A&A manuscript no.
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Your thesaurus codes are:
02.01.2 - 02.02.1 - 11.14.1 - 11.09.1 M87, M81 - 13.25.2

ASTRONOMY
AND
ASTROPHYSICS

November 28, 2000

Truncation of geometrically thin disks around massive black holes in galactic nuclei

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Received:s / Accepted:

Abstract. The concept of an advection-dominated accretion flow (ADAF), with or without wind loss, was used to describe the spectra of the galactic center source SgrA*, low-luminosity AGN and nuclei of elliptical galaxies (including M87). The spectral fits of various authors show that the transition from the geometrically thin disk to the hot flow occurs at quite different distances, apparently not uniquely related to the mass flow rate in the disk. We compare these results with the results of theoretical modelling where we determine the truncation of the thin outer disk from the efficiency of mass evaporation. The physics is the same as in the case of galactic black holes systems (Meyer et al. 2000b). For the observationally indicated mass flow rates our model predicts a truncation at 10^3 to 10^4 Schwarzschild radii. We discuss whether far inside this truncation an inert cool thin disk could exist and affect the spectrum.

Key words: accretion disks – black hole physics – galaxies: nuclei – galaxies: individual: M87, M81 – X-rays: galaxies

1. Introduction

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 (Ichimaru 1977, Rees et al. 1982, Narayan & Yi 1994, 1995a, 1995b, Abramowicz et al. 1995, Honma 1996, for a reviews see Narayan et al. 1998, Kato et al. 1998). 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 according to the "strong ADAF principle" (Narayan & Yi (1995b). At larger distance the mass is accreted via a geometrically thin standard disk. As the investigation of the equilibrium between the cool thin disk and a corona above this disk (predominantly above the inner region of the cool disk) show a continuous evaporation of gas from the cool disk to the corona occurs, an evaporation of matter which causes the transition to the hot flow (Meyer & Meyer-Hofmeister 1994). Where the evaporation of mass is efficient enough to bring all matter into the corona the cool disk in the midplane is truncated and all gas proceeds towards the black hole as an ADAF. The aim of the present paper is the application of our results for the evaporation process in black hole accretion disks (Meyer et al. 2000b) to supermassive black holes. Coronae in AGN were already considered by several authors. Recent work of Różańska & Czerny (2000a, 2000b) on the co-existence of the hot and the cold gas around galactic black holes and AGN also focuses on the transition to an ADAF.

In new investigations of the low luminosity galactic nuclei of M81 and NGC 4579 (Quataert et al. 1999) evidence was found for thin disks truncated at about 100 Schwarzschild radii, similar to the result for NGC 4258 (Gammie et al. 1999). The low luminosity in the elliptical galaxy M87 (NGC 4486) was pointed out by Reynolds et al. (1996), illustrating the problem of a "quiescent" black hole. The nuclear regions of six elliptical galaxies were studied by Di Matteo et al. (1999, 2000). From the X-ray emission together with recent high-frequency radio observations new constraints for the physical properties of any proposed ADAF were derived. These radio and submillimeter observations seem to demand that, at least in some galaxies, a significant fraction of mass, angular momentum and energy is removed from the accretion flow by a wind.

In this paper we first give a short description of the physics of evaporation, as included in our computations (Sect. 2). In Sect. 3 we present the results, and compare in Sect. 4 with findings from the spectra of low luminosity AGN and elliptical galaxies. In Sect. 5 we discuss a new suggestion for an innermost inert thin disk which comes from the evaporation/condensation picture and might help to solve discrepancies which were already found applying the ADAF model to low-luminosity galaxies.

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2. The equilibrium between thin disk below and corona above: evaporation of cool gas

The equilibrium between a cool disk and the corona above it is investigated in order to determine how much of the gas flows in the corona, that is, the amount evaporated from the cool disk into the corona. 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 (except in an innermost part).The co-existence of a cool disk and a corona had already been investigated for disks in dwarf nova systems (Meyer & Meyer-Hofmeister 1994, Liu et al. 1995). The situation is the same in disks around neutron stars, stellar and supermassive black holes. For the properties of two-temperature, optically thin ADAFs (Narayan et al. 1998) successfully applied to accretion in stellar black holes and galactic nuclei, the quantities accretion rate and distance were written in units of Eddington accretion rate and Schwarzschild radius. ($\dot{M}_{\rm Edd} = 40\pi GM/\kappa c$, $r_{\rm S} = 2GM/c^2$, with M mass of central black hole and κ electron scattering opacity). The solutions then are invariant. Our relation between evaporation rate and distance is also invariant.

We solve a set of four ordinary differential equations for motion of the gas, mass, energy and thermal flux (Meyer et al. 2000b) to model the equilibrium between cool disk and corona near the inner edge of the thin disk. The boundary conditions are: (1) at infinity no pressure (i.e. no artificial confinement, which requires sound transition at some height) and no influx of heat and (2) at the bottom of the corona chromosphere temperature and no heat inflow. For our computations we assumed the viscosity parameter in the hot gas α=0.3.

3. Results of computations

We carried out computations for massive black holes of 2.5×10^6 and $10^8 M_\odot$ with Schwarzschild radii of 7.38×10^{11} and 2.95×10^{13} cm, respectively. In Table 1 and 2 we list mass flow rates $\dot{M}$ in the corona for a number of distances r. $\dot{M}$ and r are also given in units of Eddington accretion rate and Schwarzschild radius. The relation between $\dot{M}$ and r is invariant if accretion rates and distances are measured in these units. The same is true for the coronal temperature (compare Fig. 3 and the comments in Meyer et al. 2000b) and for the fraction of matter carried away by the wind. Also given are the values of pressure and mass flow rate into the corona at the lower boundary. Note that three similar rates are considered: the evaporation rate is equal to the mass flow rate in the thin disk at its inner edge; the mass flow rate in the corona is equal to the evaporation rate minus wind loss (accretion rate onto the black hole, if no wind loss further in).

In Fig. 1 we show the relation between the location of the inner disk edge and the accretion rate. For example

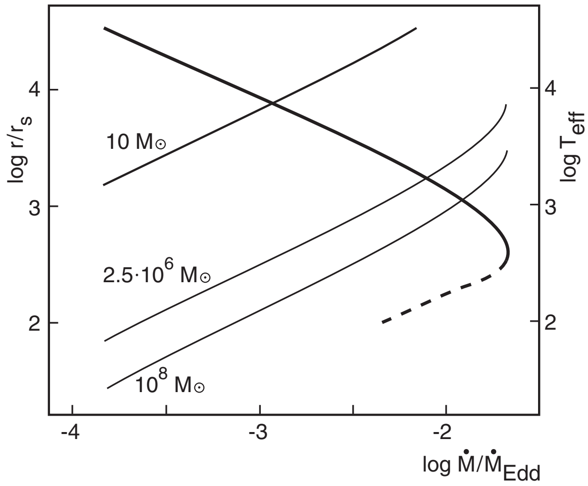

Fig. 1. Radius of transition from accretion via a geometrically thin disk to a coronal flow/ADAF (in units of Schwarzschild radius $r_{\rm S}$) as function of the mass flow rate in the corona (in units of the Eddington accretion rate $\dot{M}_{\rm Edd}$), $T_{\rm eff}$ effective temperature at the inner edge of the thin disk.

for the mass flow rate $\dot{M}/\dot{M}_{\rm Edd}$=$10^{-3}$ the thin disk is truncated at about $6{\cdot}10^3$ Schwarzschild radii. Inside the accretion flow is hot and optically thin, the thin disk has a "hole".

Also shown in Fig. 1 is a measure for the effective temperature $T_{\rm eff}^4 = 3GM\dot{M}/8\pi\sigma r^3$ near the inner edge of the thin disk. The effective temperature does not scale. The higher the black hole mass the lower is the temperature. These disk temperatures are important for the spectral fits. For comparison we also show the temperature in a disk around a stellar black hole.

The recent investigations of Różańska & Czerny (2000a, 2000b) mostly concentrate on the hot flow properties and use a two-temperature plasma. They find a slightly different relation between evaporation rate and distance. We investigate the equilibrium where the assumption of a one-temperature plasma is a still valid.

4. Comparison with observations

The investigation of nuclei of bright nearby elliptical galaxies by Fabian & Canizares (1988) already showed that the galactic nuclei are very under luminous. As suggested by Fabian & Rees (1995) and confirmed by detailed calculations of Mahadevan (1997) the problem is resolved if the galactic nuclei accrete via an ADAF. Likewise the apparently contradictory observations of SgrA* could be understood by advection-dominated accretion (suggestion by Rees (1982), first spectral model by Narayan et al. (1995)). Further successful applications of the ADAF model were carried out for the maser galaxy NGC 4258 and the nearby galactic nuclei M87 and M60 (for a review see Narayan et al. 1998).

Table 1. Evaporation of the disk around a black hole of $2.5 \times 10^6 M_\odot$

$\log r$	$\log \dot{m}_0$	$\log P_0$	T(K)	$\dot{M} = 2\pi r^2 \dot{m}_0 (M_\odot/y)$	λ	$\log r/r_S$	$\dot{M}/\dot{M}_{\rm Edd}$
15.87	-11.10	-2.44	4.51×10^7	4.30×10^{-5}	0.23	4.00	7.81×10^{-4}
15.48	-9.79	-0.93	1.10×10^8	1.47×10^{-4}	0.20	3.61	2.67×10^{-3}
15.00	-8.26	0.88	3.14×10^8	5.52×10^{-4}	0.15	3.13	1.00×10^{-2}
14.60	-7.17	2.26	6.85×10^8	1.09×10^{-3}	0.09	2.73	1.98×10^{-2}
14.40	-6.72	2.89	9.59×10^8	1.19×10^{-3}	0.04	2.53	2.16×10^{-2}
14.30	-6.57	3.14	1.06×10^9	1.07×10^{-3}	0.01	2.43	1.95×10^{-2}
14.18	-6.46	3.40	1.11×10^9	7.77×10^{-4}	$\leq 10^{-3}$	2.31	1.41×10^{-2}

Notation: $\dot{m}_0$ and P_0 vertical mass flow density and pressure at the lower boundary of the corona, T coronal temperature at the upper boundary (sound transition), $\dot{M}$ evaporation rate; λ fraction of mass carried away by the wind; quantities r/r_S and $\dot{M}/\dot{M}_{\rm Edd}$ scaled to Schwarzschild radius and Eddington accretion rate. $r, \dot{m}_0, P_0$ in cgs units.

Table 2. Evaporation of the disk around a black hole of $10^8 M_\odot$

$\log r$	$\log \dot{m}_0$	$\log P_0$	T(K)	$\dot{M} = 2\pi r^2 \dot{m}_0 (M_\odot/y)$	λ	$\log r/r_S$	$\dot{M}/\dot{M}_{\rm Edd}$
17.00	-11.12	-2.22	1.32×10^8	7.49×10^{-3}	0.19	3.53	3.40×10^{-3}
16.70	-10.16	-1.08	2.56×10^8	1.74×10^{-2}	0.16	3.23	7.91×10^{-3}
16.48	-9.49	-0.27	4.08×10^8	2.90×10^{-2}	0.14	3.01	1.32×10^{-2}
16.00	-8.32	1.28	9.63×10^8	4.77×10^{-2}	0.04	2.53	2.16×10^{-2}
15.70	-8.04	1.93	1.08×10^9	2.30×10^{-2}	$\leq 10^{-3}$	2.23	1.04×10^{-2}
15.48	-7.94	2.27	1.06×10^9	1.02×10^{-2}	$\leq 10^{-3}$	2.00	4.64×10^{-3}

Notation as in Table 1.

Recent observations in X-rays and in additional different wavelength bands brought further information and at the same time new constraints. Improvement also comes from new measurements of accurate mass and distance, e.g. for NGC 4258 (Herrnstein et al. 1997, 1999).

Di Matteo et al. (1999) examined high-frequency radio observations of three giant low-luminosity elliptical galaxies in the Virgo cluster NGC 4649, NGC 4472 and NGC 4636 using the VLA (Very Large Array) and SCUBA (Submillimetre Common-User Bolometer Array) on the Clerk Maxwell Telescope, and hard X-ray emission. They found radio fluxes lower than the emission predicted by the standard ADAF model. In a second paper Di Matteo et al. (2000) discuss constraints for the advection-dominated flow in the three Virgo ellipticals and three cluster galaxies M87 (NGC 4486), NGC 1399, and NGC 4696 and suggest that mass loss is important in the radiatively inefficient accretion flow.

In Fig. 2 we show results from several investigations. For the elliptical galaxies we show the fit values deduced by Di Matteo et al. (2000), their best and second best fit (radii of 300 or 10^4 were considered and rates $\dot{M}/\dot{M}_{\rm Edd}$ in the range 0.01 to 0.001 (in investigations including wind loss the quantity $r_{\rm out}$ is used instead of a transition radius and the wind loss is parametrisized by assuming that the mass flow rate decreases as $\dot{M} = \dot{M}_{\rm out} \cdot (r/r_{\rm out})^p$. We also show the results from recent ADAF modelling of SgrA* and the very similar galactic transient source V404 Cyg (Quartaert & Narayan 1999) which explains the spectra well without wind loss. Also the observations for M87 can be modelled without moss loss (Di Matteo et al. 2000). Quataert et al. (1999) pointed out that for accretion rates of 0.03 $\dot{M}_{\rm Edd}$ the thin accretion disks in M87 and NGC 4696 must be truncated at $\geq 10^4$ Schwarzschild radii.

More values of transition radii (or $r_{\rm out}$) and mass accretion rates were deduced for different model parameters concerning the physics in the ADAF region. The fits shown in Fig. 2 give a documentation of the wide spread of possible solutions. Our model predicts a truncation further outward for smaller mass flow rates in the thin disk. For galactic black hole binaries the constraints from an observed Hα emission line for the transition radius can be met well (Meyer et al. 2000b). For SgrA*, M87 (fit without wind loss) and NGC 4649 predictions and fit results agree reasonably. The spectral fits for elliptical galaxies show a wide range. Conclusions from a comparison with the theoretical results for nuclei of elliptical galaxies must be deferred until the infall of gas from a cooling flow is included in our model.

For the low luminosity AGN (LLAGN) M81 and NGC 4579 the observed UV flux demands a truncation far inward, which is in contradiction to our findings. 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_S for the LLAGN and 10^3 to $10^4 r_S$ for nuclei of elliptical galaxies. These authors raised the question whether the cooling flow in ellipticals could be responsible for this difference. But comparing with our results the LLAGN are the systems which need to be explained. Possibly the evaporation picture can offer an alternative view as will be discussed in the next section. For a review of UV and optical continuum emission in AGN see Koratkar & Blaes (1999).

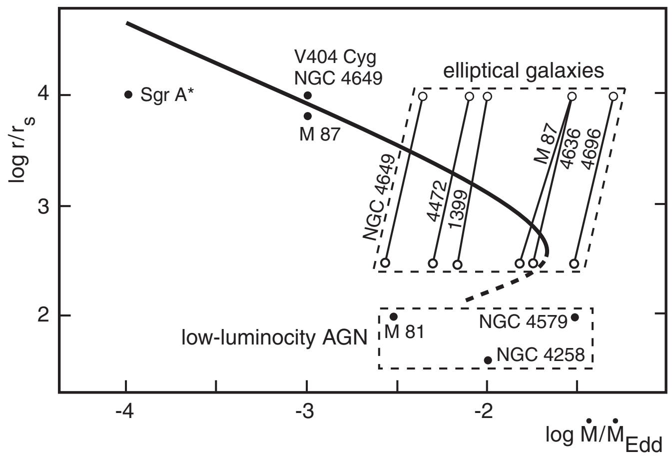

Fig. 2. Comparison of the theoretical r-$\dot{M}$ relation (same as in Fig. 1) with results from observations. Mass accretion rates and radii from spectral fits of various investigations: elliptical galaxies from Di Matteo et al. (2000) (best and second-best fit), low-luminosity AGN M81 and NGC 4579 from Quataert et al. (1999), NGC 4258 from Gammie et al. (1999), Sgr A*, NGC 4649 and the same value for V404 Cyg from Quataert & Narayan (1999), value for M87 (without wind) from Reynolds et al. (1996). Filled symbols correspond to fits without wind loss, open symbols with wind loss.

5. Discussion and conclusions

Comparing our results with accretion rates and transition radii from ADAF spectral fits without wind loss we find agreement for M87 (see also Liu et al. 1999) and NGC 4649. The same is true for the stellar black hole source V404 Cyg, the soft X-ray transient with the best X-ray data available (the agreement is generally good in the case of X-ray novae, Meyer et al. 2000b). To compare the results for elliptical galaxies the infall of gas from a cooling flow would have to be included in our modelling.

Concerning the low luminosity AGN the UV radiation demands the presence of a thin disk inward to 100 Schwarzschild radii. In our modelling the evaporation efficiency has a maximum around 300 r_S. A transition to a coronal flow/ADAF would then have to be outside of this radius (see Fig. 1, and Meyer et al. 2000b, Fig. 6). Inside, a coronal two-temperature situation holds and the formation of an interior thin disk by condensation of matter from the hot coronal flow appears possible (Meyer et al. 2000a, see also Różańska & Czerny, 2000a). Vilhu et al. (2000) modelled observations for the galactic black hole source GRS 1915+105 with a corona above an interior disk. The effective temperatures of the interior disk regions depend on the black hole mass (see Fig. 1 for effective temperatures at the transition radius). Correspondingly radiation in different wavelength bands would be expected from these regions, for the LLAGN predominantly in UV (the mass flow in the interior disk might be a fraction of the total accretion rate, the major part presumably flows in the ADAF corona). The observed UV radiation then would not necessarily point to a disk truncation at 100 r_S.

Acknowledgements. We thank Friedrich Meyer for discussions.

References

Abramowicz M.A., Chen X., Kato S. et al., 1995, ApJ 438, L37
Di Matteo T., Fabian A.C., Rees M.J. et al., 1999, MNRAS 305, 492
Di Matteo T., Quataert E., Allen S.W. et al., 2000, MNRAS 311, 507
Fabian A.C., Canizares C.R., 1988, Nature 333, 829
Fabian A.C., Rees M.J., 1995, MNRAS 277, L5
Gammie C.F., Narayan R., Blandford R., 1999, ApJ 516, 177
Herrnstein J.R., Moran J.M., Greenhill L.J. et al., 1997, BAAS, 191, 2507
Herrnstein J.R., Moran J.M., Greenhill L.J. et al., 1999, Nature 400, 539
Honma F., 1996 PASJ 48, 77
Ichimaru S., 1977, ApJ 214, 840
Kato S., Fukue J., Mineshige S., 1998, Black Hole Accretion Discs, Kyoto University Press
Koratkar A., Blaes O., 1999, PASP 111, 1
Liu B.F., Yuan W., Meyer F., et al., 1999, ApJ 527, L17
Liu F.K., Meyer F., Meyer-Hofmeister E., 1995, A&A 300, 823
Mahadevan R., 1997, ApJ 477, 585
Meyer F., Meyer-Hofmeister E. 1994, A&A 288, 175
Meyer F., Liu B.F., Meyer-Hofmeister E., 2000a, A&A 354, L67
Meyer F., Liu B.F., Meyer-Hofmeister E., 2000b, A&A 361, 175
Narayan R., Mahadevan, R., Yi, 1995, Nature 374, 623
Narayan R., Mahadevan R., Quartaert E., 1998, in: The Theory of Black Hole Accretion Discs, eds. M.A. Abramowicz et al., Cambridge University Press, p.148
Narayan R., Yi, 1994, ApJ Letters 428,
Narayan R., Yi, 1995a, ApJ 444, 231
Narayan R., Yi, 1995b, ApJ 452, 710
Quataert E., Di Matteo T., Narayan R. et al., 1999, ApJ 525, L89
Quataert E., Narayan R., 1999, ApJ 520, 298
Rees M.J., 1982, in: The Galactic Center, eds. G.R. Riegler & R.D. Blandford, AIP, New York, p.166
Rees M.J., Begelman M.C., Blandford R.D. et al., 1982, Nature 295, 17
Reynolds C.S., Di Matteo T., Fabian A.C. et al., 1996, MNRAS 283, L111
Różańska A., Czerny B., 2000a, A&A 360, 1170
Różańska A., Czerny B., 2000b, MNRAS 316, 473
Vilhu O., Petter N., Poutanen J. et al., 2000, astro-ph0010601