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Accretion disks with optical depth transition and advection

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Abstract. We consider the effects of advection and radial gradients of pressure and radial drift velocity on the structure of accretion disks around black holes. We concentrated our efforts on highly viscous disk with large accretion rate. Contrary to disk models neglecting advection, we find that continuous solutions extending from the outer disk regions to the inner edge exist for all accretion rates we have considered. We show that the sonic point moves outward with increasing accretion rate. Despite the importance of advection on it's structure, the disk remains geometrically thin. Global solutions of advective accretion disks, which describes continuously the transition between optically thick and optically thin disk regions are constructed and analyzed.

Key words. Accretion, accretion disks - black hole physics

1. The Model and the Method of Solution

In this paper we will consider the full set of solutions to the disk structure equations with advection including the optically thick, optically thin and the intermediate zones in accretion disks.

We use from now on geometric units with $G = 1$, $c = 1$, use r as the radial coordinate scaled to $r_g = M$, and scale all velocities to c. We work with the pseudo-Newtonian potential proposed by Paczyński and Wiita (1980), $\Phi = -M/(r-2)$, that provides an accurate, yet simple approximation to the Schwarzschild geometry. We normalize the accretion rate as $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$, where $\dot{M}_{\rm Edd} = L_{\rm Edd} = 4\pi M m_p/\sigma_T$, in our units.

We use the same set of equations, ingredients and boundary conditions in our models as in Artemova et al. (2001), except for changes required by the formulae for radiative flux and radiation pressure to describe correctly the intermediate zone in the accretion disk at high accretion rates. We used the same numerical method (see Artemova et al. (2001)) to solve this modified system of algebraic and differential equations.

The following equations are therefore modified:

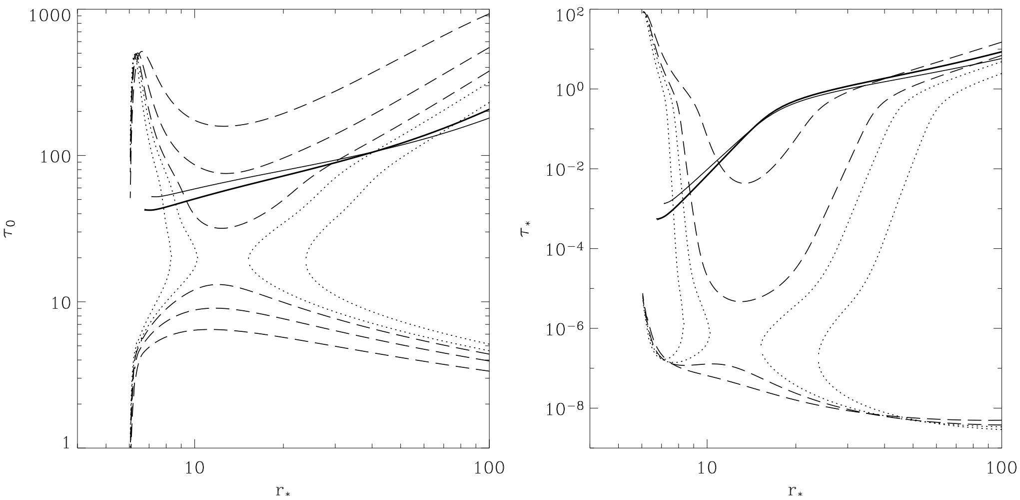

Fig. 1. The dependence of the Thomson scattering depth (left panel) and the effective optical depth (right panel) on the radius. Dashed lines correspond to the solutions without advection and $\dot{m} < \dot{m}_{cr} = 36$. Dotted lines correspond to the non-physical solutions without advection for $\dot{m} = \dot{m}_{cr} = 36$ and $\dot{m} = 50$ (from the center to the edge of the picture respectively). Solid lines correspond to the solutions with advection and the mass accretion rate higher than the critical one ($\dot{m} = 36.0$, (the upper curve) and $\dot{m} = 50.0$ (the lower curve) from the left edge of the picture).

The vertically averaged energy conservation equation:

$$Q_{adv} = Q^+ - Q^-, \qquad (1)$$

where

$$Q_{adv} = -\frac{\dot{M}}{4\pi r}\left[\frac{dE}{dr} + P\frac{d}{dr}\left(\frac{1}{\rho}\right)\right], \qquad (2)$$

$$Q^+ = -\frac{\dot{M}}{4\pi} r\Omega\frac{d\Omega}{dr}\left(1 - \frac{l_{in}}{l}\right), \qquad (3)$$

$$Q^- = \frac{2aT^4c}{3\kappa\rho h}\left(1 + \frac{4}{3\tau_0} + \frac{2}{3\tau_*^2}\right)^{-1}, \qquad (4)$$

are the advective energy, the viscous dissipation rate and the cooling rate per unit surface, respectively, T is the midplane temperature, κ is the opacity, a is the radiation constant and τ_0 is the Thompson optical depth, $\tau_0 = \kappa\rho h$. Here we have introduced the total optical depth to absorption, $\tau_\alpha \ll \tau$,

$$\tau_\alpha = \frac{\epsilon_{ff} + \epsilon_{fb}}{aT_c^4 c}\rho h \simeq 5.2 * 10^{21}\frac{\rho^2 T^{1/2} h}{acT^4}, \qquad (5)$$

and the effective optical depth

$$\tau_* = (\tau_0\tau_\alpha)^{1/2}.$$

Where ρ is the density and h is the half-thickness of the disk.

The equation of state for the matter consisted of a gas-radiation mixture is

$$P_{\rm tot} = P_{\rm gas} + P_{\rm rad}, \qquad (6)$$

where the gas pressure is given by

$$P_{\rm gas} = \rho\mathcal{R}T,$$

where $\mathcal{R}$ is the gas constant.

The expression for the radiation pressure is

$$P{\rm rad} = \frac{aT^4}{3}\left(1 + \frac{4}{3\tau_0}\right)\left(1 + \frac{4}{3\tau_0} + \frac{2}{3\tau_*^2}\right)^{-1}.$$

The specific energy of the mixture is

$$\rho E = \frac{3}{2}P_{\rm gas} + 3P_{\rm rad}. \qquad (7)$$

Our method allows us to construct a self-consistent solution to the system of equations from very large radii, $r >> 100$, and down to the innermost regions of the disk.

2. Results and Discussion

We will now compare the solutions with advection and without it. In the "standard model", for accretion rates $\dot{m} < \dot{m}_{cr} = 36$, (for α=0.5 and $M_{BH} = 10 M_\odot$, where $\dot{m}_{cr}$ is the critical accretion rate) there always exist solutions that extend continuously from large to small radii. When $\dot{m} > \dot{m}_{cr} = 36$ there are no solutions in a range of radii around $r \approx 13$, and therefore no continuous solutions extending from large radii to the innermost disk edge (see detailed discussion by Artemova et al. 1996, where however, the Newtonian potential was used, resulting in $\dot{m}_{cr} = 9.4$ for α=1.0 and $M_{BH} = 10^8 M_\odot$).

In Fig.1 we plot the Thomson scattering depth τ_0, (left panel) and the effective optical depth τ_* (right panel) as a function of radius, r, for different $\dot{m}$ (for α=0.5 and $M_{BH} = 10 M_\odot$), clearly demonstrating that the solutions to the complete system of disk structure equations including advection and radial gradients have quite different properties at high $\dot{m}$ compared to the solutions of the standard disk model. For $\dot{m} < \dot{m}_{cr} = 36$ (dashed lines), including the gradient terms gives rather small corrections to the standard disk model. When $\dot{m} > 36$ advection becomes essential and for $\dot{m} > \dot{m}_{cr}$ it changes the picture qualitatively. When $\dot{m} > \dot{m}_{cr}$ solutions do exist extending continuously from large radii to the innermost disk region (the solid lines) where the solution passes through a "sonic point". However for small values of the mass accretion rate $\dot{m} < 0.1$ all types of solutions: solutions without advection, optically thick solutions with advection and solutions with advection and optical depth transition are very similar and have the same structure.

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