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The Dynamical Effects of a Large-Scale Ordered Magnetic Field on Slim Disks *

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The dynamics of slim disk under the influence of a large-scale ordered magnetic field is investigated. The global solutions show that the radial velocity increases and the disk temperature decreases with enhancing magnetic field. The fraction of mass loss becomes smaller when the accretion rate is higher. The ratio of the jet kinetic power to disk luminosity is less than 0.1, which indirectly supports the argument that radio-loud narrow-line Seyfert 1 galaxies share similarities with blazars.

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Recent observations by Fermi gamma-ray space telescope have shown that radio-loud narrow-line Seyfert 1 galaxies (RL NLS1) can constitute a new class of MeV–GeV gamma-ray sources.[1] Such high-energy photons indicate the existence of relativistic jets in some of the RL NLS1s,[2,3] and agree with previous studies about the similarities between RL NLS1s and blazars.[4−6] Since large-scale ordered magnetic fields have been widely accepted to power and collimate jets,[7,8] the accretion disks of RL NLS1s are probably threaded by large-scale magnetic field lines.

It is well known that the accretion rate of NLS1s are quite high, close to or even at the super-Eddington rate.[9−11] Therefore, it is interesting to examine the effects of a large-scale ordered magnetic field on the dynamics of a slim disk.

For a slim disk around a neutron star, the effects of the magnetic field have been studied by Lai in 1998[12] and Lee in 1999.[13,14] In their studies, the field lines are closed and bound to the central neutron star. For black holes (BHs), the dynamical effects of a large-scale magnetic field on standard accretion disks have been extensively studied.[15,16] In recent years, the effects on optically thin advection dominated accretion flow have been investigated by several authors.[17−22] In contrast, the magnetized slim disk has been less studied. Numerical simulations have been developed to study the global structure of slim disks.[23,24] However, such simulation is extremely time consuming and it is not easy to use it to model observational data. Therefore, a slim disk with a jet or outflow driven by radiation and a magnetic field is worthwhile studying. In this Letter, as a first step, we ignore the contribution of the radiation and investigate the influences of magnetic fields on a slim disk with a jet.

The basic equations of mass, radial and azimuthal momentum and energy are as follows:[21]

$$\frac{d\dot{M}}{dr} = 4\pi r \dot{m}_w, \tag{1}$$

$$v_r\frac{dv_r}{dr} + \frac{1}{\Sigma}\frac{dW}{dr} = \frac{l^2 - l_k^2}{r^3} - \frac{W}{\Sigma}\frac{d\ln\Omega_k}{dr} + g_m, \tag{2}$$

$$\Sigma\frac{v_r}{r}\frac{d}{dr}(rv_\phi) = \frac{1}{r^2}\frac{d}{dr}(r^2\Pi_{r\phi}) - \frac{T_m}{r}, \tag{3}$$

$$\int_{-h}^{h} dz\rho T v_r\frac{ds}{dr} = -2F_z + r\Pi_{r\phi}\frac{d}{dr}\left(\frac{v_\phi}{r}\right) - 2\dot{m}_w\varepsilon. \tag{4}$$

In the above equations, r is the radius in units of $r_g \equiv 2GM/c^2$, v_r, v_ϕ, T, ρ, l, h, l_k and Ω_k are the radial and azimuthal velocities, temperature, density, angular momentum, height, Keplerian angular momentum, and angular velocity, respectively. F_z is the radiative cooling rate per unit surface area and for an optically thick case reads $F_z = 8\sigma T^4/3\kappa\rho h$, with $\kappa = 0.4 + 0.64 \times 10^{23}\rho T^{-7/2}\,\mathrm{g^{-1}cm^2}$.[26] Here $\dot{M}(r)$ is the accretion rate and $\dot{m}_w(r)$ is the mass loss rate per unit area at radius r. $\Sigma \equiv \int_{-h}^{h}\rho dz$, $W \equiv \int_{-h}^{h} pdz$ and $\Pi_{r\phi} \equiv \int_{-h}^{h}\tau_{r\phi}dz$ are the vertical integration of the density, pressure, and $r-\phi$ component of the viscous stress, respectively. For simplicity, the effects of a large-scale magnetic field on the dynamics of the disk are included by three terms, i.e., g_m, T_m and $2\dot{m}\varepsilon$. The meaning of these terms will be introduced later.

To complete or to simplify the equations, more relations are needed. Firstly, the hydrostatic condition is used to substitute the momentum equation in the vertical direction. Secondly, the α-prescription of the viscous stress is adopted, i.e., $\Pi_{r\phi} = -\alpha W$. Thirdly, the equation of state is given by $p = p_{\rm rad} + p_{\rm gas} + p_m = aT^4/3 + R\rho T/\mu + p_m$, with R being the gas constant and μ the mean molecular weight ($\mu = 0.6$ in the following). Moreover, the Paczyński–Wiita potential $\Psi = -GM/(r - r_g)$ is employed.

Since our knowledge about the magnetic field is very limited, we have to make some assumptions about the strength and configuration of the field. The pressure of the large-scale ordered magnetic field in the disk is assumed to be a tiny fraction of the total pressure, i.e., $p_m = \beta(P_{\rm rad} + p_{\rm gas})$ with $\beta \ll 1$. In the region outside the disk, the poloidal field strength is assumed to be self-similar, i.e.,

$$B_p(r) \sim B_{pd}\left(\frac{r}{r_d}\right)^{-\zeta}, \tag{5}$$

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where r_d is the radius of the field line footpoint at the disk surface and B_{pd} is the poloidal field strength at the footpoint.

The radial magnetic force is simplified to

$$g_m = \frac{B_r B_z}{2\pi \Sigma}, \tag{6}$$

where B_r and B_z are the radial and vertical components of the magnetic field at the disc surface.[12,13] The magnetic torque exerting on the accretion flow is represented by[20]

$$T_m = 2\dot{m}_w \Omega(r)(r_{\rm A}^2 - r^2), \tag{7}$$

where $r_{\rm A}$ is the radius of the Alfvén point in the magnetic flux tube, which threads the disk at radius r. If the ionized gas is assumed to be frozen by the magnetic field till the Alfvén point, then $r_{\rm A} = v_{\rm A}/\Omega$, where $v_{\rm A}$ is the Alfvénic velocity. For simplicity, $v_{\rm A}$ is described by a parameter $v_{\rm A} = \xi v_K(r_d)$. Following the previous work,[27] we take $\xi \simeq 2$. Following Li and Cao,[20] $\dot{m}_w$ is expressed as

$$\begin{aligned} \dot{m}_w &= \frac{B_{pd}^2}{4\pi c}\left[\frac{r_d \Omega(r_d)}{c}\right]^\zeta \frac{\gamma_j^\zeta}{(\gamma_j^2 - 1)^{\frac{(1+\zeta)}{2}}} \\ &\simeq \frac{B_{pd}^2}{4\pi c}\left[\frac{r_d \Omega(r_d)}{c}\right]^\zeta \frac{1}{\gamma_j}, \end{aligned} \tag{8}$$

where the Lorentz factor $\gamma_j = \sqrt{1 - (v_{\rm A}/c)^2}$. In the second equation $\gamma_j \gg 1$ is assumed for a relativistic jet. Since the jet is powered by the disk, the energy loss rate per unit area can be written as $2\dot{m}_w \varepsilon = 2(\gamma_j - 1)\dot{m}_w c^2$, where the internal energy is ignored since the disk temperature is low compared to the kinetic energy.

In general, take the outer boundary as a standard accretion disk, for a given accretion rate at the outer boundary, $\dot{M}_0$, and parameters such as α, β, ζ, the global transonic solution can be found by solving the set of accretion equations.

In our model the magnetic field is modeled with two parameters: β and ζ. The former describes the strength of the field, while the latter describes the geometry of the disk. Their influences on the disk are shown in Fig. 1. There are four curves in each panel, which represent the following cases: (i) the case without the magnetic field (black long-dashed lines), (ii) the case with the magnetic field of given strength and geometry, i.e., $\beta = 0.01, \zeta = 2$ (red solid lines), (iii) the case with a stronger field, $\beta = 0.05$ and $\zeta = 2$ (blue short-dashed lines), and (iv) the case with different geometry $\beta = 0.01$ and $\zeta = 3$ (green dotted lines).

From Fig. 1, the following results can be obtained. Firstly, with the existence of the magnetic field, the Mach number is larger, the disk temperature is lower, while the specific angular momentum changes almost ignorably. These results are easy to understand. Due to the torque exerted by the magnetic field lines, the angular momentum is removed more efficiently. Therefore the viscous torque reduces and the radial velocity increases. Since the mass loss rate is very small compared to the accretion rate, the specific angular momentum changes only slightly. Secondly, when β decreases or ζ increases, the influences of the field become less significant. This is due to the model in which the mass loss rate depends on β and ζ as expressed by Eq. (8). Thirdly, the mass loss due to the jet is dominated by the inner region.

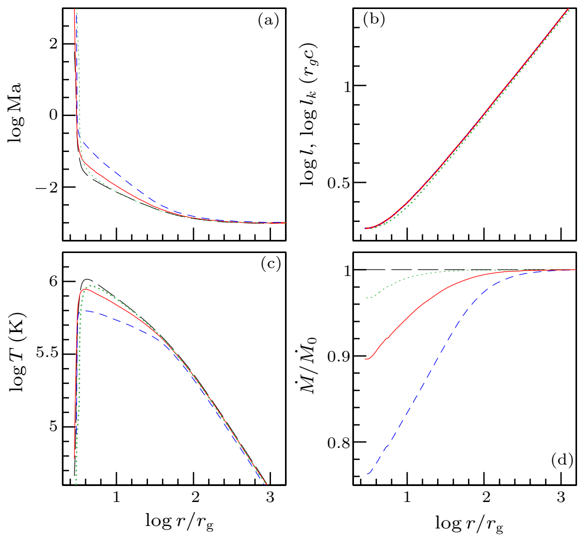

Fig. 1. Dynamical effects of the magnetic field for $\alpha = 0.3$ and $\dot{M}_0 = L_{\rm Edd}/c^2$. The long dashed line corresponds to the case without a magnetic field, the solid line corresponds to $\beta = 0.01$ and $\zeta = 2$, the short dashed line corresponds to $\beta = 0.05$ and $\zeta = 2$, and the dotted line corresponds to $\beta = 0.01$ and $\zeta = 3$. In the upper right panel, the Keplerian angular momentum is also shown, which is almost the same as the angular momentum of the disk without a magnetic field.

For smaller viscous parameter α, the influence of the magnetic field is stronger. This is because the relative contribution of the magnetic torque on the disk is larger since the viscous torque is smaller. In contrast, for a higher accretion rate, the influence of the magnetic field is much less significant. This is because the height of the disk increases with the accretion rate, as a result the fraction of the mass loss from disk surface is relatively smaller for higher accretion rate, which leads to less significant effects.

More detailed calculations show that the mass loss rate ($\dot{M}_{\rm jet}$) increases with accretion rate, but the relative mass loss rate ($\dot{M}_{\rm jet}/\dot{M}_0$) decreases with increasing accretion rate, as shown in Fig. 2. It should be noted that radiation pressure is ignored in the present model. If the radiation pressure is taken into account, as shown by the numerical simulations, the mass loss rate can be 10% for $\dot{M}_0 = 100 L_{\rm Edd}/c^2$,[23] which is much higher than our results. The contribution of radiation should be included in a future work.

The ratio between the kinetic power of a jet and the disk luminosity is also calculated as shown in Fig. 3. At a lower accretion rate the ratio decreases with accretion rate, while at a high accretion rate the ratio increases with accretion rate. Since the jet power is proportional to $\dot{M}_{\rm jet}$, which changes monotonically with accretion rate, the variation of $P_{\rm jet}/L_{\rm disk}$ is mainly due to photon trapping. At a lower accretion rate, photon trapping is not significant, and the disk luminosity is proportional to accretion rate. However, at a higher accretion rate, the disk is optically thick enough that photon trapping becomes important, and the disk luminosity gets saturated.[28] Therefore, at a lower accretion rate the jet kinetic power increases more slowly than the disk luminosity, while at a higher accretion rate, the jet kinetic power increases faster than the disk luminosity.

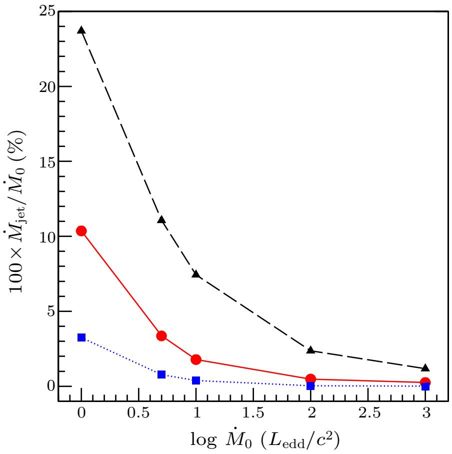

Fig. 2. Relative mass loss rate with $\alpha = 0.3$. The solid line corresponds to $\beta = 0.01$ and $\zeta = 2$, the dashed line corresponds to $\beta = 0.05$ and $\zeta = 2$, and the dotted line corresponds to $\beta = 0.01$ and $\zeta = 3$.

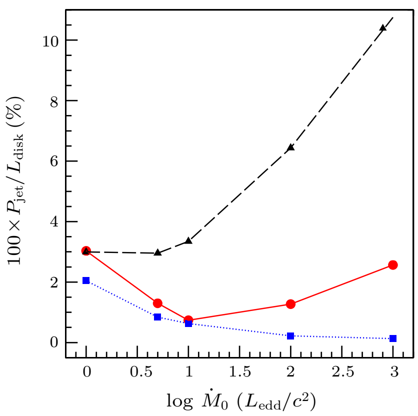

Fig. 3. The ratio of jet kinetic power to disk luminosity with $\alpha = 0.3$. The line types are the same as Fig. 2.

It can also be seen from Fig. 3 that the intrinsic jet power is only a small fraction of the disk luminosity. This result supports the argument that an RL NLS1 is similar to blazars, in which the jet axis is aligned to the eyesight. If the radiation pressure is included, this result still holds except the case that radiation is so strong that most gas is pushed away rather than accreted to the BH.

In Ref. [20], the wind power and mass loss rate of the advection dominated accretion flow were studied. Their results show that most of the gas is lost by wind and only a small fraction, about a few per cent, is accreted into the BH. However, in our results, only a small fraction of the gas is lost. This is because only jets with a Lorentz factor much greater than unity are considered in the present study. In our results the jet power is less than 10% of the disk luminosity, while in Ref. [20] the wind power is 1–1000 times of disk luminosity. This is because our disk is much more luminous than advection dominated accretion flow, in addition to the difference in mass loss rates.

In summary, we have investigated the effects of the large-scale ordered magnetic field on the dynamics of a slim disk. It is found that the field can make the gas cooler and fall to the BH faster. Our calculations also show that at a high accretion rate, the influence of radiation must be considered so as to be consistent with the numerical simulations. Moreover, our results indirectly support the opinion that the viewing angles of RL NLS1s and blazars are similar. The influence of radiation pressure will be addressed in a future work.

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