THE HIGH-EFFICIENCY JETS MAGNETICALLY ACCELERATED FROM A THIN DISK IN POWERFUL LOBE-DOMINATED FRII RADIO GALAXIES

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ABSTRACT

A maximum jet efficiency line \( R \sim 25 \) (\( R = L_{\text{jet}}/L_{\text{bol}} \)), found in FRII radio galaxies by Fernandes et al., was extended to cover the full range of jet power by Punsly. Recent general relativistic magnetohydrodynamic simulations of jet formation have mainly focused on the enhancement of jet power. In this work, we suggest that the jet efficiency could be very high even for conventional jet power if the radiative efficiency of disks was much smaller. We adopt the model of a thin disk with magnetically driven winds to investigate the observational high-efficiency jets in FRII radio galaxies. It is found that the structure of a thin disk can be significantly altered by the feedback of winds. The temperature of a disk gradually decreases with increasing magnetic field; the disk density, surface density, and pressure also change enormously. The lower temperature and higher surface density in the inner disk result in the rapid decrease of radiative efficiency. Thus, the jet efficiency is greatly improved even if the jet power is conventional. Our results can explain the observations quite well. The theoretical maximum jet efficiency of \( R \sim 1000 \) suggested by our calculations is large enough to explain all of the high jet efficiency in observations, even considering the episodic activity of jets.

Key words: accretion, accretion disks – galaxies: active – galaxies: jets – galaxies: magnetic fields

Online-only material: color figures

1. INTRODUCTION

Relativistic jets are common characteristics of active galactic nuclei (AGNs). According to the different morphologies of their radio structures, radio galaxies can be divided into two classes, i.e., FRI (defined by edge-darkened radio lobes) and FRII (defined by edge-brightened radio lobes and hot spots; Fanaroff & Riley 1974). Several recent observations discovered that the jet efficiency (defined as \( R = L_{\text{jet}}/L_{\text{bol}} \)) of some luminous lobe-dominated FRII could be very high, where \( L_{\text{jet}} \) and \( L_{\text{bol}} \) are the jet power and the bolometric luminosity of AGNs, respectively (McNamara et al. 2011; Fernandes et al. 2011; Punsly 2011, hereafter P11). A maximum jet efficiency of \( R \sim 25 \) was found by Fernandes et al. (2011), who adopted a complete sample of the most powerful radio galaxies at redshift \( z \sim 1 \). P11 extended the results of Fernandes et al. (2011) and found that the maximum jet efficiency line can cover the full four orders of magnitude of jet power by including other samples, such as a blazar sample in Ghisellini et al. (2010), a small sample of X-ray cavities in McNamara et al. (2011), etc.

So far, two main jet formation mechanisms have been most popular, i.e., the Blandford–Znajek (BZ) process (Blandford & Znajek 1977) and the Blandford–Payne (BP) process (Blandford & Payne 1982). In the BZ process, the rotating energy of a black hole can be extracted to power a jet by the large-scale magnetic fields maintained by an accretion disk. However, in the BP process, the jet power comes instead from the rotating disk itself. The bolometric luminosity of a radio galaxy can be expressed as \( L_{\text{bol}} = \eta_{\text{th}} M c^2 \), where \( \eta_{\text{th}} \) is the radiative efficiency of the accretion disk. If we specify the jet power as a function of the accretion rate, \( L_{\text{jet}} = \eta_0 M c^2 \) (where \( \eta_0 \) is the jet production efficiency), then the jet efficiency \( R(= L_{\text{jet}}/L_{\text{bol}} = \eta_0/\eta_{\text{th}}) \) will be decided by both \( \eta_0 \) and \( \eta_{\text{th}} \). The obviously different accretion rates between FRI and FRII radio galaxies implies that they should have different accretion models (Ledlow & Owen 1996; Ghisellini & Celotti 2001; Xu et al. 2009). In the general picture of FRII radio galaxies, a jet is supposed to be launched from a radiatively efficient accretion disk, where \( \eta_{\text{th}} \) varies from about 0.06 to 0.4 for a non-rotating black hole and an extreme Kerr black hole, respectively. Recent general relativistic magnetohydrodynamic simulations of jet formation have mainly focused on the improvement of jet power \( L_{\text{jet}} \) in order to explain the observed high jet production efficiency \( \eta_0 \). The jet production efficiency for a magnetically arrested disk (MAD) can reach \( \sim 30\% \) and \( 140\% \) for \( a = 0.5 \) and 0.99, respectively (Tchekhovskoy et al. 2011), which implies that the black hole spin parameter \( a \) may play a key role in the formation of jets (McKinney 2005; Tchekhovskoy et al. 2010, 2011). However, the observed \( \eta_0 \) is based on the assumption that the radiative efficiency \( \eta_{\text{th}} \sim 0.1 \), which is suggested from observational constraints on the growth of massive black holes (e.g., Yu & Tremaine 2002). Thus, if the radiative efficiency of a disk were much smaller than 0.1, it is possible to get a high jet efficiency \( R \) even for a conventional jet production efficiency \( \eta_0 \).

Li & Cao (2012) and Li & Begelman (2014) do seem to provide a possible explanation for this picture. They produced a model for a thin disk with magnetically driven winds/jets, in which the angular momentum and energy carried away by the jets are properly included. It was found that the disk properties can be changed significantly by the feedback from jets. For example, the temperature of a thin disk with jets is obviously lower compared to that of a standard thin disk (see Figure 1; Li & Cao 2012) because a large fraction of the gravitational energy released in the disk is carried away by jets. This will directly result in the decrease of the bolometric luminosity (and \( \eta_{\text{th}} \)) of the accretion disk and the increase of the jet efficiency \( R \).

In this work, we will investigate in detail the structure of a
thin disk with winds and the high-efficiency jets in powerful lobe-dominated FRII radio galaxies.

2. MODEL

We consider a thin disk with magnetically driven winds surrounding a spinning black hole. The continuity, radial momentum, angular momentum, and energy equations of the disk are as follows:

\[ \frac{d}{dr} \left( 2\pi \Delta \Sigma v_r \right) + 4\pi r \dot{m}_w = 0, \]

\[ \frac{\gamma \phi A M}{r^4 \Delta} \frac{\Omega - \Omega_k (\Omega - \Omega_k)}{\Omega_k^2 \Omega_k} + g_m = 0, \]

\[ -\frac{\dot{M}}{2\pi} \frac{dL}{dr} + \frac{d}{dr} \left( r W_r \right) + T_m r = 0, \]

\[ v \Sigma \gamma_4 A_1^2 \frac{d}{dr} \left( \frac{d\Omega}{dr} \right)^2 = \frac{16a c T^4}{3k \Sigma}, \]

where the equations and the meanings of the parameters are all the same as in Li & Begelman (2014). We focus on the fast moving jets from the disk and adopt \( B_\phi = 0.1B_p \), which corresponds to the case of fast moving jets with low mass-loss rates (Ogilvie & Livio 1998; Cao & Spruit 2002; Li & Begelman 2014). Therefore, we can simply ignore the mass-loss rate term in the continuity equation.

The bolometric luminosity of an accretion disk can be calculated as

\[ L_{bol} = \int_{r_{in}}^{r_{out}} Q_{rad} 2\pi r dr = \eta_{th} \dot{M} c^2, \]

where \( r_{in} = r_{isco} \) and \( r_{out} = 1000 r_g \) (\( r_g = GM/c^2 \)) are the inner and outer radii of a disk, respectively, and \( r_{isco} \) is the innermost stable circular orbit of a disk. \( Q_{rad} = 16a c T^4/3k \Sigma \) is the radiative cooling rate per unit surface and \( \eta_{th} \) is the radiative efficiency of the accretion disk.

Jets can be powered by both BZ and BP processes. In the general form of the BZ process, the jet power \( L_{BZ} \) can be...
Figure 2. Disk pressures as a function of radius, i.e., the gas, radiation, and magnetic pressure of a disk for \( \beta_p = 1, 10, 100, \) and \( \infty \), respectively, where \( a = 0.9 \) is adopted. The black, red, and green lines are for magnetic pressure, radiation pressure, and gas pressure, respectively. (A color version of this figure is available in the online journal.)

estimated with (Ghosh & Abramowicz 1997)

\[
L_{BZ} = \frac{1}{32} \omega_f B^2 \gamma H (J / J_{max})^2 c,  \tag{6}
\]

where \( r_H \) is the horizon radius, \( B_\perp \) is the component of the magnetic field normal to the black hole horizon, \( J \) and \( J_{max} = GM^2/c \) are the angular momentum and maximum angular momentum of a black hole, and \( \omega_f \equiv \Omega_f (\Omega_f - \Omega_H) / \Omega_H^2 \) is a factor at the black hole horizon determined by the angular velocity of the black hole and the magnetic field lines. The strength of the field threading the horizon of the black hole \( (B_\perp) \) is comparable to that threading the inner region of the disk (Livio et al. 1999). In this work, for simplicity, we adopt \( B_\perp \) as the maximal magnetic field strength in the disk. The power of the jets accelerated from an accretion disk (BP process) can be calculated with (e.g., Livio et al. 1999; Cao 2002)

\[
L_{BP} = \int_{r_m}^{r_{in}} B_\phi B_\theta \gamma \Omega^2 \pi r dr, \tag{7}
\]

where \( B_\phi \) and \( B_\theta \) are the toroidal and poloidal components of the magnetic field, respectively.

Thus the total jet power \( L_{jet} \) is

\[
L_{jet} = L_{BZ} + L_{BP} = \eta Q \dot{M} c^2. \tag{8}
\]

With \( \eta_{th} \) and \( \eta_Q \), the jet efficiency is given by

\[
R = \frac{\eta_Q}{\eta_{th}}. \tag{9}
\]

3. RESULTS

We solve Equations (1)–(4) to achieve the structure of a thin disk with winds by using the same numerical methods as Li & Begelman (2014). In all of the calculations, we adopt the conventional viscosity parameter \( \alpha = 0.1 \), a black hole mass of \( m = M/M_\odot = 10^9 \) (except for Figures 6 and 7), and an Eddington-scale accretion rate of \( \dot{m} = M / M_{\text{Edd}} = 0.25 \), where \( M_{\text{Edd}} = 1.5 \times 10^{18} m \) g s\(^{-1}\) and \( \dot{m} = 0.25 \) is the typical value of broad-line AGNs (Kollmeier et al. 2006). Our results are qualitatively the same for different black hole masses and accretion rates.

In Figure 1, it is found that the disk structure has been significantly altered by the winds. The temperature of a thin disk with
Figure 3. Radiative efficiency of a relativistic thin accretion disk with magnetically driven jets as functions of $\beta_p$ for different spins $a$. From the bottom to the top, the black, red, green, and blue lines are for $a = 0.1, 0.5, 0.9,$ and $0.99$, respectively. (A color version of this figure is available in the online journal.)

Figure 4. Same as in Figure 3, except that this figure represents the jet production efficiency. (A color version of this figure is available in the online journal.)

Winds is obviously lower than that of a standard thin disk because a large fraction of the gravitational energy released in the disk is carried away by the jets (see Figure 1(a)), and gradually decreases with increasing magnetic field strength (smaller $\beta_p$, $\beta_p = (P_{\text{gas}} + P_{\text{rad}})/(B_p^2/8\pi)$). Except for the temperature, the disk density and surface density also exhibit enormous changes, as shown in Figures 1(b) and (c). Especially for the inner disk region, both the density and surface density increase greatly. In Figure 1(d), it is found that the magnetic torque is far larger than the viscous torque for the disk with strong winds. When the magnetic field is strong enough ($\beta_p \leq 10$), the radiative-pressure-dominated inner region in a thin disk vanishes and the whole disk is dominated by gas pressure (Figure 2). The change of pressure in the inner disk also induces the change in disk density; the initial negative correlation between the density and radius has become positive (Figure 1(b)), which is a result of a gas-pressure-dominated inner disk.

The radiative efficiency $\eta_{\text{th}}$ varied with $\beta_p$ for different black hole spins is plotted in Figure 3. In this work, a minimum $\beta_p \sim 1$

Figure 5. Theoretical jet efficiency $R$ as functions of $\beta_p$ for different black hole spins. From the top to the bottom, the black, red, green, and blue lines are for $a = 0.1, 0.5, 0.9,$ and $0.99$, respectively. (A color version of this figure is available in the online journal.)

is adopted because the jet efficiency $R$ ($10^{2-3}$, see Figure 5) is high enough for $\beta_p \sim 1$ and magnetorotational instability will be totally suppressed if $\beta_p$ is smaller than 1. $\eta_{\text{th}}$ decreases quickly with decreasing $\beta_p$ and can be as low as $10^{-3}-10^{-5}$ for different $a$ with $\beta_p = 1$, which is about 0.1% of the efficiency of a standard thin disk. Contrary to $\eta_{\text{th}}$, the jet production efficiency $\eta_Q$ decreases rapidly with the increase of $\beta_p$ (Figure 4). The structure of a thin disk with lower spin is found to change relatively more easily. However, the results are qualitatively the same for different spin $a$ (Figures 3 and 4).

As $\beta_p$ becomes smaller and smaller, the simultaneous increase of $\eta_Q$ and the decrease of $\eta_{\text{th}}$ will result in a rapid increase of jet efficiency $R$ (see Figure 5). The maximum theoretical jet efficiency can reach from several hundreds to 1000 for different spins $a$ with $\beta_p = 1$, which can easily explain the observed high jet efficiency in luminous FRII radio galaxies. In Figure 6, we also draw the jet power as a function of disk bolometric luminosity as in Figure 1 in P11, where the black
hole mass varies from $10^8 M_\odot$ to $10^{10} M_\odot$. Compared with the observed maximum jet efficiency (the dashed line), our results suggest that the magnetic pressure is about 5%–10% of the gas+radiation pressure in the disk ($10 < \beta_p < 20$) when $\alpha = 0.1$ and $B_\phi = 0.1 B_p$ are adopted.

The inclination angle $\theta$ of the field line with respect to the disk surface is required to be smaller than 60° in order to successfully launch jets from a cold thin disk (Blandford & Payne 1982; Cao 2012). We simply adopt an angle of 60° in this work, except in Figure 7. In Figure 7, we investigate the effects of inclination angle $\theta$ on jet power. It is found that the inclination angle strongly affects the jet power and the jet efficiency quickly decreases with decreasing $\theta$. For $\beta_p = 1$, the jet efficiency decreases for about two orders of magnitude when $\theta$ varies from 60° to 10°. The jet efficiency $R$ is reduced to $\sim 10$ for $\beta_p = 1$ and $\theta = 10°$.

4. CONCLUSIONS AND DISCUSSION

The basic physics of the jet formation models adopted in this work are the same as in the previous works of Ghosh & Abramowicz (1997) and Livio et al. (1999). However, their estimates for the magnetic field strength of a disk are based on the conventional accretion disk models without a magnetic field, which is a good approximation in the weak magnetic field case as the disk structure has not been altered significantly by the field. However, that assumption becomes invalid if the field is strong. The high power carried by the jets greatly changes the structure of a thin disk (Figures 1 and 2). Except for the angular velocity, which is close to the Keplerian angular velocity for a thin disk (Li & Begelman 2014), all other disk properties (temperature, density, surface density, pressure) change greatly compared with the standard disk. The magnetic torque $T_m$ is found to dominate over the viscous torque $T_{vis}$ (see Figure 1(d)). The temperature decreases and the density increases significantly with decreasing $\beta_p$. It is the increase of surface density and the decrease of disk temperature in the inner disk region that result in the very low radiative efficiency in the disk. The obviously lower temperature compared with that of a standard thin disk even leads to the disappearance of the inner disk dominated by radiative pressure (Figure 2). Thus, the thin disk becomes both thermally and viscosely stable with the presence of disk winds (Li & Begelman 2014).

Previous efforts mainly focused on the improvement of jet power $L_{jet}$. However, if the accumulation of magnetic flux in the inner region of the accretion disk is indeed considered (Narayan et al. 2003; Porth & Fendt 2010; Porth et al. 2011; Tchekhovskoy et al. 2011; McKinney et al. 2012; Sikora & Begelman 2013), then the jet production efficiency can be improved significantly, but the radiative efficiency can also greatly decrease. Thus, a very high jet production efficiency $\eta_{\alpha}$ is not always needed. The jet efficiency could be quite “normal” if the radiative efficiency decreases significantly (see Figures 3 and 4). According to our model, the reason for the high jet efficiency is that most of released gravitational energy in the disk is carried away by jets, which results in the very low radiative efficiency. A theoretical maximum jet efficiency of $R \sim 1000$ is found, which is large enough even if we take the episodic activity of jets into account. Compared with the observational results in P11 (the dashed line in Figure 6), our study indicates that $10 < \beta_p < 20$ is required for $\alpha = 0.1$ and $B_\phi = 0.1 B_p$. However, if we consider smaller $\alpha$ and a larger proportion of $B_\phi$ in the field, then the magnetic torque could be more dominant (Li & Begelman 2014). Thus, the required field could be much weaker (larger $\beta_p$). From Figure 7, it seems that the jet efficiency has a positive relation with $\theta$. However, if we consider the evolution of a field in a thin disk, then the smaller $\theta$ may represent a stronger magnetic field (Lubow et al. 1994a; Cao & Spruit 2013), which should thus help to improve the jet efficiency.

The large-scale magnetic field plays a key role in the formation of a jet. However, how it forms is still an unsolved problem. A popular mechanism is that the field lines can be dragged inward with the accretion of gas. Magnification of the field seems to be difficult in a thin disk because the speed of turbulent diffusion is faster than that of advection (van Ballegooijen 1989; Lubow et al. 1994a). However, when taking the magnetically driven winds into account (Cao & Spruit 2013; Li & Begelman 2014), the field may be effectively magnified even for a thin disk with a very weak initial field ($\beta_p \sim 10^3$). However, a balance of magnetic field advection and diffusion is required in order to avoid the formation of an MAD. How such a balance can be achieved and kept stable is still unclear (e.g., Cao & Spruit 2002, 2013; Bisnovatyi-Kogan & Lovelace 2012). Lubow et al. (1994b) argued that a disk–wind system may be unstable if its angular momentum is taken away by magnetic torque only. The reason for this is that if there is a perturbation that increases the radial velocity, the inclination angle of the field will become smaller, which in turn increases the mass-loss rate and results in a higher radial velocity. Nevertheless, the linear stability analysis given by Cao & Spruit (2002) suggested that a disk could be stable if the field is weak enough. Lubow et al. (1994b) also stated that they did not do a global calculation on the disk. Thus, a global time-dependent study should be necessary in order to investigate this problem, which is beyond the scope of this work. The formation of a large-scale magnetic field also depends on the initial strength and morphology of the magnetic field, as indicated by some MHD simulations (e.g., Igumenshchev et al. 2003; Beckwith et al. 2008; McKinney et al. 2012), which is still an open issue at present.

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