JET POWER EXTRACTED FROM ADAF AND THE APPLICATIONS TO X-RAY BINARIES AND RADIO GALAXY FRI/FR II DICHOTOMY

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ABSTRACT

We calculate the jet power of the classical Blandford-Znajek (BZ) model and hybrid model developed by Meier based on the global solutions of advection dominated accretion flows (ADAFs) surrounding Kerr black holes. We find that the jet power of the hybrid model is larger than that of the pure BZ model. The jet power will dominate over the accretion power, and the objects will enter into “jet-power-dominated advective systems,” when the accretion rate is less than a critical value $\dot{m}_c = \dot{M}/\dot{M}_{\text{Edd}}$, where $3 \times 10^{-5} \lesssim \dot{m}_c \lesssim 5 \times 10^{-3}$ is a function of black hole spin parameter. The accretion power will be dominant when $\dot{m} \gtrsim \dot{m}_c$ and the objects will enter into “accretion-power-dominated advective systems.” This is roughly consistent with that constrained from the low/hard-state black hole X-ray binaries (e.g., Fender et al.).

We calculate the maximal jet power as a function of black hole mass with the hybrid jet formation model, and find it can roughly reproduce the dividing line of the Ledlow-Owen relation for FR I/FR II dichotomy in the jet power-black hole mass plane ($Q_{\text{jet}} - M_{\text{BH}}$) if the dimensionless accretion rate $\dot{m} \sim 0.01$ and BH spin parameter $j \sim 0.9 - 0.99$ are adopted. This accretion rate $\dot{m} \sim 0.01$ is consistent with that of the critical accretion rate for the accretion mode transition of a standard disk to an ADAF constrained from the state transition of X-ray binaries. Our results imply that most FR I galaxies may be in the ADAF accretion mode similar to the low/hard-state XRBs.

Subject headings: accretion, accretion disks-black hole physics-galaxies: jets–X-rays: binaries-MHD

1. INTRODUCTION

Black hole accretion is thought to power active galactic nuclei (AGNs) and X-ray binaries (XRBs). Both the UV/optical bumps observed in luminous quasars and the soft X-rays observed in the high/soft state XRBs can be naturally interpreted as blackbody emission from a cold, optically thick, and geometrically thin standard disk (SSD; e.g., Shakura & Sunyaev 1973; Sun & Malkan 1989). A hot, optically thin, geometrically thick advection dominated accretion flow model has been developed in the last several decades (ADAF, or “radiative inefficient accretion flows”; e.g., Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994, 1995; Abramowicz et al. 1995; see Kato et al. 2008 and Narayan & McClintock 2008 for reviews), which can successfully explain most features of the nearby low-luminosity AGNs and low/hard-state XRBs (see Remillard & McClintock 2006; Done et al. 2007; Yuan 2007; Ho 2008 for recent reviews). Their spectral energy distributions (SEDs) can be well reproduced by the ADAF model. It was found that the hard X-ray photon indices of both XRBs and AGNs are anti-correlated with the Eddington ratios when the Eddington ratio is less than a critical value (Wu & Gu 2008; Gu & Cao 2008), and references therein). These results provide evidence for the accretion mode transition near the critical Eddington ratio.

It is widely believed that the radio emission of both the low/hard state XRBs (e.g., Fender 2004, and references therein) and the low luminosity AGNs (LLAGNs, e.g., Wu & Cao 2005) comes from the jets. However, the detailed physical mechanism for the jet formation is still unclear for either AGNs or XRBs. The currently most favored jet formation mechanisms include the Blandford-Znajek (BZ) process (Blandford & Znajek 1977) and the Blandford-Payne (BP) process (Blandford & Payne 1982). In the BZ process, energy and angular momentum are extracted from a rotating black hole and transferred to a remote astrophysical load by open magnetic field lines. In the BP process, the magnetic fields threading the disk extract energy from the rotation of the accretion disk itself to power the jet/outflow.

Meier (1999) showed that even if the BZ process is neglected entirely, the jet power contributed by the field threading the disk alone will still be a function of the black hole spin since the rotating metric contributes to the rotation of the magnetic field. Recent magnetohydrodynamic (MHD) simulations also showed that both the BH spin and the accretion rate in the underlying accretion disk play important roles for the jet formation (Koide et al. 2006; McKinney & Gammie 2004; Hirose et al. 2004; De Villiers et al. 2005; Hawley & Krolik 2006). The relative importance of these two mechanisms was explored by many authors (e.g., Ghosh & Abramowicz 1997; Livio et al. 1999; Meier 2001; Cao 2002; Nemmen et al. 2007; Wang et al. 2008). Assuming the poloidal magnetic field component at the disk surface to be of the same order as the toroidal field component, the maximal jet power extracted from the accretion disk (BP process) may dominate over the maximal power extracted by the BZ process (e.g., Livio et al. 1999; Meier 2001; Cao 2002; Nemmen et al. 2007). However, Reynolds et al. (2006) found that the dynamics of the accretion disk in plunging region within the innermost stable circular orbit can greatly enhance the trapping of large scale magnetic field on the BH, and therefore increase the importance of the BZ mechanism effect compared to previous estimates that ignore the plunge region (e.g., Ghosh & Abramowicz 1997).

Radio galaxies are usually classified as FR I or FR II sources depending on their radio morphology. FR I radio galaxies (defined by edge-darkened radio structure) have lower radio power than FR II galaxies (defined by edge-brightened radio struc-
ture due to compact jet terminating hot spots; Fanaroff & Riley 1974). What causes the morphological difference between FR I and FR II radio galaxies is still unclear. The theoretical models fall into two different groups: (1) the morphological differences arise of the different physical conditions in their ambient medium (see Gopal-Krishna & Wiita 2000, for a summary); (2) their intrinsic difference of their central engines, i.e., different accretion modes and/or jet formation processes (e.g., Bicknell 1995; Reynolds et al. 1996; Meier 1999; Ghisellini & Celotti 2001; Marchesini et al. 2004; Wold et al. 2007; Hardcastle et al. 2007).

Most previous works on the jet power extracted from ADAFs were based on self-similar solutions of ADAFs (e.g., Armitage & Natarajan 1999; Meier 2001; Cao & Rawlings 2004; Nemmen et al. 2007). The self-similar solution can reproduce the global solution quite well at large radii, while it deviates significantly near the black hole (e.g., Narayan et al. 1997), where the relativistic jets are supposed to be formed. In this paper we calculate the jet power, incorporating some recent MHD simulation results, based on the global ADAF solutions surrounding Kerr black holes. We then compare our model calculations with the accretion power and jet power of XRBs and the radio galaxy FR I/FR II dichotomy.

2. ACCESSION AND JET MODELS

2.1. Global ADAF model

We calculate the global structure of an accretion flow using an approach similar to that of Narayan et al. (1997). However, the pseudo-Kerr potential for a rotating BH given by Mukhopadhyay (2002) is adopted in solving the equations of the accretion flow, which allows us to calculate the structure of an accretion flow surrounding either a spinning or a nonspinning black hole. The simple $\alpha$-viscosity ($\tau_{\alpha}=\alpha p$, and $p$ is total pressure, i.e., gas pressure plus magnetic pressure) is adopted and all radiative processes (synchrotron, bremsstrahlung and Compton scattering) are included consistently in our calculations for ADAF structure. The advection by ions and electrons has been considered in the energy equation, and a more realistic state of accreting gas (instead of a polytropic index $\gamma_p$) is employed in the calculations, which is similar to that used by Mannert (2000). We solve a set of hydrodynamical equations (i.e., the radial momentum, angular momentum, and energy equations) for an ADAF, and tune the parameter $t_m$, the specific angular momentum of the gas swallowed by the black hole, to let the solution pass smoothly through the sonic point near the black hole (see Narayan et al. 1997 for details). We find that the derived global solutions for Kerr black holes can reproduce all the essential properties of the solutions derived in full general relativistic frame by Mannomoto (2000) with error less than 10%. The global structure of an ADAF surrounding a BH spinning at rate $J$ with mass $M_{BH}$ can be calculated with proper outer boundaries (e.g., Mannomoto 2000), if the parameters $t_m$, $\alpha$, $\beta$, and $\delta$ are specified. The parameter $J=J/GM^2_{BH}$ is the dimensionless angular momentum, where $J$ is the angular momentum of the BH, $\alpha=M/M_{Edd}$ is dimensionless accretion rate, and $M_{Edd}$ is the Eddington accretion rate defined as $M_{Edd} = 1.4 \times 10^{15} M_{BH}/L_{Edd} \ G^{-1}$ s$^{-1}$. The value of $\alpha$ adopted in ADAF modeling is supposed to be within a very narrow range, i.e., $\alpha=0.1-0.3$ (e.g., Narayan & McClintock 2008, and references therein), which is supported by MHD numerical simulations of accretion flows $\sim 0.05-0.2$ (Hawley & Balbus 2002) and the observationally-determined values $\sim 0.1-0.4$ based primarily on studies of outbursts in dwarf novae and X-ray transients (King 2007). The magnetic parameter $B$ (defined as ratio of gas to magnetic pressure in the accretion flow, $B = \rho g/\rho m$) is not an independent parameter and can be related to $\alpha$ as $\beta \sim (0.55-\alpha)/\alpha$, as suggested by MHD simulations (e.g., Hawley et al. 1995), where $\rho_m = B_{\text{dynamo}}^2/8\pi$ and $B_{\text{dynamo}}$ is the magnetic field strength of the ADAF in the local reference frame. The parameter $\beta \sim 1-5$ for the typical value of $\alpha \sim 0.1-0.3$. Another poorly constrained parameter is $\delta$, which describes the fraction of the turbulent dissipation that directly heats the electrons in the flow. Recent ADAF models typically assume $\delta \sim 0.3-0.5$ (e.g., Yuan et al. 2003; Wu et al. 2007; see also Sharma et al. 2007 for slightly lower $\delta$ value).

Two important modifications of the above global ADAF model are also included (see Meier 2001; Nemmen et al. 2007 for more details). First, as viewed from an outside observer at infinity in the Boyer-Lindquist reference frame, the disk angular velocity $\Omega$ is a sum of its angular velocity relative to the local metric $\omega$ plus the angular velocity of the metric itself in the Boyer-Lindquist frame $\omega \equiv \dot{\rho}_{\odot}/g_{\phi\phi}$, i.e., $\Omega = \omega + \Omega$. Second, we also take into account the field-enhancing shear caused by frame dragging in the Kerr metric, as first suggested by Meier (1999), which seems to be supported by MHD simulations (e.g., Hawley & Krolik 2000). Following the work of Meier (2001), the amplified magnetic field related to the magnetic field produced by the dynamo process in the ADAF can be expressed as $B = gB_{\text{dynamo}}$, where $g = \Omega/\Omega^\prime$ is the field-enhancing factor.

2.2. Evaluating the jet power of Blandford-Znajek model

For a black hole of mass $M_{BH}$ and dimensionless angular momentum $j$, with magnetic fields $B_\perp$ normal to the horizon at $R_H = [1+(1-j)^2/2]^{1/2}$ ($R_g = GM_{BH}/c^2$ is the gravitational radius), the power extracted with the BZ mechanism is given by (e.g., Ghosh & Abramowicz 1997; MacDonald & Thorne 1982)

$$Q_{\text{BZ}} = \frac{1}{32}\alpha^2B_\perp^2R_H^2 \omega c,$$

where $\omega \equiv \Omega_{\odot}(\Omega_{\odot}-\Omega)/\Omega_{\odot}$ is determined by the angular velocity of field lines $\Omega_{\odot}$ relative to that of the hole $\Omega_{\odot}$. In order to estimate the maximal power extracted from a spinning BH, $\omega$ is always required to be $1/2$ (e.g., Livio et al. 1993; Cai 2002). The magnetic field $B_\perp$ is assumed to approximate to the poloidal component $B_p$, and Livio et al. (1999) proposed that $B_p \approx B_{\text{dynamo}}$ due to the hot thick disk of ADAF ($H \sim R$). Therefore, we use $B_{\perp} \approx B_p \approx gB_{\text{dynamo}}$ in our calculations considering the field enhancing effect. This is consistent with recent MHD simulations in which the poloidal fields are dominant in the $z$-direction near the BH (Kato et al. 2004). Following the work of Nemmen et al. (2007), all the physical quantities are evaluated at $R = R_{\text{ms}}$.

2.3. Evaluating the jet power of hybrid model

As pointed out by Meier (1999), the differential dragging of the frames will also act as a dynamo to amplify the magnetic field, and therefore even if the BZ process is neglected entirely, the jet power contributed by the field threading the disk alone will still be a function of the BH spin, since the metric of the rotating black hole contributes to the rotation of the magnetic field. Both the BP and BZ mechanisms were incorporated in this hybrid jet formation model, in which the magnetic fields extract energy both from the accretion flow and the spinning
Jet power from ADAF and the possible applications

3. RESULTS AND DISCUSSION

To estimate the jet power extracted from the inner region of the disk, we employ the global ADAF solution for a spinning black hole, and the field-enhancing shear in the Kerr metric has been taken into account (e.g., Meier 2001). Our global calculations show that the magnetic field can be amplified roughly 2 times when \( j \sim 0.9 \) in the plunging region (the zone between \( R_{\text{ms}} \) and \( R_{\text{H}} \)). We find that the jet power for either the BZ model or the hybrid model is roughly proportional to the accretion rate/BH mass, but its dependence on \( j \) is rather complicated. Figure 1 shows the spin dependence of jet power for the BZ model and the hybrid model for given \( M_{\text{BH}} = 10^8 M_\odot \) and \( m = 0.01 \) (also see similar results in Fig. 1 of Nemmen et al. 2007). The black-solids lines and blue-dashed lines in Fig. 1 denote the jet power for two different values of the viscosity parameter \( \alpha = 0.3 \) (\( \beta \approx 1 \)) and \( \alpha = 0.1 \) (\( \beta \approx 5 \)) for the case of \( \delta = 0.5 \), respectively. We find that the jet power varies little for different viscosity parameters, provided all other parameters are fixed. The physical reason is that the jet power (BZ/hybrid models) \( Q_j \propto B^2 \propto 1/\alpha(1+\beta) \propto \text{constant} \) in the ADAF (see Narayan & Yi 1995, and relation of \( \alpha \) and \( \beta \) in Sect. 2.1). The red dotted lines denote the jet power for the cases of \( \alpha = 0.3 \) (\( \beta \approx 1 \), Fig. 1) and \( \delta = 0.1 \), which indicates that the jet power is also not sensitive to the value of \( \delta \). We find that the ratio of the gas pressure to the magnetic pressure \( \sim 0.4-1 \) in the plunging region varying with different BH spin parameters \( j \) is mainly due to the field-enhancing shear caused by frame-dragging. Our results for the case of \( \alpha = 0.3 \) are roughly consistent with the MHD simulations in Kerr metric indicating the ratio \( \sim 0.3-1 \) at the inner boundary (De Villiers et al. 2003; Hirose et al. 2004). Therefore, \( \alpha = 0.3 \) and \( \delta = 0.5 \) are adopted in the following calculations. We find that the values of these parameters will not affect our main conclusions.

We find that the jet power of the hybrid model, \( Q_{\text{disk}} \), is nearly 25 times larger than that of the BZ model, \( Q_{\text{BZ}} \), for a rapidly spinning black hole with \( j \sim 0.9 \), or even higher for a smaller \( j \) (Fig. 1). The jet efficiency [defined as \( \eta = Q_j/(R_{\text{ms}} v^2) \)] for a spinning BH with \( j = 0.99 \) is 0.8% and 20% for the BZ model and the hybrid model, respectively. This suggests that the hybrid model plays a more important role than the pure BZ model in the jet formation for a black hole surrounded by an ADAF. Our results of the hybrid model are consistent with \( \eta \sim 21\% \) for \( j = 0.99 \) in the numerical MHD simulations (Hawley & Krolik 2006). Hereafter, we implicitly consider the jet power \( Q_{\text{jet}} \approx Q_{\text{disk}} \) in our calculations, since the jet power of the BZ model is always much lower than that of the hybrid model for ADAFs.

3.1. Accretion Power/Jet Power of ADAF and Comparison with XRBs

Once accretion rate \( \dot{m} \) falls below a critical value \( \dot{m}_c \), the standard disk will transit to an ADAF at radii less than the transition radius. In the ADAF scenario, the accretion power (or radiated luminosity) is much lower than that of SSD as a result of reduced radiative efficiency. The power created by accreting matter can either be radiated away, advected into the BH, or taken away by jet/wind. Normally, the radiative efficiency of the pure ADAF is a function of accretion rate, i.e., \( \eta = \eta(\dot{m}/\dot{m}_c)^{\beta} \). The radiative efficiency \( \eta \) of the ADAF is roughly proportional to the accretion rate (e.g., \( \xi \sim 1 \) at lower accretion rate and slightly flattens (\( \xi \lesssim 1 \)) at near the critical value \( \dot{m}_c \) (Merloni et al. 2003; Yuan & Cui 2005; Wu & Cui 2006; Sharma et al. 2007). However, the radiative efficiency should be slightly higher when the accretion rate is near \( \dot{m}_c \), especially considering the contribution of the outer SSD which is important when the transition radius is small, and/or the possibility of a condensation-feed inner disk (Liu et al. 2004). Here, we do not consider these two mechanisms in details due to both of them are still quite unclear. We assume that \( \xi = 1 \) when \( \dot{m} \leq \dot{m}_c \) (see also Narayan & McClintock 2008), which is consistent with that constrained from the XRBs (e.g., Kording et al. 2006), and will not affect our conclusion. Therefore, the bolometric luminosity (or accretion power) of the ADAF can be described by

\[
L_{\text{bol}} = \eta(j) \frac{\dot{m}^2}{\dot{m}_c} M_{\text{Edd}} c^2, \quad (3)
\]

where \( \eta(j) \) is radiative efficiency depending on the BH spin parameter \( j \). The exact value of the critical accretion rate \( \dot{m}_c \) is still unclear. Maclaren (2003) found \( \dot{m}_c \sim 0.02 \) from a detailed investigation of state transitions in X-ray binaries. Wu & Gd (2008) suggested that the accretion rate for the disk transition may be 2-3 times lower than that derived from the state transition. We adopt \( \dot{m}_c = 0.01 \) in our calculations. Figure 2 shows the relation of \( Q_{\text{jet}}^j / L_{\text{Edd}} \sim \dot{m} \) (solid line) and
respectively. We find that the jet power dominates over the accretion power when the accretion rate is less than a critical value $\dot{m} \lesssim \dot{m}_c$, and the objects enter into the “jet-power-dominated advective systems,” where $3 \times 10^{-4} \lesssim \dot{m}_c \lesssim 5 \times 10^{-3}$ depends on the BH spin parameter $j$. The accretion power is dominant when $\dot{m} \gtrsim \dot{m}_c$, and the objects are therefore “accretion-power-dominated advective systems.” We note that the uncertainties of $\delta$ parameter will lead to slightly different critical accretion rate $\dot{m}_c$ due to the radiative efficiency of ADAF, even the jet power is not sensitive to the parameter $\delta$. We find the uncertainties on the critical accretion rate $\dot{m}_c$ will be less than 5 times when considering $\xi \simeq 1 \pm 0.2$ for $0.1 \lesssim \delta \lesssim 0.5$ and BH spin $j=0$, and will less than 2 times for the typical value $j=0.7$~1 found in XRBs (e.g., Liu et al. 2008, and references therein), which will not affect our main conclusion.

Our calculation show that the jet power $Q_{\text{jet}} \propto B^2 \propto \dot{m}$ and accretion power $L_{\text{bol}} \propto \dot{m}^2$. The relation $Q_{\text{jet}} \propto L_{\text{bol}}^{0.5}$ is consistent with the nonlinear correlation between radio luminosity and X-ray luminosity, $L_{\text{radio}} \propto L_{\text{X}}^{1.7}$, in the low/hard state (e.g., Bursa et al. 2003), when considering the simple optically thick conical jet model, where $Q_{\text{jet}} \propto L_{\text{radio}}^{12/17}$ (e.g., Blandford & Königl 1979; Falcke & Biermann 1995) and $L_{\text{X}}$ is an indicator of $L_{\text{bol}}$. Fender et al. (2003) gave a conservative lower limit of the critical accretion rate $\dot{m}_c \sim 10^{-4}$ for the transition of “accretion-power-dominated regime” and “jet-power-dominated regime” assuming the power created by the accreting matter is radiated (accretion power) and taken away by jet (jet power) based on the XRB XTE J1118+480. Migliari & Fender (2006) further suggested that these two regime transitions may occur at the slightly higher critical value $\dot{m}_c \sim 10^{-2}$, using a slightly higher jet power normalization. These estimates based on low/hard state XRBs are roughly consistent with our result that the critical accretion rate is $3 \times 10^{-4} \lesssim \dot{m}_c \lesssim 5 \times 10^{-3}$ when considering the uncertainties in the estimates of the jet power normalization from the observation. We should note that the energy advection play an important role for jet formation, since only a small fraction of the gravitational energy of the flow is dissipated locally, and most of the energy heats the protons/electrons and is advected inward. This leads to a hot thick disk, which allows high poloidal magnetic field strength in the inner region of the flow. We find that, as an example, the fraction of output energy $\sim (Q_{\text{jet}} + L_{\text{bol}})/0.1M_*c^2 \approx 0.2$ for $\dot{m} = 10^{-3}$ and $j=0.7$, and the other 80% of the energy is advected into the central BH. Therefore, the BH central engine will be a “jet-power-dominated advective system” when the luminosity (or accretion rate) is less than a critical value, which is consistent with that constrained with the observations on the BH XRBs and neutron stars (e.g., Kording et al. 2006). It should be noted that we use “jet-power-dominated” not “jet-dominated” to discriminate the possible confusion about the origin of multilwavelength emission. For example, the X-ray emission in the low/hard state XRBs and LLAGNs is still controversial, and it may be dominated by the jet emission (e.g., Markoff et al. 2003; Falcke et al. 2004), by the underlying ADAF, or both (e.g., Yuan & Cui 2005, Wu et al. 2007).

### 3.2. FR I/II Dichotomy

The dividing line between FR I and FR II radio galaxies is clearly shown by a line in the plane of the total radio luminosity and the optical luminosity of the host galaxy (Ledlow & Owen 1996). Ghisellini & Celotti (2001) used the optical luminosity of the host galaxy and the radio luminosity to estimate the mass of its central BH and jet power, respectively. They proposed that the FR I/FR II separation can be interpreted by the systematically different ratios of the jet power to BH mass for FR I and FR II sources. This implies that the FR I/FR II division is linked to the physics (accretion and/or jet processes) on very small scales. They argued that if the jet power is related with accretion power, the accretion mode for low-power FR I sources may be different from that for powerful FR II sources. There is growing evidence to suggest that most FR I type radio galaxy nuclei may possess ADAFs (Reynolds et al. 1996; Gilmozzi et al. 2003; Meloni et al. 2003; Donato et al. 2004; Wu et al. 2007) and FR I/II dichotomy can be interpreted by the systematically different ratios of the jet power to BH mass for FR I and FR II sources. In this work, we compare the jet power of the hybrid model with the observed FR I/FR II dichotomy in the $M_{\text{BH}}-Q_{\text{jet}}$ plane.

The dividing line between FR I and FR II sources of Ledlow & Owen (1996) is given approximately by Meier (1999) as

$$\log P_{\text{rad}} = -0.66M_R + 10.35,$$

where $P_{\text{rad}}$ is the observed radio power at 1.4GHz (in W Hz$^{-1}$) and $M_R$ is the absolute optical R-band magnitude of the host galaxy. An empirical relation between $M_R$ of the host galaxy and central BH mass,

$$\log (M_{\text{BH}}/M_\odot) = -0.5(\pm 0.02)M_R - 2.96(\pm 0.48),$$

was derived by McLure & Dunlop (2002). The jet power is usually estimated from the radio luminosity by using the relation

$$Q_{\text{jet}} \approx 3 \times 10^{38} f^{3/2} Q_{151}^{6/7},$$

where $L_{151}$ is the total radio luminosity at 151 MHz in units of 10$^{38}$W Hz$^{-1}$ sr$^{-1}$ and the factor $f$ parameterizes the uncertainties of the normalization which is constrained to be between 1 and 20 (see Wilott et al. 1999, for details). Blundell & Rawlings (2000) argued $f$ to be most likely in the range of 10-20. The radio luminosity at 1.4 GHz is converted to

![Diagram showing the relation between $Q_{\text{jet}}/L_{\text{bol}}$ and $L_{\text{bol}}/L_{\text{Edd}}$ for BH spin parameter $j$.]
the luminosity at 151 MHz by assuming a radio spectra index $\alpha = 0.8$, where $L(\nu) \propto \nu^{-\alpha}$. Thus, we can obtain the dividing line between jet power and BH mass by using the Eqs. (4)-(6),

$$\log Q_{\text{jet}}(\text{erg s}^{-1}) = 1.13 \log M_{\text{BH}}(M_\odot) + 33.42 + 1.50 \log f. \quad (7)$$

The maximal jet power of the hybrid model (solid line) and the BZ model (dotted line) for ADAFs are plotted in Fig. 3 with different black hole spin parameters: $j = 0.99, 0.9, 0.7$, respectively. The accretion rate $\dot{m} = 0.01$ is adopted in all calculations, which is roughly consistent with that constrained from the ionization luminosity of the dividing line between FR I and FR II sources (see the text for more details).

The maximal jet power of the hybrid model (solid line) and the BZ model (dotted line) for ADAFs are plotted in Fig. 3 with different black hole spin parameters: $j = 0.99, 0.9, 0.7$, respectively. The accretion rate $\dot{m} = 0.01$ is adopted in our calculations. We find that the maximal power of the pure BZ model is nearly 25 times less than the dividing line between FR I and FR II radio galaxies. However, we find that the maximal jet power of the hybrid model with $j = 0.9/0.99$ can roughly reproduce the jet power dividing line with $f = 10/20$ (see Fig. 3). Thus, the dividing line between FR I and FR II sources corresponds to the maximal jet power of the hybrid model extracted from the ADAFs surrounding rapidly spinning black holes accreting at the critical rate $\dot{m}_0$, which is consistent with the analogue between FR I sources and the low/hard state of XRBs (e.g., Merloni et al. 2003, Falcke et al. 2004). We find that the jet power of the hybrid model is very sensitive to the BH spin, especially when $j > 0.9$ (Fig. 1). Therefore, it seems that this sensitivity would likely blur the FRI/FR II dividing line if the spins of black holes spread around 0.9. The FR I/FR II dividing line is indeed not very clear (one can find a few FR I sources above the dividing line, and vice versa for FR II sources, e.g., Ledlow & Owen 1996). The critical accretion rate $\dot{m}_0 = 0.01$ for the accretion mode transition is also supported by the ionization luminosity for the separation between FR I and FR II sources. Willott et al. (1999) found that the ionization luminosity of radio galaxies is roughly equal to the jet power for $f = 20$, which corresponds to $L_{\text{ion}}/L_{\text{Edd}} \sim 2.5 \times 10^{-2}$ for typical BH mass $M_{\text{BH}} \sim 10^{7.5-9.5} M_\odot$ in sample of Ledlow & Owen (1996). This ionization luminosity Eddington ratio roughly corresponds to $\dot{m} \sim 0.1$ if we assume that the bolometric luminosity is equal to the ionization luminosity and the BH is spinning rapidly [e.g., $\eta j \gtrsim 0.2$ for $j \gtrsim 0.95$]. It is still unclear why the jet power of FR II radio sources is always above this dividing line, which is beyond the scope of this work.

Our calculations on the jet power for either the BZ or BP mechanisms are based on the pure ADAF model. Narayan & Yi (1994) found that the ADAF has a positive Bernoulli parameter, and the accretion flow is therefore gravitationally bound, which implies that the gas may escape as outflows. In this case, the accretion rate of the advection-dominated inflow-outflow solution (ADIOS) is a function of the radius instead of a constant accretion rate for the pure ADAF (e.g., Blandford & Begelman 1999). For ADIOS, the gas swallowed by the BH is only a fraction of the rate at which it is supplied, as part of the gas is carried away in the winds before it reaches the BH. Therefore, both the accretion power and jet power will decrease in the ADIOS compared the pure ADAF case for given accretion rate at the outer boundary. The accretion power $L_{\text{bol}}$ is roughly $\propto \dot{m}_{\text{in}}^2$, while the jet power $Q_{\text{jet}}$ is roughly $\propto \dot{m}_{\text{in}}$ at the inner edge of the flow. It means that, in Fig. 2, the lines for $L_{\text{bol}}$ shift down more than those for $Q_{\text{jet}}$ in the presence of winds. Thus, the critical accretion rate $\dot{m}_c$ for the transition between “jet-power-dominated advective systems” and “accretion-power-dominated advective systems” in the ADIOS should be slightly higher than that derived from the pure ADAF case. Therefore, the critical accretion rate in the ADIOS may be close to $\dot{m}_c \sim 10^{-2}$ for the case of $j \gtrsim 0.9$, which is roughly consistent with that constrained from the XRBs (e.g., Mihalas & Fender 2006). The ADIOS has a structure and a upper limit on the accretion rate at the inner edge of the disk similar to those of a pure ADAF if the wind is not very strong (e.g., Chang et al. 2002, Nemmen et al. 2007). The jet power of BZ/BP mechanisms is dominantly extracted from the inner region of the flow, so the maximal jet power for an ADIOS should be similar to that for an ADAF without winds, provided that their accretion rate at the inner edge of the flow are the same. Therefore, the maximal jet power from ADIOS with $\dot{m}_{\text{in}} \simeq 0.01$ and $j \sim 0.9-0.99$ can still reproduce the dividing line of the FR I/FR II dichotomy (Fig. 3).

4. SUMMARY AND CONCLUSION

The main conclusions of this work can be summarized as follows:

1. We investigate the jet power of the BZ mechanism and hybrid mechanism for the ADAFs surrounding rotating black holes based on our global ADAF solutions in Kerr metric. We find that the jet power of the hybrid model is about 1 order of magnitude higher than that of the BZ model, and the jet efficiency of the hybrid model is roughly consistent with that of the numerical MHD simulations for Kerr black holes (Hawley & Krolik 2006).

2. The jet power dominates over the accretion power when the accretion rate is less than a critical value $\dot{m}_c$, while the accretion power will be dominant when the accretion rate is larger than this critical value (Fig. 2), which is roughly consistent with that constrained from the observations of XRBs (e.g.,

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We note that the differences of the Eddington ratio in Ghisellini & Celotti (2001) and Wold et al. (2007) from ours are caused by using different factor $f$, and $f = 1$ is adopted in their work, and some coefficients of Eqs. in Ghisellini & Celotti (2001) may be erroneous as pointed out by Wold et al. (2007).
Kerr black holes are accreting at $m \lesssim 0.01$ in FR I sources (Fig. 3). The ionization luminosity corresponding to the dividing line also suggests the critical accretion rate to be $\sim 0.01$ if the empirical relation between the photo-ionizing luminosity and the radio luminosity is adopted. These strongly imply that most FR I radio galaxies may have a different accretion mode from FR II sources.

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