Mem. S.A.It. Vol. XY, 1

Memorie della

Time-dependent two-phase models of black hole accretion discs

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Abstract. We present first results for time-dependent simulations of a two-phase accretion flow around a black hole. The accretion flow consists of an optically thick and cool disc close to the mid plane, while above and below the disc there is a hot and optically thin corona. We consider several interaction mechanisms such as heating of the disc by the corona and Compton cooling of the corona by the soft photons of the disc. Mass and energy can be exchanged between the disc and the corona due to thermal conduction. Given the computational and physical challenges, we concentrate on one example of a stellar mass black hole accreting at low accretion rates. We confirm earlier both theoretical and observational results which show that at low accretion rates the disc close to the black hole cannot survive and evaporates. Given the framework of this model, we now can follow through this phase of disc evaporation time-dependently.

Key words. Hydrodynamics – Instabilities – Accretion, accretion disks – X-rays: binaries – Conduction

1. Introduction

Observations of accreting X-Ray sources show at least two distinct spectral components. One component, at comparably low energy, is usually attributed to a geometrically thin but optically thick disc which emits as a black body. The other component at higher energy, the so-called power-law, reflects the existence of a likely geometrically thick but optically thin corona. The relative importance of these two components changes with time. This characteristics together with the accretion rate (Esin et al. 1997) is generically used to distinguish several states (e.g. Remillard & McClintock 2006). The low/hard state exhibits a hard spectrum dominated by a power-law and is usually attributed to low accretion rates, while at high accretion rated there is the high/soft state which shows a soft spectrum dominated by the black-body component.

Eardley et al. (1975) and Shapiro et al. (1976) introduced the concept of a two-phase accretion model. At small radii their disc consists of a hot, optically thin and geometrically thick corona. Further out there is a cool, standard optically thick but geometrically thin disc. The plasma in the inner parts of the corona is a two-temperature plasma, where electrons and ions interact via Coulomb collisions. The main aim of the model was to provide an explanation of the spectrum of Cyg X-1.

Różańska & Czerny (2000a) discuss radiative and conductive equilibrium for two-phase accretion disc models. They find sta-

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bility/instability strongly dependent on the assumed coronal heating mechanism. In a later paper (Różańska & Czerny 2000b) they consider mass loss/gain of both phases due to thermal conduction for stationary accretion disc models following the considerations of Begelman & McKee (1990).

In the following, we briefly present our model for a two-phase accretion disc. More details can be found in Mayer & Pringle (2006).

2. The model ingredients and assumptions

We treat the thermal and viscous evolution of both the disc and corona time-dependently. The corona consists of electrons and protons which do not necessarily have the same temperature. Viscous processes mainly heat the ions. They transfer their energy to the electrons via Coulomb collisions. The electrons and the protons emit bremsstrahlung. The electrons are cooled by Compton scattering of soft photons from the disc.

The hard radiation of the corona and viscous processes within the optically thick disc lead to a heating of the disc. The optically thick disc radiates as a blackbody.

At the transition between the corona and the disc we assume a thin transition layer. The pressure across the transition layer is uniform. Given the different temperatures in the disc and the corona, there is thermal conduction across the transition layer. We use a prescription by Różańska & Czerny (2000b). This basically considers the imbalance between heating and cooling within the transition layer. Depending on which process dominates, the disc evaporates into the corona or the corona condenses into the disc.

At some point in the evolution of the disc-corona sandwich, either the disc and corona cease to exist. For this case, detailed procedures are at hand. If the disc ceases to exist at some radius, then soft photons from both sides will Compton cool the coronal electrons. If the corona ceases to exist at some radius, the the disc will be heated from the hard radiation coming from nearby parts of the corona.

We integrate the model with an explicit one-step solver. The model is computationally very expensive. Given the geometrical thickness of the corona, the viscous and thermal timescale of the corona are fairly similar and thus only a small multiple of the dynamical timescale. For the disc however, the viscous timescale is at least 10^4 times longer than the thermal timescale ($H/R < 10^{-2}$). In order to develop the disc for one viscous timescale, we need to follow the corona for 10^4 timescales.

Our disc extends from the last stable orbit for a non-rotating black hole ($R = 3R\mathrm{g}$) to typically $3 \cdot 10^3 R\mathrm{g}$. At the inner boundary both mass and energy can be lost from both the corona and the disc. At the outer boundary we supply mass and energy to the disc only and prevent any mass and energy loss from the corona by setting the radial velocity to zero.

For the model presented in this contribution, we set the viscosity parameter $\alpha = 0.1$, $M = 10\,\mathrm{M}_\odot$ and the external disc accretion rate $10^{-3}\dot{M}_{\mathrm{Edd}}$.

3. The time-evolution

We start with both a stationary disc and corona neglecting mass exchange due to thermal conduction. The corona is separated radially into a two-temperature plasma close to the black hole, where Compton cooling dominates (Zone I), and a one-temperature plasma further out, where bremsstrahlung is the dominant cooling mechanism (Zone II,see Fig. 1.1). The disc evaporates into the corona in zone II, while the corona condenses into the disc in zone I. With the exception of a small radial range close to the transition radius where the disc is decreting (moving outwards), both the disc and corona globally accrete.

At the point in the disc, where the accretion turns into decretion, most of the matter of the disc evaporates into the corona and subsequently a gap develops (see Fig. 1.2).

The inner remnant disc gets accreted and finally the system is left with a corona-only inner flow in zone I and a disc-corona sandwich further out in zone II (see Fig. 1.3).

For a more detailed discussion, we refer the reader to Mayer & Pringle (2006).

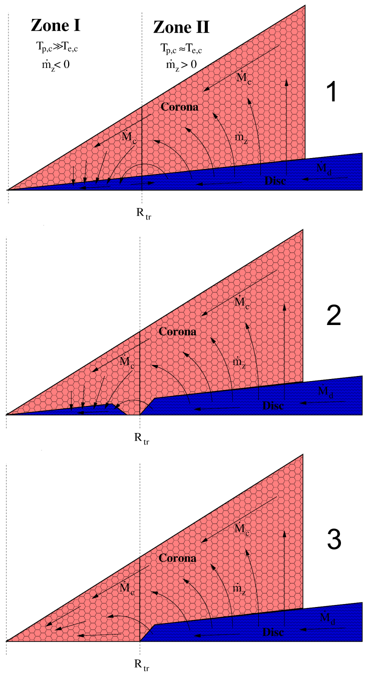

Fig. 1. Schematic evolution of the disc-corona sandwich.

4. Conclusions

The behaviour of the system is note unexpected. There are both observational and theoretical arguments that at low accretion rates a standard accretion disc close to the black hole cannot exist any more.

From simple arguments as described in Haardt & Maraschi (1991) it is evident, that if the disc-corona sandwich exists at any radial distance from the black hole, the coronal luminosity can never greatly exceed the disc luminosity. Our results confirm Esin et al. (1997) who suggest that the different states in X-Ray binaries can be ordered according to the accretion rate. At low accretion rate, the disc close to the black hole vanishes and only hot coronal gas is left there.

Observationally for low mass black holes Barrio et al. (2003) find that only a weakly illuminated, truncated disc can fit Cyg X-1 data for energies from 3-200 keV. Ptak et al. (2004) present observations of NGC 3398. They fail to find any sign of reflection from an optically thick disc. They conclude that the disc must be truncated at 100-300 Schwarzschild radii.

The model presented here certainly still bears a number of oversimplifications. For example we do not treat any mass loss. There are observational hints, that especially in the low/hard state, these objects lose mass in form of a wind/jet. For the cooling processes in the corona we only consider bremsstrahlung and Compton cooling. Especially in the outer parts there will be contributions from atomic cooling which will possibly lead to a collapse of the corona. Further in, mechanisms like pair production and synchrotron cooling are likely to be important.

Despite all the limitations discussed in the last section, the model presented here nevertheless exhibits the sort of behaviour one would expect from such a system at low accretion rate.

Acknowledgements. MM acknowledges interesting discussions with A. Laor, J. Malzac and A. Różańska in the course of the conference.

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