We investigate the correlation between 151 MHz radio luminosity, $L_{\text{151 MHz}}$, and jet power, $P_{\text{jet}}$, for a sample of low-power radio galaxies, of which the jet power is estimated from X-ray cavities. The jet power for a sample of Fanaroff–Riley I radio galaxies (FR Is) is estimated with the derived empirical correlation. We find that $P_{\text{jet}}/L_{\text{Edd}}$ is positively correlated with $L_{X}^{2–10 \text{ keV}}/L_{\text{Edd}}$ for FR Is, where $L_{\text{Edd}}$ is the Eddington luminosity and $L_{X}^{2–10 \text{ keV}}$ is the 2–10 keV X-ray luminosity. We calculate the jet power of a hybrid model, as a variant of a Blandford–Znajek model proposed by Meier, based on the global solution of the advection-dominated accretion flow (ADAF) surrounding a Kerr black hole (BH). Our model calculations suggest that the maximal jet power is a function of the mass accretion rate and the BH spin parameter $j$. The hard X-ray emission is believed to be mainly from the ADAFs in FR Is, and the mass accretion rate is therefore constrained with the X-ray emission in our ADAF model calculations. We find that the dimensionless angular momentum of BH $j$ ≥ 0.9 is required in order to reproduce the observed relation of $P_{\text{jet}}/L_{\text{Edd}} = L_{X}^{2–10 \text{ keV}}/L_{\text{Edd}}$ for FR Is. Our conclusion will be strengthened if part of the X-ray emission is contributed by the jets. Our results suggest that BHs in FR Is are rapidly spinning, which are almost not affected by the uncertainty of the BH mass estimates.

Key words: accretion, accretion disks – black hole physics – galaxies: jets – magnetohydrodynamics (MHD) – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

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 (BH) 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. The so-called hybrid model, as a variant of the BZ model, was proposed by Meier (1999), which combined the BZ and BP effects through the large-scale magnetic fields threading the accretion disk outside the ergosphere and the rotating plasma within the ergosphere. The recent magnetohydrodynamic (MHD) simulations showed that both BH spin and accretion process may play important roles in jet formation (e.g., McKinney & Gammie 2004; Hirose et al. 2004; De Villiers et al. 2005; Hawley & Kroll 2006), which seem to support the hybrid model.

Recent high-resolution Chandra observations of the galaxy clusters and giant elliptical galaxies have revealed prominent X-ray surface brightness depressions corresponding to cavities or bubbles created by active galactic nucleus (AGN) activities (e.g., Fabian et al. 2000; Birzan et al. 2004; Allen et al. 2006; Rafferty et al. 2006). The X-ray cavities were found to be coeval with the radio lobes in nine nearby low-power radio galaxies, which suggest that these cavities are most likely inflated by the interaction of radio jet and surrounding hot gas (e.g., McNamara et al. 2000; Allen et al. 2006). Therefore, the X-ray cavities provide a direct measurement of the mechanical energy released by the jet through the work done on the hot gas surrounding them. Measurements of this energy, combined with measurements of the timescale required to inflate the cavities, can be used to estimate the jet power (e.g., Allen et al. 2006).

Low-power Fanaroff–Riley I radio galaxies (FR Is) are believed to be BL Lac objects with the relativistic jet misaligned to our line of sight, and high-power FR II objects correspond to misaligned radio quasars (Urry & Padovani 1995). The Eddington ratios $L_{\text{bol}}/L_{\text{Edd}}$ of FR I/BL Lac objects are systematically lower than those of FR II/radio quasars, with a rough division at $L_{\text{bol}}/L_{\text{Edd}} \sim 0.01$, which implies that the accretion mode in FR I/BL Lac objects may be different from that of FR II/radio quasars (e.g., Ghisellini & Celotti 2001; Xu et al. 2009). Low mass accretion rates $\dot{m}$ may lead to the accretion flows to be advection dominated (e.g., Narayan & Yi 1994), and such hot, optically thin, geometrically thick advection-dominated accretion flows (ADAFs) are suggested to be present in low-luminosity AGNs (LLAGNs, e.g., FR Is, low-luminosity Seyferts, etc.; Wu et al. 2007; Yuan 2007; Narayan & McClintock 2008, and references therein).

The BH spin remains one of the most intriguing aspects of astrophysics. At present, only a few observations allow spins to be estimated for supermassive BHs, which are based on the fitting of the “reflection” component of iron line around 6.4 keV (e.g., Wilms et al. 2001; Fabian et al. 2002). The spin energy of the BH is thought to play an important role in powering the large-scale jets from AGNs based on the BZ process or the hybrid model of BZ and BP processes. In the last few years, many groups tried to investigate the BH spins of radio galaxies from their jet power based on different jet formation models. Nemmen et al. (2007) proposed that the BHs in the elliptical galaxies should be rapidly rotating in order to drive powerful jets to heat the intracluster medium and quench cooling flows. They constrained the BH spins for nine nearby elliptical galaxies by comparing the jet power estimates with the BZ model and
the hybrid model, where the self-similar structure of ADAF and Bondi accretion rates are used (see Nemmen et al. 2007 for more details). McNamara et al. (2011) further investigated the roles of the BH spin and accretion in generating powerful AGN outbursts in the cores of 31 clusters or galaxies based on the model of Nemmen et al. (2007). However, they found that Bondi accretion from hot atmospheres is generally unable to fuel these powerful AGNs and other fuel supply should be important (see Wu et al. 2007 for a similar conclusion). Therefore, it is difficult to place strong constraints on the spin parameter based on the jet power and Bondi accretion rates of these radio galaxies. Daly (2009) showed that the BH spins of low-power radio sources may range from about 0.1 to 0.8, where their results are based on the two unclear assumptions: (1) the magnetic field strength is equal to approximately the Eddington magnetic field strength and (2) the field strength is proportional to the BH spin. Wu & Cao (2008) proposed that the dividing line of FR I/II dichotomy can be well reproduced if the BH is rapidly rotating and the putative dimensionless accretion rate $\dot{m} \simeq 0.01$ is adopted, where the accretion rate $\dot{m} \simeq 0.01$ is roughly consistent with that of the critical rate for the accretion-mode transition from a standard disk to an ADAF.

One of the difficulties in constraining the BH spin is that the mass accretion rate $\dot{m}$ and the BH spin parameter $j$ are degenerate in jet formation models, which means that the BH spin parameter cannot be well constrained even after the jet power is measured. The purpose of this paper is to constrain the BH spin parameters for a sample of FR Is, in which the mass accretion rates are constrained with their nuclear X-ray emission. Most previous work on the jet power extracted from ADAFs was based on the self-similar structure of ADAFs (e.g., Nemmen et al. 2007; McNamara et al. 2011). In this work, we will calculate the jet power based on the global solution of ADAF surrounding Kerr BHs, since the self-similar solution can reproduce well the global solution at large radii, while it deviates significantly near the BHs. A $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$ is adopted in this work.

2. SAMPLE

Our sample consists of two parts. The first part is the low-power radio sources with jet power estimated from their X-ray cavities (part I). In the literature, X-ray cavities have been divided into two categories: radio-filled cavities and radio-ghost cavities, depending on the presence or absence of bright 1400 MHz radio emission in the cavities (e.g., Birzan et al. 2008 and references therein). In this work, we only consider the cavities with relatively strong radio emission (radio-filled cavities, e.g., FR I and low-power FR II), where the particle injection is still occurring, and ghost cavities have been excluded due to the conjecture that they are only the relics of earlier outbursts whose radio emission has faded and it is no longer an indicator of current jet power (e.g., Birzan et al. 2008). Twelve sources are selected from Merloni & Heinz (2007) and Cavagnolo et al. (2010; see Table 1). Ten of them are FR I or FR I-like sources, and two low-power FR IIs (3C 388 and 3C 405) are also included. These two low-power FR IIs stay around the dividing line of the FR dichotomy in the $M_{\text{BH}}-P_{\text{jet}}$ plane (Wu & Cao 2008), and, therefore, they are smoothly connected to high-power FR I. The empirical correlation between their radio emission and jet power can be established with this sample. We note that cavity buoyancy ages, $t_{\text{buoy}}$, are used to estimate the jet power in Cavagnolo et al. (2010), while the sound speed ages, $t_c$, are used in Merloni & Heinz (2007, and references therein). To be consistent with each other, we use the buoyancy age in this work, and $t_{\text{buoy}}$ was estimated from $t_c$ with the mean value of the ratio $t_c/t_{\text{buoy}} = 0.65$ (Birzan et al. 2004). The second part of the FR I sample is primarily selected from the 3CR sample of radio galaxies with $z < 0.3$ (Buttiglione et al. 2011), and some other low-redshift FR Is in the literature are also included (part II). We only select the FR Is with observed nuclear X-ray luminosities and estimated BH masses (for part of them, the jet power is estimated by using the empirical relation in this work). The high-resolution data of Chandra are preferentially adopted to estimate the nuclear X-ray emission, and several sources with X-ray emission observed from XMM-Newton, ASCA, and BeppoSAX were also included (see Table 1). Because the X-ray data were acquired with a variety of different instruments and analyzed with different techniques, we convert all the luminosities to one standard bandpass, 2–10 keV, using the available power-law flux at a given wave band and the best-fit spectral slope. Some sources with only detected upper limits for the nuclear X-ray emission have not been included. Our final sample includes 33 FR Is (see Table 1).

3. ADAF AND JET MODEL

We use the ADAF–jet model surrounding a Kerr BH to investigate the BH spins of FR Is with their accretion/jet power. Only the main features of the model are described here, the details of which can be found in Wu & Cao (2008, and references therein). We employ the approach suggested by Manmoto (2000) for calculating the global structure of the ADAF in the general relativistic frame, which allows us to calculate the structure of an ADAF surrounding either a spinning or a nonspinning BH. All radiation processes (synchrotron, Bremsstrahlung, and Compton scattering) are included consistently in the calculations of the ADAF structure. The global structure of an ADAF surrounding a BH spinning at a rate $j$ with mass $M_{\text{BH}}$ can be calculated with proper outer boundaries, if the parameters $\dot{m}$, $\alpha$, $\beta$, and $\delta$ are specified (e.g., Manmoto 2000). The parameter $j = J/(G M_{\text{BH}}^{-1})$ is the dimensionless angular momentum of the BH ($J$ is the angular momentum of the BH), and $\dot{m} = M/M_{\text{Edd}}$ is the dimensionless accretion rate (the Eddington accretion rate is defined as $M_{\text{Edd}} = 1.4 \times 10^{15} M_{\odot}/(L_*/ M_{\odot} \text{ g s}^{-1})$). The viscosity parameter $\alpha$ in ADAF models is supposed to be within a very narrow range $\alpha \simeq 0.1–0.3$, which is supported either by the MHD simulations or the observations (e.g., Narayan & McClintock 2008 and references therein). The magnetic parameter $\beta = P_\text{m}/P_\text{in}$ in our calculations is not an independent parameter but relates to $\alpha$ as $\alpha \simeq (0.55 - \alpha)/\alpha$, as suggested by the MHD simulations (e.g., Hawley et al. 1995). The parameter $\beta \simeq 1–5$ for the typical value of $\alpha \simeq 0.1–0.3$. The most poorly constrained parameter is $\delta$, describing the fraction of the turbulent dissipation that directly heats the electrons in the flow. Sharma et al. (2007) found that the parameter $\delta$ may be in the range of $\sim 0.01–0.3$ based on the simulations, depending on the model details. Recent ADAF models typically require $\delta \sim 0.3$ in order to fit the spectra of Sgr A* and other LLAGNs (e.g., Yuan et al. 2006 and references therein). The field-enhancing effect caused by frame dragging is also considered (Meier 2001). The amplified magnetic field related to the magnetic field produced by the dynamo process in the ADAF can be expressed as $B = g B_\text{dyno}$, where $g = \Omega/\Omega_*$ is the field-enhancing factor, and the disk angular velocity $\Omega$ is the sum of its angular velocity relative to the local metric $\Omega_*$ plus...
the angular velocity of the metric itself in the Boyer–Lindquist frame \( \omega \equiv -\frac{\dot{R}}{R^2} \), i.e., \( \Omega = \Omega + \omega \). We can calculate the spectrum of the accretion flow based on the global structure of ADAF. In the spectral calculations, the gravitational redshift effect is considered, while the relativistic optics near the BH is neglected (e.g., Manmoto 2000).

To evaluate the jet power extracted from the inner region of ADAF, we adopt the hybrid model proposed by Meier (2001), where both the BZ and BP mechanisms were incorporated. The total jet power is given by

\[
P_{\text{jet}} = B_p^2 R^4 \Omega^2 / 32 c, \tag{1}
\]

where \( R \) is the characteristic size of jet formation region and the poloidal magnetic field \( B_p \approx g B_{\text{dynamo}} \) (see Meier 2001 for the details). Following the work by Nemmen et al. (2007), all the quantities are evaluated at the innermost marginally stable orbit of the disk \( R = R_{\text{ms}} \), which are roughly consistent with the jet-launching regions in the numerical simulations (e.g., Hirose et al. 2004).

4. RESULTS

4.1. Jet Efficiency of ADAF Surrounding a Spinning BH

We calculate the jet power extracted from the inner region of the ADAF surrounding a rotating BH. We define the jet efficiency as \( \eta_{\text{jet}} = P_{\text{jet}} / \dot{M} c^2 \), and the relations between the jet efficiency, \( \eta_{\text{jet}} \), and the BH spin parameter \( j \) calculated with different values of the ADAFs are shown in Figure 1. We find that the jet efficiency is insensitive to the values of the model

\[
\eta_{\text{jet}} = \frac{P_{\text{jet}}}{\dot{M} c^2}.
\]
The relation between the host galaxy absolute magnitude and BH mass (e.g., McLure & Dunlop 2002) was usually used to estimate the BH mass of nearby low-power radio sources. At present, the BH mass derived from the velocity dispersion of the host bulge, $\sigma_*$, is believed to be more accurate based on the empirical correlation of the $M_{\text{BH}}-\sigma_*$ relation (e.g., Gebhardt et al. 2000; Tremaine et al. 2002),

$$M_{\text{BH}} = 10^{8.13} \left( \frac{\sigma_*}{200 \text{ km s}^{-1}} \right)^{4.02} M_\odot, \quad (3)$$

We estimate the BH mass of FR Is from their velocity dispersions of host bulges $^3$ or select the mass from the literature with the same method. The BH masses of some FR Is estimated from other methods are also selected from the literature if there are no observational data for $\sigma_*$ (see Table 1).

$^3$ The velocity dispersions were obtained from the HyperLEDA online database: http://leda.univ-lyon1.fr.

4.4. Constraints on the BH Spins for FR Is

The relation between $P_{\text{jet}}/L_{\text{Edd}}$ and $L_X^{2–10 \text{ keV}}/L_{\text{Edd}}$ for the FR Is in our sample is shown in Figure 3, where the filled circles and empty circles represent the jet power estimated from the X-ray cavities and the empirical correlation of Equation (2), respectively. We find that $P_{\text{jet}}/L_{\text{Edd}}$ is positively correlated with $L_X^{2–10 \text{ keV}}/L_{\text{Edd}}$ for FR Is. Considering the uncertainties in deriving the jet power and BH mass, the binned data with the standard deviation as the error bar are also plotted in the figure.

We calculate the jet power and X-ray luminosity based on the structure of the ADAFs surrounding Kerr BHs with different masses, and find that both the jet power and X-ray luminosity are roughly proportional to the BH mass for $M_{\text{BH}} \gtrsim 10^6 M_\odot$, provided all other parameters are fixed. We calculate the $P_{\text{jet}}/L_{\text{Edd}}$ and $L_X^{2–10 \text{ keV}}/L_{\text{Edd}}$ based on our model varying $\dot{m}$ from $10^{-5}$ to $10^{-2}$ with $M_{\text{BH}} = 10^9 M_\odot$ (solid lines in Figure 3). We find that the relation between $P_{\text{jet}}/L_{\text{Edd}}$ and $L_X^{2–10 \text{ keV}}/L_{\text{Edd}}$ calculated with $\alpha = 0.3$ and $\delta = 0.3$ can roughly reproduce the observational relation if the BH spin $j \simeq 0.99$ is adopted (see the red solid line in Figure 3). For comparison, the relations for the case of $M_{\text{BH}} = 10^9 M_\odot$ are shown as dashed lines, which almost coincide with the solid lines. Our results suggest that the $P_{\text{jet}}/L_{\text{Edd}}-L_X^{2–10 \text{ keV}}/L_{\text{Edd}}$ relation is insensitive to BH mass, since their ratios are roughly scale free from the BH mass. We further investigate this relation for the case of $\delta = 0.01$ (dotted lines), in which all the other parameters are unchanged. We find that $j \simeq 0.9$ is required in the model calculations in order to reproduce the observational relation in this case (blue dotted line in Figure 3). The physical reason is that the X-ray emission from the ADAF with $\delta = 0.01$ is much weaker than with an intrinsic scatter $\gtrsim 0.3$ dex. We estimate the BH mass of FR Is from their velocity dispersions of host bulges $^3$ or select the mass from the literature with the same method. The BH masses of some FR Is estimated from other methods are also selected from the literature if there are no observational data for $\sigma_*$ (see Table 1).

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The relation between $P_{\text{jet}}/L_{\text{Edd}}$ and $L_X^{2–10 \text{ keV}}/L_{\text{Edd}}$ for the FR Is in our sample is shown in Figure 3, where the filled circles and empty circles represent the jet power estimated from the X-ray cavities and the empirical correlation of Equation (2), respectively. We find that $P_{\text{jet}}/L_{\text{Edd}}$ is positively correlated with $L_X^{2–10 \text{ keV}}/L_{\text{Edd}}$ for FR Is. Considering the uncertainties in deriving the jet power and BH mass, the binned data with the standard deviation as the error bar are also plotted in the figure.

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that for $\delta = 0.3$ provided all other model parameters are fixed, which is due to much less dissipated energy heating electrons directly, while the jet power is not sensitive to the value of $\delta$. Therefore, our results suggest that the BHs in FR Is are rapidly spinning with $j \gtrsim 0.9$ in order to drive the observed strong jets.

It should be noted that we assume X-ray luminosities of FR Is to be dominantly from the ADAF in our calculations. We test this issue by comparing the relations between the hard X-ray luminosities and narrow-line luminosities ($L_{[\text{O}\text{III}]}$) for radio galaxy FR Is and radio-quiet Seyferts (jet is weak or absent), as both the narrow-line regions in FR Is and Seyferts are believed to be photoionized by the photons emitted from the accretion disks (e.g., Willott et al. 1999). The results are plotted in Figure 4, in which FR Is of both part I (filled circles) and part II (open circles) of our sample are included, and 17 radio-quiet, Compton-thin Seyferts are selected from Panessa et al. (2006). We find that the $L_{\text{X}} - L_{[\text{O}\text{III}]}$ correlation of FR Is is roughly consistent with that of radio-quiet Seyferts. This means that the X-ray emission of the FR Is and Seyferts should have the same origin. Therefore, the X-ray emission of FR Is should be mainly from the accretion flows.

5. DISCUSSION

We investigate the accretion/jet activities surrounding a spinning BH, where the accretion flow is described by the ADAF model. The ADAF may have winds, and a power-law radius-dependent accretion rate $m(r) \propto r^{-p_w}$ ($p_w > 0$) is usually assumed, although the detailed physics is still unclear (Blandford & Begelman 1999). Therefore, the Bondi accretion rate may not be a reliable rate of the mass that eventually flows into the BH due to the possible wind, even if it can be estimated from the X-ray observations. As most of the X-ray emission comes from the inner region of the accretion flow near the BH, the spectrum of ADAF is similar to that of an ADAF with winds, provided they have the same accretion rate at their inner edges. As both the X-ray emission and the jets are from the inner region of the accretion flow, the main conclusion will not be altered even if the winds are included in the ADAF model.

The jet power of radio galaxies can be estimated from the relation between jet power and 151 MHz radio luminosity proposed by Willott et al. (1999). The radio emission at low frequency, e.g., 151 MHz, is usually dominated by the optically thin radio lobes which is free from Doppler boosting effects, since the lobe material is generally thought to be of low enough bulk velocity. However, the relation proposed by Willott et al. (1999) is only calibrated for high-power FR IIs, and it is still unclear if it can be simply extrapolated to low-power FR Is. The X-ray cavities in galaxies or clusters provide a way to estimate the jet power. The relation between jet power estimated from the X-ray cavities, and 327 MHz, 1400 MHz, 5000 MHz, and the radio bolometric luminosity have been investigated by different groups (e.g., Bırzan et al. 2004, 2008; Merloni & Heinz 2007; Cavagnolo et al. 2010). Bırzan et al. (2008) proposed that the radio-source aging may be responsible for some of the scatter in the relation between jet power and radio luminosity due to the possible variation of radiative efficiency of the jet, and the scatter is reduced by $\sim 50\%$ after correcting for the effect of radio aging. For example, the relation between jet power and the radio luminosity becomes tighter when only considering the radio-filled sources where the jet is still active and particle injection is occurring (see Bırzan et al. 2008 for more details). However, there are only five radio-filled sources used to build the jet power and radio bolometric luminosity relation in Bırzan et al. (2008), which is also affected by errors in measuring the radio bolometric luminosity. In this work, we add seven more radio sources (FR I or low-power FR II) to investigate the relation between the jet power and 151 MHz radio luminosity, where most of the radio sources have relatively strong 1400 MHz radio emission which should belong to radio-filled sources. Compared with the relations in Bırzan et al. (2008) and Cavagnolo et al. (2010), our relation predicts slightly lower jet power at a given
radio luminosity, which is due to the fact that only the cavities with strong radio emission (most are FR Is) are considered, while the previous works even included ghost cavities, parts where the radio emission has faded. The low-frequency radio emission from lobes at 151 MHz does not suffer from the Doppler boosting effects as compared to the radio-core emission used in Merloni & Heinz (2007). Our relation (Equation (2)) should be more accurate for the estimate of the jet power for the sources with relatively strong radio emission (e.g., radio-filled sources or FR Is in this work). The intrinsic scatter is \( \sigma = 0.23 \) dex for the \( P_{\text{jet}} - L_{151 \text{ MHz}} \) relation derived in our sample, which is similar to 0.3 dex for five radio-filled sources used in B\ü{}rzan et al. (2008). The scatter of the relation for these radio-filled sources is much smaller than those of Merloni & Heinz (2007, \( \sigma \approx 0.47 \) dex), B\ü{}rzan et al. (2008, \( \sigma \approx 0.80 \) dex), or Cavagnolo et al. (2010, \( \sigma \approx 0.70 \) dex), in which the radio core emission is used or ghost cavities are included. We note that the FR Is with observed X-ray cavities are still limited, and more observations are desired for further investigations on this issue.

We employ our ADAF–jet model for Kerr BHs to constrain the BH spins of FR Is based on the relation between \( P_{\text{jet}} / L_{\text{Edd}} \) and \( L_X^{2–10 \text{ keV}} / L_{\text{Edd}} \). For the typical viscosity parameter \( \alpha = 0.3 \), we find that \( j \approx 0.99 \) is required to reproduce the observed relation for the case of \( \delta = 0.3 \), or \( j \approx 0.9 \) for the case of \( \delta = 0.01 \). Our results suggest that the BHs in FR Is should be rapidly spinning with \( j \gtrsim 0.9 \), even if the uncertainty of the poorly constrained parameter \( \delta \) is considered (see Figure 3). The BH mass used in this work is mainly derived from the velocity dispersion of the host bulge. Lauer et al. (2007) argued that the galaxy luminosity may be a better tracer of the BH mass than the velocity dispersion for the most massive BHs, and the uncertainties in the high-mass end of the \( M_{\text{BH}} - \sigma \) relation can lead to underestimation of BH mass up to a factor of several. If this is the case, the observational data points will move from the top right to the bottom left along the 45 deg line in Figure 3, and our main conclusion is almost unaltered compared with the model calculations. Davis & Laor (2011) found a strong correlation between BH spin and BH mass, where the spin \( j \sim 0 \) for low-mass BHs with \( M_{\text{BH}} \sim 10^7 M_{\odot} \), while it is fast rotating with \( j \sim 1 \) for supermassive BHs with \( M_{\text{BH}} \sim 10^9 M_{\odot} \), based on the estimation of radiative efficiency for a sample of quasars (see Sikora et al. 2007; Lagos et al. 2009; Fanidakis et al. 2011, for a similar conclusion). Our conclusion for the fast rotating BHs in FR Is is similar to their conclusion, since the typical BH mass of FR Is is around \( 10^9 M_{\odot} \).

In this work, we assume that most of the X-ray emission of FR Is is from the ADAFs. It should be noted that the X-ray emission of some FR Is with very low Eddington ratios (\( L_X^{2–10 \text{ keV}} / L_{\text{Edd}} \)) may be dominated by the jet emission (e.g., Wu et al. 2007). Yuan & Cui (2005) also pointed out that the X-ray emission should be dominated by the emission from the ADAFs when the Eddington ratio of X-ray luminosity is larger than a critical value, and jet contribution will be dominant if the ratio is less than the critical value. The critical ratio \( L_X^{2–10 \text{ keV}} / L_{\text{Edd}} \) \( \sim 10^{-2} \) if the typical BH mass \( M_{\text{BH}} \sim 10^7 M_{\odot} \) is assumed for FR Is. We find that most FR Is in our sample have \( L_X^{2–10 \text{ keV}} / L_{\text{Edd}} \) \( \gtrsim 10^{-7} \) (see Figure 3), and their X-ray emission should be dominantly from ADAFs considering the criterion suggested by Yuan & Cui (2005). This is consistent with our results based on the \( L_X^{2–10 \text{ keV}} - L_{\text{OIII}} \) relation for FR Is and Seyferts. Our main conclusions will not be changed even if the jets contribute part of the X-ray emission, since the intrinsic X-ray emission from ADAFs will be less than the observed values (points in Figure 3 move to left). This will require even higher BH spins in our model calculations of jet power.

The mass accretion rates of FR Is can be derived from their X-ray luminosity with our ADAF model calculations for measured BH masses. We find that the accretion rates are in the range of \( \sim 10^{-4} \) to \( 10^{-3} M_{\text{Edd}} \) for the FR Is in our sample if \( \delta = 0.3 \) is adopted. The BH spins of FR Is can be constrained from the jet power and the derived accretion rates (from their X-ray luminosities) based on the hybrid jet model (Meier 2001). In this work, the jet power is calculated with the mass accretion rate inferred with the X-ray emission from the ADAF, which should be better than that estimated from the Bondi accretion rate (e.g., Nemmen et al. 2007), since it may not be the real mass accretion rate that eventually flows into BHs due to the possible outflowing winds or the gas released by the stellar population inside the Bondi radius (e.g., Pellegrini 2005; Wu et al. 2007; McNamara et al. 2009, 2011). The magnetic field strength constrained from the Eddington accretion rate should be the upper limits since the real accretion rate should be much less than the Eddington rate in the low-power radio sources of their sample, and, therefore, the BH spins should be the lower limits (Daly 2009). Wu & Cao (2008) proposed that the dividing line of the FR I/II dichotomy can be well reproduced if the BHs are fast rotating with \( j \sim 0.9–0.99 \) and the putative dimensionless accretion rate \( \dot{m} \sim 0.01 \) for the accretion-mode transition is adopted. We calculate the accretion rate from the X-ray activities for FR Is in this work and evaluate the BH spins from their jet power and magnetic field strength near the BHs based on the global solution of ADAFs. We find that the BHs should be rapidly rotating in FR Is, which further strengthen our conclusion of Wu & Cao (2008).

The accretion rates of low-power FR Is are very low compared to other high-power FR IIs, which suggest that the accretion disk in FR Is is most probably in an ADAF state. The ADAF radiates inefficiently and most of the gravitational energy of the accreting matter released is not dissipated locally but advected inward, and the advected energy may be taken away by the jet or eventually carried into the BH. Energy advection plays an important role for jet formation, since most of the gravitational energy heats the protons/electrons and lead to a hot thick disk, which allows a high poloidal magnetic field strength in the inner region of the flow (e.g., Livio et al. 1999). Meier (2001) further proposed that the magnetic field produced by the dynamo process in the ADAF can be amplified due to the frame-dragging in the Kerr metric. We estimate the jet power extracted from the inner region of the ADAF surrounding a Kerr BH (see Section 3), where 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 around two times in the plunging region if the BH spin parameter \( j \sim 0.9–0.99 \). Therefore, the jet power was also enhanced roughly four times after the frame-dragging effect was considered. The jet efficiency of \( j \sim 0.99 \) is around 20%, which is 2–3 orders higher than that of low-spin BHs with \( j \simeq 0 \) based on our ADAF–jet model (see Figure 1). Our results suggest that a large fraction of the advected energy can be extracted by the jet if the BH is rapidly spinning (e.g., \( j \simeq 0.9–0.99 \)), while most of the released energy will be advected into the BH if it is slowly spinning (e.g., \( j \simeq 0 \)). It is interesting to note that the radio luminosity of radio-loud AGNs is always 2–3 orders higher than that of radio-quiet AGNs with similar X-ray or optical luminosities, which may imply that the BHs have low spins (\( j \simeq 0 \)) in radio-quiet AGNs if the jet power is scaled with their radio luminosity. It is still unclear
how to derive the jet power accurately for radio-quiet AGNs (if jets exist in these radio-quiet sources), since there is no evident extended radio emission as that in radio-loud AGNs, and the detailed calculation for radio-quiet sources is beyond the scope of this paper. Our results roughly support the so-called spin paradigm that radio-loud AGNs have relatively high BH spins, while radio-quiet AGNs have lower BH spins (e.g., Sikora et al. 2007; Tchekhovskoy et al. 2010, and references therein).

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