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Letter to the Editor

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

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Abstract. We suggest that magnetic fields in the accretion disks of AGN reach into the coronae above and have a profound effect on the mass flow rate in the corona. This strongly affects the location where the accretion flow changes from a geometrically thin disk to a pure vertically extended coronal or advection-dominated accretion flow (ADAF). We show that this can explain the different disk truncation radii in elliptical galaxies and low luminosity AGN with about the same mass flow rate, a discrepancy pointed out by Quataert et al. (1999). Without disk magnetic activity the disk truncation is expected to be uniquely related to the mass flow rate (Meyer et al. 2000b). Whether dynamo action occurs depends on whether the electrical conductivity measured by a magnetic Reynolds number surpasses a critical value (Gammie & Menou 1998). In elliptical galaxies the disk is self-gravitating at the radii where the truncation should occur. It is plausible that instead of a cool disk a "layer of clouds" may form (Shlosman et al. 1990; Gammie 2001) for which no dynamo action is expected. For low luminosity AGN the magnetic Reynolds number is well above critical. Simple model calculations show that magnetic fields in the underlying disks reduce the strength of the coronal flow and shift the truncation radius significantly inward.

Key words. accretion, accretion disks – black hole physics – X-rays: stars – galaxies: nuclei – galaxies: magnetic fields

1. Introduction

Accretion onto supermassive black holes can occur via an advection-dominated accretion flow (ADAF) or via a standard geometrically thin accretion disk. The mode depends on the accretion rate. In an ADAF advection rather than radiation removes the locally generated accretion heat. This is only possible in the inner region around the central accretor. At larger distance the mass accretes via a cool geometrically thin standard disk. The situation is the same for supermassive and galactic black holes (for a review on the now already "classical" advection-dominated accretion and applications see Narayan et al. 1998). Confirmation for this picture, an ADAF in the inner region near the black hole and a surrounding cool standard disk with a corona above came from the successful modeling of the spectral transitions of low-mass X-ray binaries (LMXRBs) which arise from the changing mode of accretion (Esin et al. 1997, 1998).

The change from disk accretion to an ADAF was investigated for several low luminosity AGN. The low luminosity in the elliptical galaxy M 87 (NGC 4486) was pointed out by Reynolds et al. (1996). Quataert et al. (1999) investigated the low-luminosity galactic nuclei of M 81 and NGC 4579 and from the spectral fits found evidence for thin disks truncated at about 100 Schwarzschild radii, similar to the result for NGC 4258 (Gammie et al. 1999). Di Matteo et al. (1999, 2000) studied the nuclear regions of six elliptical galaxies and derived larger truncation radii from the X-ray and high-frequency radio observations. In these fits wind loss was included which seems to be demanded at least in some galaxies. This means a significant fraction of mass, angular momentum and energy is removed from the accretion flow by a wind. Large radii were found also for M 87 and NGC 4696 by Quataert et al. (1999) (see detailed discussion of constraints for the different objects in their paper). That mass loss via wind may be important was also stated by Quataert & Narayan (1999), who pointed that different combinations of parameters characterizing wind loss and micro physics lead to equally good models. That means comparably good fits to the spectra can be found for different mass flow rates and truncation radii. But despite this ambiguity the fits showed, that there is a clear discrepancy of truncation radii in nuclei of elliptical galaxies of order 10^3 to 10^4 r_S and those in low luminosity AGN (LLAGN) of only 10^2 r_S as pointed out by Quataert et al. (1999) (truncation radii are measured in Schwarzschild radius $r_S = 2\,GM/c^2$, M mass of central black hole).

Since the transition to the ADAF can be understood as caused by evaporation of mass from the thin cool disk to a hot corona above, the truncation of the thin disk depends on the amount of mass flow there (Meyer & Meyer-Hofmeister 1994; Meyer et al. 2000b). If one measures the radii r in Schwarzschild radius and the mass accretion rate $\dot{M}$

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in Eddington mass accretion rates ($\dot{M}_{\rm Edd} = 40\pi GM/\kappa_{\rm es}c$, $\kappa_{\rm es}$ electron scattering opacity) theory predicts a unique relation between truncation radius and mass accretion rate. But in fact the disks in LLAGN reach much closer in, to only 100 Schwarzschild radii, demanded by the observed UV radiation while the accretion rates $\dot{M}/\dot{M}_{\rm Edd}$ are comparable to those in the nuclei of elliptical galaxies.

In the following we suggest that the presence or absence of a disk dynamo explains the observed difference of truncation radii between LLAGN and elliptical galaxies with the same mass accretion rate. Section 2 gives a short description of the transition from disk accretion to a coronal flow. In Sect. 3 we investigate the presence or absence of disk dynamos in AGN. In Sect. 4 we present results of our computations including a magnetic field. A discussion follows in Sect. 5, conclusions in Sect. 6.

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

In previous work (Meyer et al. 2000b) we presented a model for the corona above a geometrically thin standard disk around a black hole. This corona is fed by matter continuously evaporating from the cool disk. The accretion flow is thus divided into a hot coronal flow and a part remaining in the cool disk. The strength of the coronal flow increases inward so that at a certain distance in the inner region all matter is transferred to the coronal flow and the disk is truncated. The situation is the same for galactic and supermassive black holes. The theoretically derived relation for the dependence of evaporation rate on black hole mass and distance allows to determine the truncation radius for each accretion rate. This relation was successfully applied to X-ray transients. Liu & Meyer-Hofmeister (2001) discussed the application to AGN and found reasonable agreement, except that the truncation radii for LLAGN clearly were much smaller than predicted.

3. 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 to occur the magnetic fields generated will penetrate also into the corona and affect the coronal accretion flow. Magnetic dynamos require sufficiently long Ohmic decay times compared to the dynamical time of the dynamo process. This ratio is measured by a magnetic Reynolds number, which is strongly temperature dependent for low temperatures.

Numerical simulations by Hawley et al. (1996) determined a critical value of the magnetic Reynolds number of about $10^{3.5}$. Below this value dynamo action becomes significantly suppressed. Gammie & Menou (1998) showed that dwarf nova accretion disks in quiescence are sufficiently cool to be below this critical value. AGN accretion disks have much larger physical dimensions. Menou & Quataert (2001) have demonstrated that the magnetic Reynolds numbers in such disks are above the critical value in the corresponding quiescent state. Here we are concerned with even further out ranges in elliptical galaxies where temperatures become extremely low.

In elliptical galaxies the black hole masses are about 10^9 $M_\odot$ or more, in LLAGN only a few 10^6 $M_\odot$. For higher black hole masses the midplane temperature is lower when normalized radii $r/r_{\rm S}$ and accretion rates $\dot{M}/\dot{M}_{\rm Edd}$ are kept the same. As an example we consider the situation for a mass flow rate $10^{-2.5}\dot{M}_{\rm Edd}$ as derived for M 81. For this rate we consider the disk structure at a radius of $10^{3.5}$ $r_{\rm S}$ where the truncation would be expected from the standard curve (Fig. 1).

Structure and evolution of accretion disks in AGN were investigated mainly in connection with the ionization instability in these disks (Mineshige & Shields 1990; Cannizzo & Reiff 1992; Cannizzo 1992; Siemiginowska et al. 1996). The radii of interest for our evaluation are larger than those considered there. For high central masses self-gravitation becomes important at such radii.

To explore a possible influence of disk dynamo action on the corona we refer to investigations for self-gravitating disks. Shlosman et al. (1990) discussed an attractive model of a "disk of clouds": when the angular momentum transport is locally mediated gravitational interaction, the disk breaks up and possibly forms a layer of clouds (which should occur if the cooling time is short compared to the Kepler time). Recent numerical computations of Gammie (2001) for a thin horizontally extended layer confirm this picture with the formation of blobs. The clouds then by interaction have to transport the angular momentum, no effective dynamo would be expected. How can in this case the accretion flow via the clouds be transformed to a coronal flow? According to the standard evaporation model these clouds must be embedded in a corona in equilibrium with the cool surfaces of the blobs. Thermal conduction of the hot corona to the cool surfaces establishes an equilibrium density and a mass flow rate from the blobs to the coronal gas, similar to the case of an underlying cool disk. The conductive flux requires a large enough surface area. Estimates give that a cloud covering factor $C \geq 10^{-2}$ is required, which seems possible. Then the cloud layer is cut off and closer to the center only a coronal flow (ADAF) exists.

Balbus & Papaloizou (1999) discuss an alternative picture, in which waves propagating over long-range distances transport angular momentum and also energy (note that Gammie 2001 gives arguments against the formation of large scale coherence). The effective removal of angular momentum in this way might allow the existence of a disk marginally stable against break up. Because of non-local energy transport the disk would be cooler than a corresponding "high-α" disk with the same angular momentum transport. For the latter disk (for a marginally stabilized disk see Paczyński 1978) in our case the formal values of α would be $\geq$10. The midplane temperature in such a disk can be derived using a technique for solving the full vertically averaged disk equations similar to the accretion disk modeling in Cannizzo & Reiff (1992). We get for the temperature

$$T = 10^{2.7}\left(\frac{M}{10^9\ M_\odot}\right)^{-4/7}\left(\frac{r}{10^{3.5}\ r_{\rm S}}\right)^{-9/7}\left(\frac{\dot{M}}{10^{-2.5}\ \dot{M}_{\rm Edd}}\right)\ {\rm K} \qquad (1)$$

and for the density

$$\rho = 10^{-12.6} \left(\frac{M}{10^9\ M_\odot}\right)^{-2} \left(\frac{r}{10^{3.5}\ r_S}\right)^{-3}\ \mathrm{g\ cm^{-3}}. \tag{2}$$

The value of α is then dependent on M, r and $\dot{M}$, incorporated in the formulae above. In the derivation of Eqs. (1) and (2) we used dust opacities, $\kappa = 1\ \mathrm{cm^2/g}$. The heating in the disk is due to internal dissipation. Direct and indirect (by scattering on the clouds) irradiation is negligible for the example M 87 because of the low luminosity.

With these numbers we can evaluate the magnetic Reynolds number

$$Re_M \equiv V_s H/\eta = \sqrt{2}\frac{\Re}{\mu} T/\Omega^2 \eta \tag{3}$$

with V_s isothermal sound velocity, H disk scale height, η magnetic diffusivity, $\Re$ gas constant, μ molecular weight, Ω Kepler rotation frequency.

With the magnetic diffusivity $\eta = m_e c^2 \nu_{en}/n_e e^2$ (n_e electron number density, e electron electric charge, m_e electron mass, ν_{en} electron neutral collision frequency proportional to the number of neutral particles n_n) the Reynolds number becomes proportional to the ratio $x_e = n_e/n_n$ (Gammie & Menou 1998). This gives

$$Re_M = 10^{9.7} \left(\frac{M}{10^9\ M_\odot}\right) \left(\frac{r}{10^{3.5}\ r_S}\right)^{3} [X(T) \cdot T]^{1/2} \tag{4}$$

with $X(T) = n_n x_e^2$ is a function of temperature only determined by the Saha equation. The ionization state of the electron providing alkali metals becomes extremely low for the low temperatures. This yields a Reynolds number below the critical value of $10^{3.5}$ for $T \leq 10^{2.9}$ K. At the low densities of these disks ambipolar diffusion (Cowling 1976) increases the magnetic diffusivity (see also recent simulations by Sano & Stone 2002) and thereby reduces the magnetic Reynolds number. With typical dynamo values $\beta \approx 20$ (β ratio of gas pressure to magnetic pressure) the reduced Re_M is below the critical value for $T \leq 10^{3.1}$ K. Then no effect of disk magnetic fields is expected.

We conclude that in both these cases, a disk of clouds and a disk marginally stabilized by wave transport, the evaporation of cool gas into the corona occurs without the influence of a disk magnetic field.

For the disks in LLAGN we derived the temperature in the same way (such disks are not self-gravitating and we took $\alpha = 0.01$). At the same (scaled) distance and mass accretion rate one obtains $T = 10^{3.3}$ K. This is in the range already considered by Menou & Quataert (2001). In agreement with their analysis the magnetic Reynolds number becomes large enough to allow dynamo action.

4. The effect of the disk magnetic field on the truncation radius

We investigated how a magnetic field in the thin disk affects the coronal mass flow. The amount of matter that has evaporated from the disk and flows in the corona at a given distance from the black hole can be determined by solving a set of ordinary differential equations which describe vertical dynamical equilibrium, conservation of mass and energy and heat flux (Meyer et al. 2000b). Our earlier computations take magnetic fields of a coronal dynamo only implicitly, as a source of friction, into account as in standard disk theory. But an analytical estimate was given how β enters into numerical results (Meyer et al. 2000b). For the present investigation we explicitly model the effect of additional magnetic fields (e.g. from an underlying disk) on coronal dynamical equilibrium, energy release, and diffusive inward mass flow. To a first approximation all effects can be accounted for if in all equations one formally replaces the gas pressure P by the product $P(1 + 1/\beta)$. The result is a remarkable reduction of the strength of the coronal mass flow, i.e. of the evaporation efficiency, with increasing magnetic field.

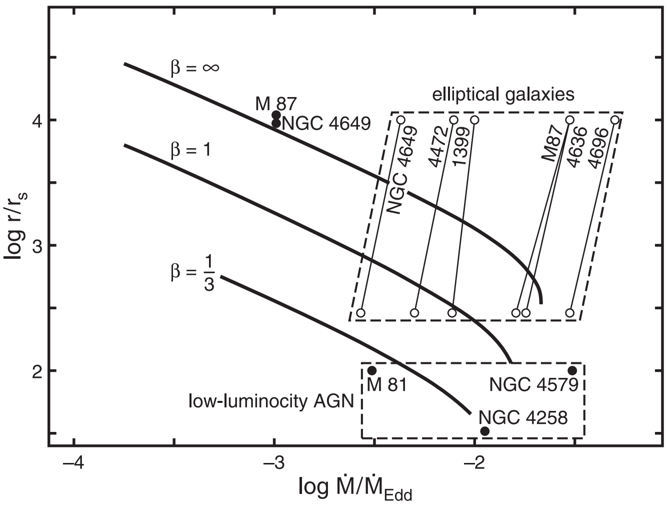

Fig. 1. The dependence of the truncation radius on the magnetic field strength. Solid lines: theoretical r–$\dot{M}$ relations for different ratios β = gas pressure/magnetic pressure. - For comparison results for $\dot{M}$ and truncation radius from fits to observed spectra. Open circles (fits including wind loss): elliptical galaxies from Di Matteo et al. (2000) (best and second-best fit); filled circles (without wind loss): NGC 4649 from Quataert & Narayan (1999), M 87 from Reynolds et al. (1996), same value also from Di Matteo et al. (2000), LLAGN M 81 and NGC 4579 from Quataert et al. (1999), NGC 4258 from Gammie et al. (1999).

Matter therefore remains in the cool disk down to much smaller radii before the coronal flow has picked up all the accretion flow and the disk is truncated. Figure 1 shows the truncation radius as a function of the distance from the black hole. The values are scaled to $\dot{M}_{Edd}$ and r_S. (Inside of the truncation radius all matter flows in the form of a hot corona). The additional field shifts the truncation radius to smaller distances r. A moderate magnetic field strength in the corona ($\beta = 1$) reduces the truncation radius by about a factor 5, a three times higher magnetic pressure results in a reduction by a factor 25. This is an important change.

In addition Fig. 1 shows data derived from observations by various authors. The observational data show a wide range of truncation radii. In particular only radii of 10^4 or 300 r_S were considered in the investigation of nuclei of elliptical galaxies (Di Matteo et al. 2000) dealing with spectral fits based on an extension of the ADAF model including loss of mass and angular momentum by a wind. Note that spectral fits with wind loss yield only lower limits of truncation radii. For M 87 both, models with and without wind loss agree with the observed spectra. (Different results for NGC 4649 are due to different black hole mass.) Despite this spread in acceptable r–$\dot{M}$ combinations there is a clear discrepancy between the truncation radii for LLAGN and nuclei of ellipticals with comparable mass flow rates (Quataert et al. 1999).

5. Discussion

5.1. Dynamos in AGN disks

We expect dynamo action for LLAGN, but not for elliptical galaxies with a very high central mass. Otherwise if accretion rates are low it is possible that the temperature even in disks around 10^6 $M_\odot$ is low enough to forbid dynamo action (an example could be Sgr A* with a central mass of 2.5×10^6 $M_\odot$ indicated by observations, Genzel et al. 1997, and an accretion rate from spectral fits based on ADAF models of 10^{-4} $\dot{M}_{\rm Edd}$, Quataert & Narayan 1999 – if the thin disk really exists, doubts come from new Chandra observations, Narayan 2002). On the other hand for higher mass accretion rates disks around the high mass black holes in elliptical galaxies are hot enough to allow dynamo action at the standard truncation radius, so that the true truncation radius becomes shifted inward to smaller radii.

5.2. The strength of the disk magnetic fields in the corona

To estimate the field strength of disk dynamo fields in the corona is difficult. The data for M 81 (Fig. 1) indicate a value of $\beta \approx 1/3$ as appropriate. Near the truncation radius mass flow rates in corona and disk are of comparable size. This implies that the product $\left(1 + \frac{1}{\beta}\right)HP$ is about the same. From this one can estimate the required magnetic pressure in the corona $\left(\frac{B^2}{8\pi}\right)_{\rm corona} \approx 10^{-1.2}\left(\frac{B^2}{8\pi}\right)_{\rm disk}$ where the temperature ratio $T_{\rm disk}/T_{\rm corona} \approx 10^{-4.6}$ estimated for M 81 and $(\beta)_{\rm disk} = 20$ were used. Such values may be reached if a corresponding fraction of the dynamo magnetic energy is cascaded to scales of the coronal scale height or larger (e.g. Arlt & Brandenburg 2001).

6. Conclusion

The investigation of the effect of magnetic fields of the underlying cool disk penetrating into the corona leads to interesting aspects for accretion in AGN. Our work suggests that the difference in truncation radii derived for LLAGN and ellipticals with similar accretion rates is due to the very different black hole masses, $10^{6.5}$ $M_\odot$ and 10^9 $M_\odot$ respectively. For the same mass flow rate and at the same distance from the black hole (when measured in units of $\dot{M}_{\rm Edd}$ and $r_{\rm S}$) the disks in LLAGN are hot enough, but those in ellipticals are cool and self-gravitating, no magnetic dynamo work. In LLAGN the magnetic fields affect the coronal flow and shift the truncation to much smaller radii. The truncation of disks in X-ray binaries and the spectral transitions from hard to soft state (Meyer et al. 2000a) will also be affected when disk dynamos occur.

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