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Jets Accelerated From the Disk Coronae in Active Galactic Nuclei

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Abstract We calculate the maximal jet power extractable from a rapidly spinning black hole or the accretion disk (standard thin disk or advection dominated accretion flow, ADAF) surrounding the black hole. Compared the theoretical calculations with the observational data, ADAFs are required to be present in the inner regions of the disks and transit to standard thin disks at radii of $\sim 40-150\, GM_{\rm bh}/c^2$ for BL Lac objects. For some radio quasars, their jets are too powerful to be extracted from the standard thin accretion disks or rapidly spinning black holes surrounded by standard thin disks. If the ADAFs are present in these quasars, their bright optical continuum luminosity cannot be produced by pure-ADAFs due to their low accretion rates and low radiation efficiency, unless the dimensionless accretion rates $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$ can be as high as $\gtrsim 0.05$ and the ADAFs transit to standard thin disks at rather small radii of $\sim 20GM_{\rm bh}/c^2$. We propose that the disk-corona structure is present at least in some radio quasars. The plasmas in the corona are very hot, and the scale-height of the corona $H_{\rm c} \sim R$. Powerful jets with $Q_{\rm jet} \sim L_{\rm bol}$ (bolometric luminosity) can form by the large-scale magnetic fields created by dynamo processes in the disk coronae of some radio quasars.

Key words: galaxies: active — galaxies: jets — accretion, accretion disks — black hole physics

1 INTRODUCTION

Relativistic jets have been observed in many radio-loud AGNs and are believed to form very close to the black holes. In currently most favored jet formation models, the power is generated through accretion and then extracted from the disk/black hole rotational energy and converted into the kinetic power of the jet, namely, the Blandford-Payne (Blandford & Payne 1982) and Blandford-Znajek mechanisms (Blandford & Znajek 1977). The magnetic fields are maintained by the currents in the accretion disk surrounding the rapidly spinning black hole, so the power extracted from a rapidly spinning black hole by the Blandford-Znajek mechanism also depends on the properties of the disk near the black hole.

It's still unclear which mechanism is responsible for jet formation in AGNs. The relative importance of these two jet formation mechanisms is explored by different authors (e.g., Ghosh

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& Abramowicz 1997; Livio et al. 1999, hereafter L99; Cao 2002b). The length scale of the fields created by dynamo processes is of the order of the disk thickness $\sim H$. The large-scale field can be produced from the small-scale field created by dynamo processes as $B(\lambda) \propto \lambda^{-1}$ for the idealized case, where λ is the length scale of the field (Tout & Pringle 1996). So, the large-scale fields are very weak, if the fields are created in the thin accretion disks. L99 argued that the maximal jet power extracted from an accretion disk (the Blandford-Payne mechanism) dominates over the maximal power extracted by the Blandford-Znajek process. For the ADAF cases, the disk thickness $H \sim R$ and the jets can be driven by the large-scale magnetic fields created by dynamo processes (e.g., Armitage & Natarajan 1999). Instead of the ADAF model, it is proposed that the jets in low-luminosity AGNs may be magnetically (or thermally) driven from the coronae above the geometrically thin, optically thick disks accreting at low rates (Merloni & Fabian 2002). The gases in the corona are almost virilized, and the thickness of the corona is $\sim R$. The large-scale magnetic fields created by dynamo processes in the corona are significantly stronger than the thin disk due to the fact of the corona thickness being much larger than the cold thin disk, and the disk corona may therefore power a stronger jet than the thin disk. In principle, the maximal jet power can be extracted for different jet formation mechanisms can be calculated if the central black hole mass and accretion rate are known.

2 BLACK HOLE MASSES AND ACCRETION RATES

The central black hole masses of BL Lac objects are estimated from their host galaxy luminosity by using the empirical relation between the hole mass $M_{\rm bh}$ and the absolute magnitude M_R at R-band (McLure & Dunlop 2002). The optical continuum emission of BL Lac objects may be dominated by the synchrotron emission from the jets, so their ionizing luminosities are derived from their narrow-line luminosity (see Cao 2003 for detail). For radio quasars, the sizes of the broad-line regions (BLRs) are estimated by using the empirical relation between the optical luminosity $L_\lambda(5100\text{Å})$ at 5100 Å and the BLR size $R_{\rm BLR}$ suggested by Kaspi et al. (2000). The central black hole masses of radio quasars are estimated from the broad-line profiles of Hβ and the BLR sizes by assuming the clouds in BLRs to be virilized (Cao 2004).

3 JET POWER

The jet power can be estimated from low-frequency radio luminosity by

$$Q_{\rm jet} \simeq 3 \times 10^{38} f^{3/2} L_{\rm ext,151}^{6/7}\ {\rm W}, \tag{1}$$

where $L_{\rm ext,151}$ is the extended radio luminosity at 151 MHz in units of 10^{28} W Hz^{-1} sr^{-1} (Willott et al. 1999)). This formula describes the average jet power over a timescale of $\sim 10^3 - 10^4$ years. The factor f (≥ 1) describes the uncertainties of the estimate. In this paper, we conservatively adopt the lower limit $f = 1$. For some flat-spectrum sources, their radio/optical continuum emission is strongly beamed towards us because of their relativistic motions and small viewing angles of the jets with respect to the line of sight (e.g., Fan 2003). So, the observed low-frequency radio emission at 151 MHz may still be Doppler beamed. We therefore use the extended radio emission measured by VLA to estimate the jet power (Cao 2003). The extended radio emission measured by the VLA has to be K-corrected to 151 MHz in the rest frame of the source assuming $\alpha_{\rm e} = 0.8$ ($f_\nu \propto \nu^{-\alpha_{\rm e}}$) (Cassaro et al. 1999).

4 JET FORMATION MECHANISMS

L99 estimated the maximal strength of the large-scale fields driving the jets, and then the maximal jet power extracted from the rapidly spinning black hole or the accretion disk on the assumption of the fields being created by dynamo processes. Following L99, the maximal jet power extracted from a rotating black hole or an accretion disk can be calculated for a standard thin disk, if the black hole mass $M_{\rm bh}$ and accretion rate $\dot{m}$ are specified.

4.1 Jet power extracted from the disk coronae

In this work, we also consider the case of the jets being magnetically driven by the fields created in the coronae of the disks.

Assuming the gases in the coronae are nearly virilized, their thermal velocity $V_{\rm th} \sim (GM/R)^{1/2}$ (Haardt & Maraschi 1991). Thus, the thickness of the corona $H_{\rm c} \sim c_{\rm s}/\Omega_{\rm K} \sim R$, as the sound speed $v_{\rm s} \sim V_{\rm th}$, where $\Omega_{\rm K}$ is the Keplerian angular velocity. The maximal magnetic stress created by the dynamo processes is

$$\frac{B_{\rm dyn}^2}{4\pi} \sim \frac{W_{\rm c}}{2H_{\rm c}}, \tag{2}$$

where $W_{\rm c} = 2H_{\rm c}w_{\rm c}$ is the integrated shear stress of the corona (Shakura & Sunyaev 1973; Livio et al. 1999). As the scale-height of the corona $H_{\rm c} \sim R$, the fields created by dynamo processes have length scales of R. The maximal jet power can be extracted from the corona in unit surface area is

$$q_{\rm j}^{\rm max} \sim \frac{B_{\rm dyn}^2}{4\pi} R\Omega_{\rm K}(R). \tag{3}$$

The viscous dissipation in the corona is

$$f_{\rm vis}^{+} = \frac{1}{2} W_{\rm c} R \left| \frac{d\Omega}{dR} \right| = \frac{3}{4} W_{\rm c} \Omega_{\rm K}(R) \tag{4}$$

in unit surface area (Shakura & Sunyaev 1973). Combing Eqs. (2)-(4) and noting $H_{\rm c} \sim R$ for the corona, we have

$$q_{\rm j}^{\rm max} \sim \frac{2}{3} f_{\rm vis}^{+}. \tag{5}$$

Integrating Eq. (5) over the the surface of the corona on the assumption of local equilibrium between the radiation and energy dissipation in the corona, we obtain

$$Q_{\rm jet}^{\rm max} \sim \frac{2}{3} L_{\rm c}, \tag{6}$$

where $L_{\rm c}$ is corona luminosity. In the disk-corona scenario, almost all gravitational energy of the accretion matter is released in the corona, i.e., $L_{\rm c} \simeq L_{\rm bol}$ (Haardt & Maraschi 1991). Thus, we have

$$Q_{\rm jet}^{\rm max} \sim \frac{2}{3} L_{\rm bol}, \tag{7}$$

which indicates that the maximal jet power can be extracted from the coronae above the disks is significantly larger than that extractable from the thin disks.

5 SPECTRA OF THE DISKS

The ADAF will transit to a standard optically thick, geometrically thin accretion disk at a radius outside $R_{\rm tr}$. Here, we consider a general case, i.e., an ADAF is present near the black hole and it transits to a cold standard disk (SD) beyond the transition radius $R_{\rm tr}$. In this ADAF+SD scenario, the ionizing luminosity from the disk is a combination of the emission from the inner ADAF and outer standard disk regions (Cao 2003).

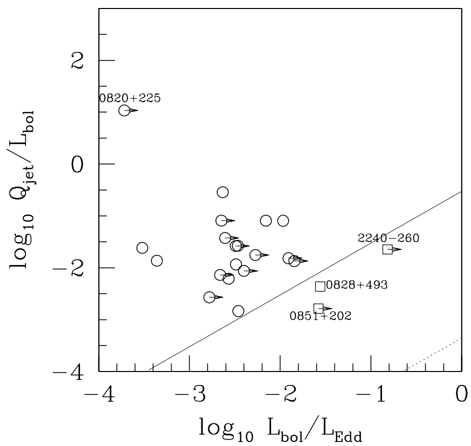

Fig. 1 The ratio $L_{\rm bol}/L_{\rm Edd}$ versus the ratio $Q_{\rm jet}/L_{\rm bol}$ ($f = 1$ is adopted) for BL Lac objects. The solid line represents the maximal jet power $L_{\rm BP}^{\rm max}$ extracted from a standard accretion disk (the Blandford-Payne mechanism), while the dotted line represents the maximal jet power $L_{\rm BZ}^{\rm max}$ extracted from a rapidly spinning black hole $a = 0.95$. The sources below the solid line are labelled as squares.

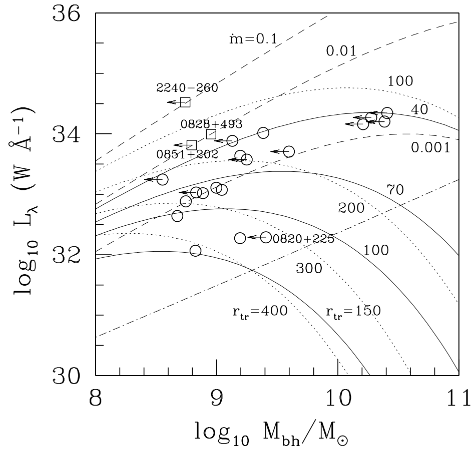

Fig. 2 The black hole mass $M_{\rm bh}$ versus optical luminosity L_λ at 3727 Å for BL Lac objects. The solid lines represent for ADAF+SD models with different transition radii $r_{\rm tr}$ for $\dot m = 0.01$, while the dotted lines represent the cases of $\dot m = 0.1$. The dashed lines represent standard accretion disks with $\dot m = 0.001$, 0.01, and 0.1, respectively. The dash-dotted line is the maximal optical luminosity as a function of black hole mass $M_{\rm bh}$ for the pure ADAF case.

6 RESULTS

6.1 BL Lac objects

The ratio $L_{\rm bol}/L_{\rm Edd}$ versus $Q_{\rm jet}/L_{\rm bol}$ is plotted in Fig. 1 for BL Lac objects. It is found that most sources have jet power larger than the maximal power predicted by the Blandford-Payne mechanism *(the solid line)* or the Blandford-Znajek mechanism *(the dotted line)*, if the standard thin disks are present in these sources. The relation between black hole mass $M_{\rm bh}$ and the central optical ionizing continuum luminosity L_λ at 3727 Å is plotted in Fig. 2. The optical continuum emission from a pure ADAF can be calculated by using the approach proposed by Mahadevan (1997). We use the same approach proposed by Cao (2002a) to calculate the maximal optical continuum emission from an ADAF as a function of black hole mass. It is found that all sources have optical ionizing luminosity higher than the maximal optical luminosity expected from pure ADAFs, which implies that the emission from pure ADAFs is unable to explain the optical ionizing luminosity of these sources. Most sources, except three square sources, have optical ionizing luminosity below the line of $\dot m = 0.01$ expected from the standard disk. We further calculate the optical spectra of ADAF+SD systems as described in Sect. 5, for different values of transition radius $R_{\rm tr}$. All these sources lie in the region between $R_{\rm tr} = 40$ and 150 $GM_{\rm bh}/c^2$ for $\dot m = 0.01$. If $\dot m = 0.1$ is adopted, the transition radii of the disks are required to be in the range of $100 - 400$ $GM_{\rm bh}/c^2$ to explain the optical ionizing emission.

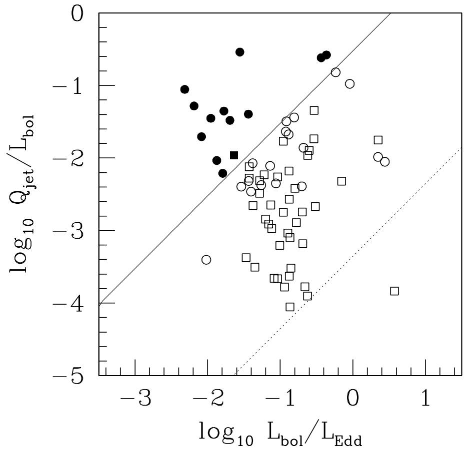

Fig. 3 The ratio $L_{\rm bol}/L_{\rm Edd}$ versus the ratio $Q_{\rm jet}/L_{\rm bol}$ for radio-loud quasars. The squares represent flat-spectrum sources, and the circles are for steep-spectrum sources. The solid line represents the maximal jet power extracted from a standard thin accretion disk (the Blandford-Payne mechanism), while the dotted line represents the maximal jet power extracted from a rapidly spinning black hole $a = 0.95$ surrounded by a standard thin accretion disk (the Blandford-Znajek mechanism). The sources above the solid line, referred as high-jet-power sources, are labelled as filled circles(square).

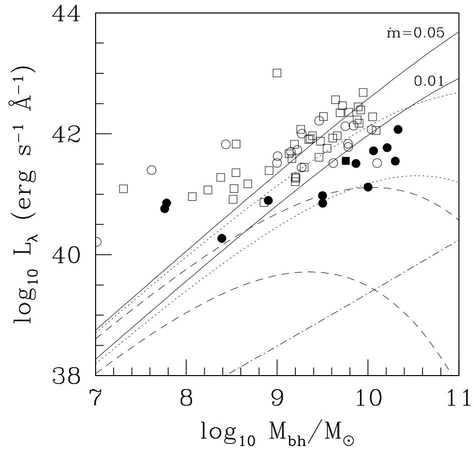

Fig. 4 The black hole mass $M_{\rm bh}$ versus optical luminosity L_λ at 5100 Å for radio-loud quasars. The dash-dotted line represents the maximal optical continuum luminosity from pure-ADAFs. The solid lines represent standard disks accreting at $\dot{m} = 0.01$ and 0.05, respectively. The dotted and dashed lines represent the ADAF+SD models with different transition radii $R_{\rm tr} = 20GM/c^2$ and $50GM/c^2$, respectively. The upper lines are plotted for $\dot{m} = 0.05$, while the lower lines are for $\dot{m} = 0.01$. The symbols are same as Fig. 3.

6.2 Radio quasars

For some radio quasars, their jets are too powerful to be extracted from the standard thin accretion disks or rapidly spinning black holes surrounded by standard thin disks (see Fig. 3), which is similar to BL Lac objects. If the ADAFs are present in these quasars, the dimensionless accretion rates $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$ as high as $\gtrsim 0.05$ and the transition of the ADAFs to the standard thin disks at rather small radii of $\sim 20GM_{\rm bh}/c^2$ are required (see Fig. 4).

7 DISCUSSION

For BL Lac objects, the powerful jets can be accelerated by the magnetic fields from the ADAFs surrounding the black holes. In order to reproduce the observed ionizing luminosity, the standard thin disks with inner edges truncated at radii $\sim 40 - 150\ GM_{\rm bh}/c^2$ are required to be in the outer regions of the disk.

For some radio quasars, their jets are too powerful to be extracted from the standard thin accretion disks or rapidly spinning black holes surrounded by standard thin disks. If the ADAFs are present in these quasars, their bright optical continuum luminosity cannot be produced by pure-ADAFs due to their low accretion rates and low radiation efficiency, unless the dimensionless accretion rates $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$ can be as high as $\gtrsim 0.05$ and the ADAFs transit to standard thin disks at rather small radii around $\sim 20GM_{\rm bh}/c^2$. This is roughly consistent with the theoretical results presented by Lu et al. (2004). We also find that the uncertainties on the estimates of the black hole masses and accretion rates have not affected our main conclusions (see Cao, 2004 for detail). In this work, we propose that the disk-corona structure is present at least in some radio quasars. The plasmas in the corona are very hot, and the pressure scale-height of the corona $H_{\rm c} \sim R$. Our theoretical calculations show that powerful jets with $Q_{\rm jet} \sim L_{\rm bol}$ (bolometric luminosity) can be accelerated from the disk coronae. Thus, the powerful jets in some quasars can be explained by this disk-corona scenario.

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