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Analytical calculations of the radial structure of self-gravitating and magnetized accretion disks in AGN

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Abstract. The variation with radius of the physical parameters(scale height, central temperature, and central density) of a self-gravitation and magnetized accretion disk is examined.We have adopted the different opacities in different regions as in the work by Collin-Souffrin and Dumont(1990II), and we consider a disc model with a $10^7 M_{\odot}$ black hole at the center and with an accretion rate of $0.01 M_{\odot}$/yr. Most of our results are very similar to theirs, but there are some differences between ours and theirs, that is: the critical radius where X-rays are able to heat significantly the disc is not sensitive to self-gravitation. However, self-gravitation has an influence on the location of the radius which emits the bulk of UV radiation, and the magnetic field affects both of them.

Key words: accretion disks – galaxies: active – galaxies: nuclei

1. Introduction

Studies of the broad emission lines in AGN have attracted very large numbers of Astronomers. It is commonly admitted that the accretion disk model is a possible and successful theory to explain the line and continuum emission. Several spectral features of the AGN, such as the continuum excess in the UV and the broad line spectrum, involving different physical processes of emission (thermal for the UV continuum, photoionization for the line sprectrum) have been proposed as signatures of the disk. Schield (1977) was the first to show that the broad line emission can be induced in AGN by the illumination of an accretion disk at a distance of $10^3 - 10^4$ gravitational radii (Jones & Raine 1980; Raine & Smith 1981). This possibility has been explained later by Begelman and Mckee (1983) and by Mardaljevic et al.(1988). Collin-Souffrin and Dumont (1987I, 1990II, 1990III 1990IV, hereafter CSD) have done a lot of research on the line and continuum emission from the outer region of accretion disks in AGN, and gotten several interesting and important results. CSD pointed out that the amount of energy available in the HI zone from which the bulk of the Bulmer lines and the FeII, MgII, and CII lines are emmitted depends on the column density N of the medium, the typical radii (such as X_{BB}, X_{25}), and correct opacities. However, all the parameters which are related to the line and continuum formations are involved with the structure of accretion disk. So a self-consistent structure of accretion is necessary for explaining the line and continuum spectra.

It is well known that the magnetic field can play an important role in accretion disks(Galeev et al.1979, Blandford & Payne 1982,Yang et al.1995). Field and Rogers (1993) explained the spectral emission from far infrared to X-ray with a magnetized accretion disk in AGN. Self-gravitation of an accretion disk have a bigger influence on the vertical and radial disk structure (Paczynski 1978; Yang et al. 1990; Storzer 1993). Sakimoto et al.(1981) and Schneider (1996) examined the structure and the stability of magnetized accretion disk with self-gravitation, but Sakimoto and Schneider did not discussed the effects of magnetic field and self-gravitation on the line and continuum emission

In this paper, we adopted the CSD's method (1990II), and extended Sakimoto's model (1981) to investigate the structure of self-gravitation and magnetized accretion disk, which is important to discuss the line and continuum emission from the outer region of the disk. We derive the scale height, central density, and central temperature, as well as the column density,and several typical radii of the disk. we also compared our results with the work by CSD (1990II). In Sect. 2, we present the basic equations of magnetized accretion disk with self- gravitation. We give the results in Sect. 3, and discuss them in Sect. 4.

2. Basic equations

Let us consider a very flat disk rotating around a central object of mass M, The basic equations are (Shakura & Sunyaev 1973):

$$\dot{M} = 2\pi r v_r \Sigma \tag{1}$$

$$\dot{M}\Omega = 4\pi t_{r\phi} H \tag{2}$$

$$Q^{+} = \frac{3}{8\pi}\frac{GM\dot{M}}{r^3} \tag{3}$$

$$bT_c^4 = \frac{3}{4}\tilde{\kappa}\Sigma\frac{Q^{-}}{c} \tag{4}$$

$$Q^{-} = \sigma T_{eff}^4 \tag{5}$$

$$Q^{+} = Q^{-} \tag{6}$$

In the above expressions, $\dot{M}$ is the accretion rate at infall velocity v_r, H is the density scale heights,Σ is the surface mass density, T_c is the central temperature. Ω is the Keplerian angular velocity, $\tilde{\kappa}$ is the mean opacity, Q^{-} is the emergent energy(radiation) flux from one face of the disk, Q^{+} is the release of gravitation potential and viscous dissipation energy, $t_{r\phi}$ is the $r\phi$ component of stress tensor, and T_{eff} is the effective temperature, other symbols σ, G, b, c have their usual meanings.

$$\Sigma = 2m_p n_c h \tag{7}$$

where n_c and m_p are the central density and the proton mass respectively. Using the conservation model of the magnetic flux (Sakimoto et al.1981), we have

$$t_{r\phi} = \Gamma H^2 m_p^2 n_c^2 \tag{8}$$

where Γ is defined as $\Gamma = \pi G\alpha/2$. α is the viscosity constant.

When we consider the effect of the self-gravitation, g is written as (Paczynski 1978)

$$g = g_s + g_z \tag{9}$$

$$a^2 = \frac{2\pi G\Sigma/H}{GM/R^3} = \frac{g_s}{g_z} \tag{10}$$

where $g_s = 2\pi G\Sigma_z$ is due to the disk's self-gravitation, $g_z = \frac{GM}{R^2}$ is due to the central mass M. we assumed $0 \le a \le 10$, the large values of a correspond to a strong self-gravity and the small values of a to a weak self-gravity. Here we should point out that the limit value of $a = 10$ is marginally acceptable (Paczynski 1978).

For the vertical mechanical stucture, the disk is assumed to be in hydrostatic equilibrium, the equation of hydrostatic equilibrium can then be written as (Paczynski, 1978)

$$\frac{1}{\rho}\frac{P}{H^2} = \frac{G[M + 4\pi\rho R^3]}{R^3} \tag{11}$$

From Eqs. (9) $--$(11), we get

$$H = \frac{c_s}{\Omega}\left(\frac{1}{1+a^2}\right)^{-1/2} \tag{12}$$

where $c_s \sim (p/\rho)^{1/2}$, ρ is the mass density of the disk, and P is the total pressure.

If the gas pressure dominate, the Eq. (12) becomes

$$H = 2\left(\frac{kT_c}{\mu m_p}\right)^{1/2} R^{3/2}(GM)^{-1/2}(1+a^2)^{-1/2} \tag{13}$$

where μ is the mean molecular mass. μ is equal to 0.65(CSD 1990II), k is a constant of Boltzmann.

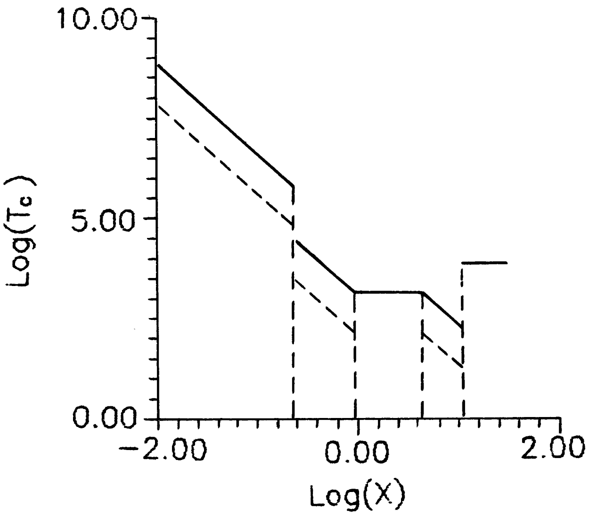

Fig. 1. The solid line corresponds to a=0, and the dashed line a=10.

3. Result

3.1. Several physical parameters of different regimes

From Eqs. (1)–(13), we get

$$m_p n_c = \frac{\pi G}{2}(1+a^2)^{-1/2}R^{-3}(GM) \tag{14}$$

$$T_c = 4.5\times 10^{10}(1+a^2)^{-1/4}M^{3/4}\alpha^{1/2}f_\varepsilon^{1/2}R^{-9/4}\tilde{\kappa}^{1/2} \tag{15}$$

Where f_ε is the efficiency of mass-energy conversion divided by the canonical value 0.1 (CSD 1990II)

If we adopt the different opacities from different regimes as in the work by CSD(1990II), then from Eq. (14), we get

$$n_{c15} = 1350 f_L^2 L_{44}^{-24/11} X^{-3}(1+a^2)^{1/2} \tag{16}$$

Here f_L has the same meaning as in CSD's (1990II), L_{44} is the luminosity in $10^{44}ergs^{-1}$, n_{c15} is the central density in $10^{15}cm^{-3}$, and X is a dimensionless quantity as in CSD's ρ (1990II), that is

$$X = R/(10^4 R_g) \tag{17}$$

where R_g is the Schwarzschild radius. According to CSD (1990II), we have

$$T_c = T_{eff}(0.75\tau)^{1/4} \qquad (\tau > 1) \tag{18}$$

Results obtained from equ.14 to 18 are given in Table 1, and illustrated in Fig. 1–3, which display T_c, n_c, H and τ as functions of the radius X for the different regimes.L_{44}, f_ε, f_L, α all being set equal to unity for simplicity, and we let $M = 10^7 M_\odot$, $\dot{M} = 0.01$. The scale height H_{10} is in $10^{10}cm$, the central density n_{c15} is in $10^{15}cm^{-3}$, and

$$n_{25} = \sqrt{\frac{\pi}{2}}H_{10}n_{c15} \tag{19}$$

Table 1.

regime	A	C	E	
opacity	0.4	0.001	1 cm^2/g	
T$_c$	22802	1157.3	36675 K	$(1+a^2)^{-1/4}\alpha^{1/2}f_\varepsilon^{1/2}f_L^{3/2}L_{44}^{-7/10}X^{-9/4}$
N$_{25}$	1184.6	24.6	150.2 cm^{-2}	$(1+a^2)^{-1/8}\alpha^{1/4}f_\varepsilon^{1/4}f_L^{7/4}L_{44}^{-3/2}X^{-21/8}$
H$_{10}$	7.02	0.16	0.89 cm	$(1+a^2)^{-5/8}\alpha^{1/4}f_\varepsilon^{1/4}f_L^{-1/4}L_{44}^{-13/20}X^{3/8}$
n$_{c15}$	1350	1350	1350 cm^{-3}	$(1+a^2)^{1/2}f_L^2L_{44}^{-24/11}X^{-3}$
τ	158.5	0.0089	50.24	$(1+a^2)^{-1/8}\alpha^{1/4}f_\varepsilon^{1/4}f_L^{7/4}L_{44}^{-24/11}X^{-21/8}$
regime	D	F		
opacity	1	1cm^2/g		
T$_c$	1400	7000 K		
N$_{25}$	928.1	2092.5 cm^2	$f_LL_{44}^{-13/11}X^{-3/2}$	
H$_{10}$	0.55	1.24 cm	$(1+a^2)^{-1/2}f_L^{-1}L_{44}X^{3/2}$	
n$_{c15}$	1350	1350 cm^{-3}	$(1+a^2)^{1/2}f_L^2L_{44}^{-24/11}X^{-3}$	
τ	$\ll 1$	$\ll 1$		

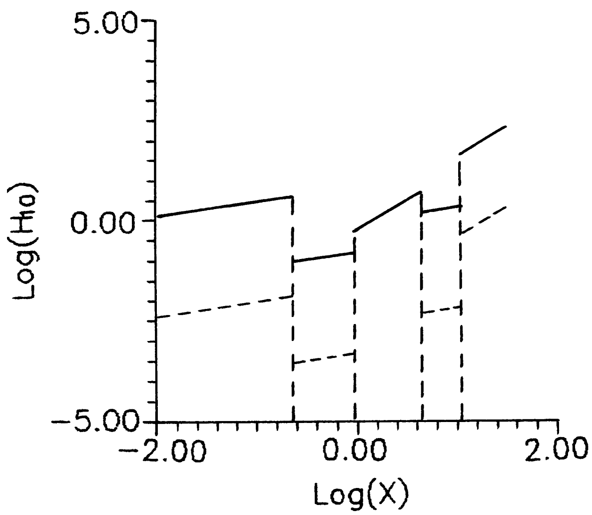

Fig. 2. Both the solid line and the dashed line hold the same meaning as Fig. 1.

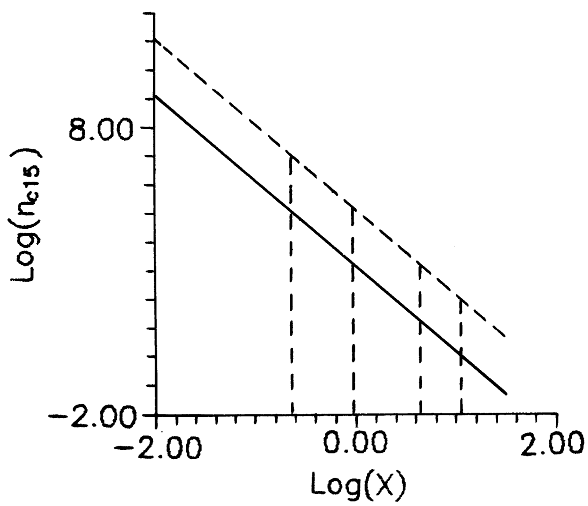

Fig. 3. Both the solid line and the dashed line hold the same meaning as Fig. 1.

The solid lines correspond to the case with a = 0, and dashed lines correspond to the case with a = 10.

In regimes A, C, and E, the physical parameters have the same functional dependence, and differ only by constant multiplication factors. In these regimes, T_c changes with radius as $X^{-9/4}$, and changes with self-gravitation as $(1 + a^2)^{-1/4}$. H_{10} changes with radius as $X^{3/8}$, and with self-gravitation as $(1 + a^2)^{-5/8}$. In regimes D and F, T_c is the same as in CSD's(1990II), but H_{10} differs with CSD's (1990II) because of self-gravitation and magnetic field, H_{10} is related to self-gravation as $(1 + a^2)^{-1/2}$. In regimes A, C, D, E and F, n_{15} changes uniformly with X as X^{-3}, and changes with self-gravitation as $(1+a^2)^{1/2}$. Fig. 1 shows that T_c decreases with increasing self-gravitation. Fig. 2 expresses that the thickness H_{10} becomes flat with increasing self-gravitation. This result is very similar to the work by Schneider(1996). Fig. 3 shows that the central density n_{15} increases with increasing self-gravitation.

3.2. Several typical radii of different regions and two important radii

We consider that the temperatures of two adjacent regions are the same.

Region 1, corresponding to regime A, for $X < X_1$ with

$$X_1 = 0.241(1 + a^2)^{-1/9}\alpha^{2/9}f_\varepsilon^{2/9}f_L^{2/3}L_{44}^{-2/5} \tag{20}$$

Region 2, corresponding to regime C, for $X_1 < X < X_2$ with

$$X_2 = 3.81X_1 \tag{21}$$

Region 3, corresponding to regime D, for $X_2 < X < X_3$ with

$$X_3 = 4.64X_2 \tag{22}$$

Region 4, corresponding to regime E, for $X_4 > X_3$

One important quantity is the radius X_{BB}, where the effective temperture is equal to 10^{4}K.

It is given by

$$X_{BB} = 5.53 \times 10^{-2}(1+a^2)^{-7/51}\alpha^{14/51} f_{\varepsilon}^{14/51} f_L^{34/51} L_{44}^{-3/25} \quad (23)$$

If we let $\alpha, f_\varepsilon, f_L, L_{44} \sim 1$, then

$$X_{BB} \sim 5.53 \times 10^{-2} \qquad (a = 0) \quad (24)$$

$$X_{BB} \sim 5.02 \times 10^{-2} \qquad (a = 1) \quad (25)$$

This value is greater than CSD's result (1990II) about 2 times, when we adopt a smaller value of a.

Another important quantity is the radius X_{25} which corresponds to a column density of $2 \times 10^{25} cm^{-2}$, that is given by

$$X_{25} = 10.3 f_L^{2/3} L_{44}^{-4/5} \quad (26)$$

It is easy to see that X_{25} is independent with self-gravitation(this is the same as CSD's result, 1990II), but is greater than CSD's result (1990II) about 1.54 times because of the magnetic field.

4. Diccussion

We have examined the radial structure of the outer region of self-gravitation and magnetized accretion disk, which is closely related to the line and continuum emission from the outer region of the disk. We have adopted the different opacities in different regime as the work by SCD (1990II). Our some results are very similar to SCD's, such as in regimes A, C, E, T_c, N_{25}, n_{15} and τ decrease with increasing radii of different functions. In regimes D and F, T_c are constant, and N_{25},n_{15} decrease with increasing radii of different functions. In addition, the profiles of our figures are also very similar to CSD's(1990II) figures. But our results have some differences from CSD's work (1990II). That is: the first is that our X_{BB} is greater than X_{rad}. (X_{rad} is the same as CSD's ρ_{rad}, 1990II), so our X_{BB} may be important to the line formation (next paper we are going to disscuse its effect on the line forming).The second is the line formation region extents to the outer region because our X_{25} is bigger than CSD's(1990II) about 1.54 times. The third is that our H_{10} is much thinner than CSD's(1990II). All these differences come from the effects of self-gravitation and magnetic field.

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