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The effect of magnetic fields on the truncation of geometrically thin accretion disks in AGN

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Abstract. The concept of a hot advection-dominated accretion flow (ADAF), with or without wind loss, was used to describe the spectra of low-luminosity AGN and nuclei of elliptical galaxies (including M87). These spectral fits of various authors show that the transition from the geometrically thin disk to the hot flow occurs at quite different distances. From the investigations of the interaction of disk and corona, the evaporation of gas from the cool disk into the coronal flow/ADAF one would expect a unique relation between mass flow rate in the cool outer disk and the truncation radius. The fact that this is apparently not the case requires an explanation as pointed out by Quataert, di Matteo and Narayan (1999). We show that this difference might arise from disk magnetic fields extending into the corona depending on whether a disk dynamo works or it is prevented by low conductivity.

1. Accretion onto galactic and supermassive black holes

The form of accretion around black holes depends on the accretion rate. For low sub-Eddington accretion rates a solution was found in which the accreting gas has a very low density and is unable to cool efficiently within an accretion time. In this mode of accretion (advection-dominated accretion flow, ADAF) advection rather than radiation removes the locally generated accretion heat. This is only possible in the inner region around the black hole. At larger distance the mass accretes via a cool geometrically thin standard disk. The situation is the same for galactic and supermassive black holes. This picture was confirmed by the successful modeling of the spectral transitions of LMXRBs (see e.g. Esin, McClintock and Narayan (1997)). For advection-dominated accretion onto supermassive black holes first spectral models were presented by Narayan, Mahadevan and Yi (1995).

2. Transition from thin disk accretion to an ADAF caused by evaporation

The transition to the ADAF can be understood as caused by evaporation of mass from the thin cool disk to the hot corona above (Meyer & Meyer-Hofmeister 1994, Meyer et al. 2000). Such a corona exists predominantly above the inner region of the cool disk. This evaporation efficiency strongly depends on the mass of the compact central object. For a given mass the efficiency increases with decreasing distance to the center. Where at a certain distance from the black hole the evaporation rate becomes equal to the mass flow rate in the outer cool disk, all matter enters the coronal flow and the thin disk is truncated. If one measures the radii r in Schwarzschild radius ($r_{\rm S} = 2GM/c^2$, M mass of central black hole) and the mass accretion rate $\dot M$ in Eddington mass accretion rates ($\dot M_{\rm Edd} = 40\pi M/\kappa c$, κ electron scattering opacity) theory predicts a unique relation between truncation radius and mass accretion rate.

3. Is the disk truncation different in elliptical galaxies and in low luminosity AGN (LLAGN)?

We discussed the truncation of the thin disk in elliptical galaxies for which a mass flow rate was deduced by spectral fits (di Matteo, Quataert and Allen, 2000), NGC 4649 (Quataert and Narayan 1999) and in the LLAGN (Quataert, di Matteo and Narayan 1999). We find a reasonable agreement between the truncation predicted by the evaporation model (Liu and Meyer-Hofmeister 2001), except for the LLAGN M81 and NGC 4579 for which the observed UV flux demands a truncation far inward. Quataert et al. (1999) already pointed out that it needs to be explained how for similar mass flow rates such different transition radii are found, about 100 $r_{\rm S}$ for the LLAGN and 10^3 to $10^4 r_{\rm S}$ for nuclei of elliptical galaxies.

4. Disk dynamos in AGN ?

Up to now the evaluation of the transition from disk accretion to a coronal flow/ADAF has neglected a possibly important aspect: If the temperature in the underlying cool disk is high enough for dynamo action the magnetic fields generated in the underlying disk penetrate into the corona by buoyancy and contribute to the magnetic effects in the coronal accretion flow. The question whether magnetic fields are present or not depends mainly on the temperature in the disk midplane (Gammie & Menou 1998).

In elliptical galaxies the black hole masses are about $10^9 M_\odot$ or more, in LLAGN only about $4{\cdot}10^6 M_\odot$. The midplane temperature is lower for higher black masses when normalized radii r/r_S and accretion rates $\dot M/\dot M_\mathrm{Edd}$ are kept the same. As an example we consider the situation for a mass flow rate $10^{-2.5}\dot M/\dot M_\mathrm{Edd}$ as derived for M81. For this rate we evaluate the disk temperature for both 10^9 and $4\cdot10^6 M_\odot$. The standard curve (Fig.1) would place the truncation radius at $10^{3.5} r_\mathrm{S}$.

At this radius we now evaluate the midplane temperature of the accretion disk using standard algebraic approximations to the vertical structure of the disk. We obtain $T = 10^{2.71}$K for $M = 10^9 M_\odot$ and $T = 10^{3.96}$K for $4 \cdot 10^6 M_\odot$. For the low temperature in disks of elliptical galaxies the gas is neutral and the magnetic Reynolds number $(R_\mathrm{e})_\mathrm{M} \equiv V_\mathrm{s} H/\eta$ (V_s isothermal sound velocity, H disk scaleheight, η electrical resistivity) is very low, $log(R_\mathrm{e})_\mathrm{M}$ is less than -3. For the LLAGN ionization of hydrogen starts to become significant and yields a value several orders above $10^{3.5}$, the critical value. These numbers show that the disk dynamo is quenched for high black hole masses: no effect of disk magnetic fields in the coronal flow is expected. Menou & Quartaert (2001) investigated the magneto-rotational instability in disks around supermassive black holes where the ionisation instability is present. We here consider cooler regions further out.

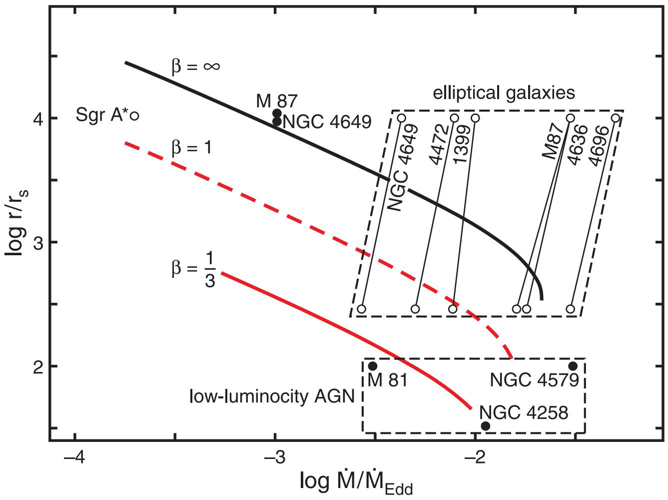

Fig. 1. The dependence of the truncation radius on the magnetic field strength. Theoretical r-$\dot M$ relation for different ratios β = gas pressure/magnetic pressure (black solid line: without magnetic field, red lines: with magnetic field). - For comparison results for $\dot M$ and truncation radius from fits to observed spectra. Open circles (fits including wind loss): Sgr A* from Quataert & Narayan (1999), elliptical galaxies from Di Matteo et al. (2000) (best and second-best fit); filled circles (without windloss): NGC 4649 from Quataert & Narayan (1999), M87 from Reynolds et al. (1996), same value also from Di Matteo et al. (2000), LLAGN M81 and NGC 4579 from Quataert et al. (1999), NGC 4258 from Gammie et al. (1999).

5. Disk truncation - dependence on the magnetic fields

We have performed model calculations including magnetic fields of disk origin. The result is shown in Fig. 1. which gives the truncation radius as function of the accretion rate. We show the recently computed relation (Liu & Meyer-Hofmeister 2001, without disk magnetic fields) and the relations for two values of magnetic field strength. The parameter β is the ratio of gas pressure to magnetic pressure. The mass flow rate of coronal gas towards the center is reduced, therefore less matter is evaporated from the cool disk to replace the inward flowing coronal gas. Due to this reduction a cool disk with a given mass flow rate can extend further inward towards the black hole until all gas is transferred to a coronal flow/ADAF. We also plot values for mass accretion rate and truncation radius for a number of AGN derived by spectral fits (based on an ADAF in the inner region, with or without windloss).

The change of the truncation radius affected by the additional magnetic field is obvious. Such truncation predicted as much closer to the black hole seems appropriate for the LLAGN.

6. Conclusions

We suggest that the presence or absence of a disk dynamo explains the observed difference of truncation radii for the same mass accretion rates between LLAGN and elliptical galaxies.

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