheric radius will be approximately:

$$r_{\text{in}} \sim \left(\frac{B_S^2 R_*^6}{4\pi GM_*^{1/2} \dot{M}}\right)^{2/7}.$$  

(1.3)

Material passing through $r_{\text{in}}$ will be channelled onto a small region near the magnetic pole, and add a considerable amount of angular momentum ($\sim \dot{M}(GM_*/r_{\text{in}})^{1/2}$) to the star, causing the star to spin faster.
Since \( r_{\text{in}} \) can be considerably larger than \( R_* \), a rapidly-spinning star could in principle spin faster than the Keplerian rotation rate at \( r_{\text{in}} \). In this case, the spinning magnetosphere will create a centrifugal barrier at \( r_{\text{in}} \) that can prevent gas from accreting (Pringle & Rees 1972; Illarionov & Sunyaev 1975). This introduces a second characteristic length scale into the problem, the corotation radius, defined as the point where the Keplerian frequency in the disc is equal to \( \Omega_* \), the star’s rotation frequency:

\[
r_c \equiv \left( \frac{GM_*}{\Omega_*^2} \right)^{1/3}.
\] (1.4)

When \( r_{\text{in}} < r_c \), accretion can proceed normally, while for \( r_{\text{in}} > r_c \) the centrifugal barrier will likely reduce or even halt accretion onto the star. As we describe in section 1.4, the behaviour of the disc in the latter case is subject to considerable uncertainties.

Beyond \( r_{\text{in}} \) the magnetic field is not strong enough to completely disrupt the disc, but can still strongly influence its behaviour. This is especially true for the region close to \( r_{\text{in}} \) where the magnetic pressure and gas pressure are still of similar order. Exactly how the magnetic field and disc interact in this region remains the subject of considerable controversy and active research. (For an excellent review of the current state of magnetospheric accretion studies, please see Uzdensky 2004). The picture summarized below represents the closest current consensus between analytical and numerical study.

Provided that the disc is somewhat ionized, magnetic field lines will likely become strongly embedded in the disc’s surface, so that the field’s footpoint rotates with the Keplerian rate of the disc (Lovelace et al. 1995). The other footpoint of the field line is of course attached the star and will rotate at \( \Omega_* \). Except for at \( r = r_c \), the relative rotation rate of the star and the disc will distort the field lines and create an additional \( B_\phi \) component. This will generate a magnetic torque which allows additional angular momentum exchange between the star and the disc:

\[
\tau = \pm \int_{r_{\text{in}}}^{r_{\text{in}}+\Delta r} 4\pi r^2 B_\parallel B_\phi \frac{\partial}{\partial Z},
\] (1.5)

where \( \Delta r \) is the width of the region coupling the disc and the star. The sign of the angular momentum exchange depends on the relative location of the connected field line and \( r_c \): if \( r < r_c \), this exchange adds angular momentum to the star, while if \( r > r_c \), angular momentum is extracted.

Analytic arguments suggest that the region of coupling between the magnetic field lines and the disc (which we call the interaction region, \( \Delta r \) in our work) will be small, with \( \Delta r < r_{\text{in}} \) (Lovelace et al. 1995). This is because the induced \( B_\phi \) component can only grow to a maximum of \( \sim B_\parallel \) before the twisted magnetic field line inflates and eventually opens, severing the connection between the star and the disc (Aly 1985; Uzdensky et al. 2002). The opened field lines could then launch an outflow of material from the disc (e.g. Blandford & Payne 1982; Lovelace et al. 1999), or provide a site for reconnection (Uzdensky et al. 2002). In the late 1990’s, magnetohydrodynamical simulations of a magnetic field interacting with a disc confirmed this basic picture (Hayashi et al. 1996; Miller & Stone 1997; Goodson et al.
Simulations have typically found that the field adopts a largely open geometry (shown schematically in fig. 2.1 in the next chapter), with only the inner regions of the disc strongly interacting with the star. Both outflows and accretion are also typically seen, as field lines open and then reconnect.

A number of questions remain unresolved within the picture outlined above. Particularly unclear is the relative importance of the interaction with the disc and outflows in regulating the angular momentum of the star. Outflows provide an additional way for the star and disc to shed angular momentum, but the details of how they are powered and how much mass can be lost via outflow is uncertain (Spruit 2010). The star-disc coupling can in principle be very efficient in transporting angular momentum, but this depends on the extent of the connected region (which in turn depends on the rate at which field lines can reconnect above the disc or diffuse through it). Additionally, some authors have suggested that on long timescales the field itself could evolve radially through the disc, either spreading out radially (Agapitou & Papaloizou 2000), or being dragged in by the accreting matter (as in the X-wind model of Shu et al. 1994). All of these factors will influence the efficiency and importance of disc-field coupling on angular momentum transport through the disc.

In our work we construct a parameterized model for the disc-field interaction that incorporates most of the uncertainties listed above, and assume that any variability created by field line opening and reconnection can be time-averaged over the timescales that we are interested in. We explicitly neglect the (unknown) role of outflows in our calculations, in order to focus on the evolution as a result of the coupling between the disc and the field.

1.3.1 Observations of magnetospheric accretion

Observations of accreting magnetic stars offer both support and challenges for the basic picture of magnetospheric accretion outlined above. Below we summarize the evidence for magnetospheric accretion in two different types of accreting magnetic stars: T Tauri stars and X-ray pulsars. Both these stars show strong evidence for magnetically-regulated accretion, as well as unexplained observations.

T Tauri Stars

T Tauri stars are often observed to have strong stellar magnetic fields (up to \(1 - 2 \, kG\)), and show some evidence of spin regulation by the interaction between the disc and magnetic field. They also show a significant amount of X-ray activity, which is attributed to magnetic flares in either the star or the star-disc coupling (Getman et al. 2008). In this thesis we focus particularly on observations of one class of T Tauri stars known as ‘EXors’. EXors, like their prototype, EX Lupi are characterized by repeated large outbursts: changes by up to four magnitudes in luminosity lasting several months, with a characteristic total period of several years (Herbig 2007, 2008). The timescale of the outbursts suggests variations in the
disc structure in the inner region of the disc, which could arise as a result of the interaction between a disc and field.

**X-ray pulsars**

Accreting X-ray pulsars show direct evidence of magnetospheric accretion, through their pulsations on timescale between $\sim 10^{-3} - 10^2$ seconds, which is attributed to the magnetic pole sweeping through our line of sight (Davidson & Ostriker 1973). In some pulsars, this probe of the star’s rotational period shows an evolution in time (e.g. Bildsten et al. 1997), and variations in the derivative of the period that correlate (or anticorrelate) with luminosity changes in the star.

X-ray pulsars also show more indirect evidence of magnetic field-disc interaction. Two millisecond accreting X-ray pulsars, NGC 6440 X-2 (Patruno et al. 2010; Hartman et al. 2010) and SAX J1808.4-3658 (Patruno et al. 2009) show strong quasi-periodic oscillations on timescales similar to the evolution timescales in the inner disc, which might be powered by the same mechanism as the accretion bursts in EXors. NGC 6440 X-2 also shows short-duration outbursts of accretion with a very short recurrence time, which could be a result of magnetic fields suppressing accretion.

### 1.4 Magnetic Accretion at Low $\dot{M}$: ‘Propellers’, Outflows and Dead Discs

In sec. 1.3 we presented the standard argument for determining the truncation radius of an accretion disc in the presence of a magnetic field. This calculation presupposes that there is some accretion at the inner edge of the disc. However, when $r_{\text{in}} > r_c$, the interaction between the disc and the field creates a centrifugal barrier that opposes accretion onto the star, so this reasoning no longer holds. Matter will continue to move inwards from large distances, but will be prevented from accreting onto the star. What then happens in this case?

A common assumption is that once $r_{\text{in}} > r_c$, the interaction between the disc and the magnetic field will completely expel the mass at $r_{\text{in}}$ in an outflow. This is known as the ‘propeller’ regime, with the behaviour of the spinning magnetosphere likened to a propeller flinging matter out of the system (Illarionov & Sunyaev 1975). The propelling disc ‘solves’ the problem of (1.3) by assuming that when $r_{\text{in}} > r_c$ the matter flowing through the disc will be expelled rather than accreted.

It is not clear what the accretion rate (if any) onto the star should be for the propeller regime, although one would assume that it should decrease sharply around $r_{\text{in}} = r_c$ if most of the mass flowing through the disc is being expelled in an outflow and only a small amount accreted onto the star (and hence render the source observable). Despite this, observational results often refer to sources as being in the ‘propeller’ regime, meaning only that $r_{\text{cr}}[\text{eqn (1.4)}]$ is larger than $r_{\text{in}}$ (as calculated using (1.3) for the observed accretion rate). This clearly
does not make sense: if the ratio of accreted to outflowing matter were very small, then the total accretion rate through the disc (incorporating the unobserved outflow) could be large enough to make (1.3) smaller than (1.4)!

The problem is caused by what is understood by ‘propeller regime’. The original suggestion referred to systems in which the disc is truncated at a considerable distance outside $r_c$, so that $\Omega_s \gg \Omega_K(r_{in})$. In this case the rotational energy of the magnetosphere is much larger than that of the disc, so it seems reasonable to expect that the majority of the disc mass will be expelled in the disc-field interaction. However, in order to avoid a logical problem (i.e. what happens if most but not all the mass is expelled at $r_{in}$?), models of the propeller regime are typically constructed to ensure that the disc is completely expelled in a magnetic outflow by the time it reaches $r_{in}$ (e.g. Lovelace et al. 1999). This is in spite of the fact that the physics of powering magnetospheric outflows (e.g. how much energy is required, or how much mass can be expelled) is still uncertain (Spruit 1997). Further adding to the confusion is the tendency (as noted above), to define the ‘propeller’ regime as the one where $r_{in} > r_c$ as determined by (1.3) and (1.4), despite the fact that the definition of a propeller implies a system in which matter is expelled rather than accreted. The logic is thus: a) the centrifugal barrier at $r_{in}$ will prevent accretion onto the star, b) there is (probably) enough energy in the rotation of the magnetosphere to expel the disc in an outflow, c) since the accretion rate in the disc is determined far from $r_{in}$, the disc must be expelled, otherwise, where would the mass go?

This logic fails most obviously for cases where $r_{in} < 1.26 r_c$, where the rotation rate of the magnetosphere is less than the escape speed of the gas. As the gas at $r_{in}$ is brought into corotation with the star, the added rotational energy will not be enough to expel it, but the centrifugal barrier will prevent it from accreting onto the star (Spruit & Taam 1993). The same condition could of course hold for a disc truncated even further from $r_c$: having enough energy for the gas to escape is a necessary but not sufficient condition for the disc to be expelled, and some of the gas at $r_{in}$ could remain confined in the disc.

The solution to this problem is that the standard disc solution that describes accretion onto a star or magnetosphere (Shakura & Sunyaev 1973) does not necessarily apply to discs truncated outside $r_c$. This is not such a problem as it initially appears, since there are in fact a whole class of time-independent accretion disc solutions with different boundary conditions at $r_{in}$. The most well-known of these is the solution for a disc accreting onto the surface of a non-magnetic star spinning close to break-up. Popham & Narayan (1991) and Paczynski (1991) independently demonstrated that the interaction between the disc and the rapidly spinning star can transfer angular momentum outwards so that accretion can proceed while the star remains spinning at breakup. This changes the inner boundary condition, and alters the surface density profile in the inner regions of the disc so that the angular momentum added at $r_{in}$ can be transported outward.

A similar disc solution exists for the case where accretion onto the star is completely suppressed but the disc-field interaction adds angular momentum to the inner edge of the disc. This solution (described in more detail in chapter 2) was first proposed by Sunyaev
and Shakura (1977), who dubbed it a ‘dead disc’ since the accretion rate onto the star is close to zero and the temperature of the disc itself is low enough to render the disc nearly undetectable. The inner edge of the disc in a dead disc is determined by the location where the rate of angular momentum being injected into the disc at $r_{in}$ balances the rate at which the disc can transport it outwards (which depends on the surface density of the disc). In a dead disc, the inner radius is thus determined by the amount of mass in the disc, rather than the accretion rate through it. More mass in the inner parts of the disc means that the disc can transport more angular momentum outwards, and $r_{in}$ will move to $r_c$. This disc solution will also be relevant for systems in which there is an outflow near $r_{in}$ that is not strong enough to expel gas at the same rate at which it is being accreted from further away.

If the average accretion rate falls enough that accretion onto the star is suppressed, then mass can begin to pile up in the inner regions of the disc. This will last until there is enough mass in the disc to push $r_{in}$ inside $r_c$, where the excess mass can be accreted. The result will be bursts of accretion onto the star, with the timescale regulated by the viscous diffusion timescale in the inner regions of the disc (Sunyaev & Shakura 1977; Spruit & Taam 1993). A new physical description of this instability (which incorporates the dead disc phase) is presented in chapter 2, where we investigate the nature of the resulting outburst (e.g. its shape, amplitude and duration). In chapter 4 we continue this investigation more quantitatively, and explore how the instability evolves together with the spin evolution of the star.

This picture for magnetospheric accretion has a number of other consequences in addition to accretion bursts. It also predicts that the disc will remain truncated very close to $r_c$ as long as there is accretion onto the star. As a result, the disc can efficiently spin down the star even when the accretion rate is essentially zero. In chapter 3 we investigate the long-term evolution of dead and marginally accreting discs, following their evolution as the spin-rate of the star also changes.

### 1.5 Accretion around Black Holes at Low Luminosities

Observations of accreting black hole binaries offer a unique opportunity to test accretion physics. Since black holes themselves have no detectable intrinsic radiation, virtually all of the detectable radiation comes from accretion processes. As well, the deep potential well of a black hole means that accreted matter will lose a substantial fraction (between 6-40%) of its rest mass energy as it falls into the hole (Frank et al. 2002). Accreting black holes thus also offer the opportunity to probe the physics of matter at very high energies and densities, far above what is accessible to terrestrial laboratories. The early development of the theory of accretion flows and discs (e.g. Pringle & Rees 1972; Shakura & Sunyaev 1973) arose as a consequence of early X-ray observations of black holes, and the field of accretion physics has evolved in tandem with improving spectral and photometric observations. Chapter 5 concerns accretion around black holes at very low accretion rates. As we outline below,
much of the physics of accretion at these low accretion rates remains uncertain.

1.5.1 X-ray spectra of black holes

The X-ray spectra of accreting black hole binaries change dramatically as a function of the accretion rate. This is illustrated in figure 1.1, which is taken from McConnell et al. (2002). The crosses (with spectral fit models overlaid) shows two observations of X-ray and γ-ray emission for Cyg X-1 (a ∼ 10 $M_\odot$ accreting black hole) at different accretion rates. At high accretion rates (above ∼ 10% $L_{\text{Edd}}$, the ‘high/soft’ state), the spectrum is typically dominated by a soft X-ray quasi-thermal profile, peaking at 1−2 keV, with a steep, power-law tail extending up to γ-rays. As the X-ray luminosity of the source drops, the X-ray spectrum becomes dominated by hard roughly power-law emission that cuts off in the hard X-rays (∼ 200 keV), and the soft X-ray thermal component disappears (the ‘low/hard’ state). Both spectra show excess emission around 6−7 keV produced by iron K-α emission and broadened by rotation and relativistic effects (Remillard & McClintock 2006). The interpretation of black hole X-ray spectra is somewhat controversial. In the high/soft state, the quasi-thermal spectrum is attributed to a standard optically thick accretion disc (Shakura & Sunyaev 1973), and the iron K-α line (and related ‘reflection’ spectrum, Ross & Fabian 2007) is attributed to back-scattering of the high-energy spectral component off the surface of the disc. The power-law component itself is likely generated by inverse Compton scattering, the up-scattering of soft (∼ 1 keV) X-ray photons to much higher energies as they collide with a population of high-energy (∼ 100 keV) electrons (e.g. Rybicki & Lightman 1986) in an optically-thin corona above the disc. In the low/hard state, the power-law emission is usually also attributed to inverse Compton scattering, but both the geometry of the upscattering plasma and the fate of the optically thick disc are unclear.
1.5.2 Is the thin disc truncated at low $\dot{M}$?

The change in X-ray spectra indicate dramatic changes in the accretion flow as the accretion rate decreases. The thermal disc becomes nearly undetectable, indicating that it does not contribute much to the overall accretion energy budget. The upscattering electrons must be hot enough to produce the hard X-ray spectrum, which means that only a small fraction of the disc can interact with the corona (Haard & Maraschi 1991). This has led some researchers to suggest that the optically thick disc might vanish in the inner regions of the accretion flow when the mean accretion rate drops. Instead, the inner regions of the flow are filled with an optically thin, hot plasma that is the source of upscattering electrons needed to produce Inverse Compton radiation.

The most well-known model of this type is the ‘Advection-Dominated Accretion Flow’ (ADAF) solution proposed by Narayan & Yi (1994). In an ADAF the gas is fully ionized, and the density of the plasma is so low that the collision timescale between protons and electrons becomes comparable to the viscous timescale of the flow (the time it takes material to flow into the black hole). Since the protons can only effectively cool through collisions with electrons (which can then cool via bremsstrahlung or inverse Compton scattering), as viscous turbulence heats up the plasma, the protons will keep heating up while the electrons can cool. The result is a two-temperature plasma, with an electron temperature of about 200 keV and a proton temperature of about 20 MeV. Since the protons carry most of the energy of the flow (due to their much larger mass), the majority of the accretion energy is advected into the hole rather than radiated (hence ‘advection dominated’). The electrons will upscatter seed photons (either from the truncated disc or other processes like synchrotron radiation), which then produce the observed spectra.

The ADAF solution is only one of a large class of radiatively inefficient accretion solutions for the inner disc region. However, for the entire class the picture is very different from a standard optically thick accretion disc. Instead, the inner disc is truncated when the accretion rate is very low, and the inner regions close to the star are optically thin, radiatively inefficient, and much hotter.

1.5.3 Accretion discs bombarded by ions

It is not known how the accretion flow transitions from an outer cool disc to a hot inner ADAF, although in order for the ADAF to accrete, it must be able to shed excess angular momentum outward (cf. sec. 1.2). Spruit (1997) considered the interaction between the 20 MeV protons of an ADAF and a cool (1 keV) accretion disc. He suggested that as the protons bombarded the disc, the large energy transfer would evaporate the upper layers of the disc into a hot ($\sim 100$ keV) surface corona. Deufel & Spruit (2000); Deufel et al. (2001, 2002) further developed this work using Monte Carlo simulations of ions bombarding a cool disc to confirm the presence of a surface corona and determine its temperature and optical depth. Since the surface corona has a much higher temperature than the cool disc, its viscosity will
also be higher (1.2), so that the corona will flow inside the cool disc. In Spruit & Deufel (2002) the authors found that this process would heat up the corona in this inner region until it finally evaporated back into an ADAF, making the cycle self-sustaining. Finally, Dullemond & Spruit (2005) constructed a steady-state model for the accretion flow, incorporating the interaction between the ADAF and the disc. This allowed them to calculate the energetic contribution of each part of the flow. The main conclusion of this work is that some fraction of energy from the ADAF (which would otherwise be advected) can instead be converted somewhat indirectly into detectable radiation. The result emphasizes the importance of energy exchange (either by radiation or matter) between the different components of the accretion flow – particularly at low luminosities when the disc does not directly contribute much to the overall energy budget.

1.5.4 Soft excesses: evidence of an untruncated disc?

Recent observations of two X-ray sources (GX339-4 and SWIFT J1753.5-0127) have challenged the picture of a truncated emission disc at low accretion rates (Miller et al. 2006a,b). These researchers found soft emission below 2 keV in both sources in excess of the power-law component. By fitting their data with thermal disc models, they claimed that the spectra showed direct evidence of very faint thermal accretion discs ($kT \sim 0.2 - 0.3$ keV), consistent with being untruncated. Their interpretation of the spectra was somewhat simplistic (in particular, they account for reflected emission off the cool disc but not reprocessing), but nonetheless posed a challenge for the truncated disc paradigm.

In Chapter 5 we re-examine this conclusion, considering the energy exchange between different components of the accretion flow. Using the results of Dullemond & Spruit (2005) we construct a model spectrum for the accretion flow, to demonstrate that the soft excesses seen in the low/hard state of black hole binaries can be consistent with a moderately truncated accretion disc.

1.6 SUMMARY OF THE MAIN RESULTS OF THESIS

- When an accretion disc is truncated by a strong stellar magnetic field close to the corotation radius ($r_c$; where the spin of the star equals the Keplerian rotation of the disc), the angular momentum transferred from the star to the disc can remain confined in the disc and be transferred outward, preventing the disc from accreting (called a ‘dead disc’). A dead disc is characterized by a very low accretion or outflow rate, but active angular momentum transport outward. Chapter 2

- The dead disc state can result in cyclic accretion bursts, in which mass builds up and is periodically accreted onto the star. The presence, duration, magnitude, and outburst profile of these bursts depend on the time-averaged accretion rate in the disc, and the
radial width of the transition region between accreting ($r_{in} < r_c$) and non-accreting ($r_{in} > r_c$) regions. The timescale for the accretion bursts varies by more than five orders of magnitude. Chapter 2

- The instability timescale and burst magnitude agrees with observed variability in several classes of magnetic stars. In particular, low-frequency QPOs observed in accreting Neutron Stars (such as appear in the tail of outbursts in SAX J1808.3-3658 and NGC 6440-X2) happen on the order of viscous frequencies in the inner accretion disc, and could be the result of this instability. As well, a class of T Tauri stars known as ‘EXors’, show periodic outbursts that could also be caused by this instability. Chapters 2 and 4.

- If the accretion rate in the disc falls to zero, a dead disc can persist and spin down the star. The evolution of the system in this case will follow one of two paths. In the first, the disc will move gradually away from $r_c$ as angular momentum is added, and stellar spin-down will effectively stop. In the second, the dead disc will remain trapped close to $r_c$ as $r_c$ moves outwards, and the star can spin down indefinitely. We refer to these as ‘trapped’ discs. This bifurcation could account for observed magnetic white dwarfs and Ap stars, some of which rotate rapidly, and some very slowly. Chapter 3

- Accretion in a trapped disc will typically be very low, and can proceed either as steady-state accretion (Chapter 3) or accretion bursts (Chapter 4). The presence of cycles in a trapped disc can appear transiently as the star’s spin changes. Chapter 4

- Whether or not a disc will become trapped will depend on the physical extent of the disc, and whether it has a sink for angular momentum at the outer edge of the disc (for example, a companion). It will also depend on the detailed disc-field coupling, and ratio of the viscous diffusion timescale at $r_c$ compared to the spindown timescale of the star. Chapter 3

- Two forms of accretion instability exist: one at low $\dot{M}$ with periods of quiescence (as envisioned in previous work), and one at higher $\dot{M}$ with no periods of quiescence and much higher frequency. The presence of the instability in both cases can modify the rate of angular momentum transfer between the star and the disc (with respect to steadily accreting cases). Chapter 4

- In the low-luminosity state around accreting black holes, different components in the accretion flow are responsible for different components in the observed X-ray spectrum. These different components exist in close proximity and likely exchange energy via matter or radiation, so that considering this energetic coupling is critical when modelling the spectrum. Chapter 5.

- The energy exchange (by matter and radiation) between a cool truncated accretion disc and a hot ADAF produces a 100 $keV$ corona above the disc and hot ring 200 $keV$ just
inside it. The energy exchange between the corona and the disc will heat the disc and produce an excess of soft X-ray emission even at low luminosities. This excess can reproduce the soft excesses observed in black hole binaries in the low-luminosity state. Chapter 5.

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