Jet magnetically accelerated from disk-corona around a rotating black hole†

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A jet acceleration model for extracting energy from disk-corona surrounding a rotating black hole is proposed. In the disk-corona scenario, we obtain the ratio of the power dissipated in the corona to the total for such disk-corona system by solving the disk dynamics equations. The analytical expression of the jet power is derived based on the electronic circuit theory of the magnetosphere. It is shown that jet power increases with the increasing black hole (BH) spin, and concentrates in the inner region of the disk-corona. In addition, we use a sample consisting of 37 radio loud quasars to explore their jet production mechanism, and show that our jet formation mechanism can simulate almost all sources with high power jet, that fail to be explained by the Blandford-Znajek (BZ) process.

Accretion and accretion disks, jets, corona

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1 Introduction

Jets exist in many astronomical cases, such as quasars, active galactic nuclei (AGNs), and stellar binaries. Although the precise mechanism for the acceleration and collimation of jets are still unclear, the association of jets with magnetized accretion disks or magnetized central objects is strongly supported by the observations of Hubble Space Telescope, Chandra, and VLBI. Some author [1-3] have agreed that jet formation should involve a large-scale magnetic field threading an accretion disk or black hole (BH).

Several theoretical models [3-5] have been proposed for the acceleration and collimation of jets. These models belong to two main regimes, the Poynting regime and the hydrodynamic regime. In the Poynting regime, energy is extracted in the form of purely electromagnetic energy, but it is in the form of magnetically driven material wind in the hydrodynamic regime. Major progress has been made in the hydrodynamic regime of jet formation, while observed jets with bulk Lorentz factor $\Gamma \sim 10$ in quasars and AGNs suggest that these jets are likely to be in the Poynting regime [6].

In the Blandford-Znajek (BZ) process [4], energy and angular momentum can be extracted from a rotating BH by an ordered poloidal magnetic field threading the BH horizon. Macdonald and Thorne [7] reformulated and extended the BZ theory in a 3+1 split of the Kerr spacetime, and derived the analytic expressions of BH power and disk power by using an equivalent electric circuit. The Blandford-Payne process [5] is also an important mechanism for disk wind and jet production. In the Blandford-Payne process, energy and angular momentum are removed magnetically from accretion disk by the magnetic field lines that leave the disk surface and extend to large distances.

The relative importance of these two process is discussed by different authors [1,8]. Ghosh and Abramowicz [8] argued that the BZ power was overestimated, and it is, in general, dominated by the electromagnetic power output of the inner
region of the disk, provided that the poloidal magnetic field threading the BH does not differ significantly in strength from that threading the disk. This argument is strengthened by the realization that the currents that generate the field threading the horizon must be situated in the disc rather than in the BH. Li [9] re-investigated the BZ process and discussed the magnetic coupling between the disk and a rotating black hole based this equivalent electric circuit theory [10-12]. He proposed that the toroidal electric current residing in a thin disk can generates a poloidal magnetic field threading the BH and disk [9]. The rotation of the disk and BH can induce an electromotive force (EMF) on the disk and the BH’s horizon. This EMF could be the energy source for the jets in AGN. The proposed that the toroidal electric current residing in a thin disk can generates a poloidal magnetic field threading the BH and disk [9].

The large-scale magnetic field plays an important role in jet modelling. Observations reveal that large-scale magnetic fields exist in compact objects. The popular treatment of large-scale magnetic field is invoked magnetohydrodynamical simulations. Though the origin of large-scale magnetic field is still under controversy, some previous work [13,14] have proposed that the large-scale field can be produced from the small-scale field created by dynamo processes. The length scale of the fields created by dynamo processes is of the order of the disk thickness \( H \), and the poloidal component of the magnetic field is given approximately by \( B_p \sim (H/r)B_{\text{dynamo}} \). If the field is created in the thin accretion disks \( (H \ll r) \), the large-scale field is very weak. In the case of advection dominated accretion flow (ADAF) [15,16], the disk thickness \( H \sim r \) and the poloidal component of the magnetic field is stronger. In the disc-corona scenario, the energetically dominant corona is the ideal situation for launching the powerful jets/outflows [17]. 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. Thus the corona can power a stronger jet than the thin disk.

Recently Gong et al. [18] investigated a disc-corona model, in which part of gravitational energy is dissipated in the hot corona, and simulated the emerged spectra from the disc-corona system for the different parameters using the Monte-Carlo method.

Motivated by the above works, in this paper we propose a coronal jet model, in which a geometrically thin, optically thick disk surrounds a rotating Kerr BH, and the corona is assumed to be heated by the reconnection of the magnetic fields generated by buoyancy instability [19] in the disk. In our model, the large scale poloidal magnetic field can be derived from the magnetic energy density in the corona. We then get the coronal jet power using the equivalent electric circuit method in the magnetosphere. Finally, we use our jet formation mechanism to stimulate a sample consisting of 37 radio loud quasars. Throughout this paper the geometric units \( G = c = 1 \) are used.

## 2 Disk-corona model

In our accretion disk-corona system, a geometrically thin and optically thick disk is sandwiched by a slab magnetic corona, and part of gravitational energy of accretion matter is released in the hot corona. The general relativistic model for a steady, axisymmetric, and thin Keplerian disk around a Kerr black hole, has been investigated in detail by Novikov and Thorne [20]. In their model, it has been assumed that there is no stress at disk’s inner edge, that is, the so-called “no-torque inner boundary condition”. In this case, the gas that reaches the stable circular orbit of minimum radius \( r = r_{\text{ms}} \), will “fall out” of the disk and spiral rapidly down the BH. Consequently, the gas density at \( r < r_{\text{ms}} \) is virtually zero compared to that at \( r > r_{\text{ms}} \), which means that no viscous stresses can act cross the surface \( r = r_{\text{ms}} \).

The total gravitational power dissipated in unit surface area of the accretion disk-corona system \( Q \) is given by [21]

\[
Q = (\dot{M}/2\pi)e^{-\psi}\, f, \tag{1}
\]

where \( \dot{M} \) is the accretion rate of the disk, \( \nu, \psi, \mu \) are the metric coefficients, and the function of radius \( f \) is defined as

\[
f = -\frac{d\Omega}{dr}(E^{\pm} - \Omega L^{\pm})^{-2} \int_{r_{\text{ms}}}^{r} (E^{+} - \Omega L^{+})\frac{dL^{+}}{dr}dr. \tag{2}
\]

The specific energy \( E^{\pm} \) and the specific angular momentum \( L^{\pm} \) of a particle in the disk, can be written as

\[
E^{\pm} = (1 - 2\chi^{-2} + a_{\ast}\chi^{-3})\left(1 - 3\chi^{-2} + 2a_{\ast}\chi^{-3}\right)^{1/2}, \tag{3}
\]

\[
L^{\pm} = M\chi\left(1 - 2a_{\ast}\chi^{-3} + a_{\ast}^{2}\chi^{-4}\right)^{1/2}(1 - 3\chi^{-2} + 2a_{\ast}\chi^{-3})^{1/2}, \tag{4}
\]

where \( \chi = \sqrt{r/M} \) is the dimensionless radial coordinate, and \( a_{\ast} = a/M \) is the dimensionless black hole spin parameter.

The power dissipated in the corona [17,18] is

\[
Q_{\text{cor}} = P_{m}u_{p} = \frac{B_{0}^{2}}{8\pi}u_{p}, \tag{5}
\]

where \( P_{m} \) is the magnetic pressure, and \( u_{p} \) is the velocity of magnetic flux transported vertically in the disk. Here we assume the velocity \( u_{p} \) of magnetic flux tubes is proportional to their internal Alfven velocity, i.e. \( u_{p} = b\nu_{A} \), and \( b \) is related to the efficiency of buoyant transport of magnetic structure.

Now we give the equations of the disk structure as follows. The equation of vertical pressure balance in the vertically-averaged form is

\[
H = (P/\rho)^{1/2}(r^{3}/M)^{1/2}AB^{-1}C^{1/2}D^{-1/2}E^{-1/2}, \tag{6}
\]

where \( H \) is the height of the accretion disk, \( P \) and \( \rho \) are pressure and density of the disk respectively; \( A, B, C, D, E \) are general relativistic correction factors [20].
The equation of energy conservation is [20]

\[ W = \frac{4}{3}(M/r^3)^{1/2}CD^{-1}Q, \tag{7} \]

where \( W \) is integrated shear stress, defined as \( W = 2 \int_0^H t_\phi dz \sim 2t_\phi H \). The interior viscous stress \( t_\phi \) and the pressure \( P \) are related by

\[ t_\phi = \alpha P, \tag{8} \]

where \( \alpha \) is the viscous parameter, and \( \alpha = 0.3 \) is adopted in our calculations.

The equation of state for gas on the disk is

\[ P = P_{mag} + P_{tot} = P_{mag} + \frac{1}{2}aT^4 + \frac{\rho_0 T}{m_p}. \tag{9} \]

where \( P_{tot} \) is the total pressure (gas pressure plus radiation pressure) at disk mid-plane, \( a \) is the radiative constant, \( m_p \) is the rest mass of proton, \( \rho_0 \) and \( T \) are the density of rest mass and the temperature in the disc, respectively. Here we assume

\[ P_{mag} = \alpha_0 \sqrt{P_{gas}P_{tot}}. \tag{10} \]

The energy transport equation for the disk is

\[ aT^4 = 2\kappa H\rho_0(Q - Q_{cor} + \frac{1 - \alpha_0}{2}Q_{cor}) \tag{11} \]

where \( \alpha_0 \) is the reflection albedo in the disk-corona. It is relatively low and most of the incident photons from the corona are re-radiated as black body radiation [22]. \( \alpha_0 = 0.1 \) is adopted in our model, and \( \kappa \) is the Rosseland mean of total opacity [20].

Solving eqs.(1)-(11) numerically, the power dissipated in the corona \( Q_{cor} \) and the structure of the disk can be derived as function of radius \( r \). The ratio of the power dissipated in the corona to the total for such disk-corona system is given as

\[ f_{cor}(r) = \frac{Q_{cor}(r)}{Q(r)}. \tag{12} \]

For the different black hole spin parameter \( a_* \), the curves of \( f_{cor} \) versus parameter \( \xi \) defined as \( \xi = r/r_{ms} \), and the accretion rate \( \dot{m} = M/M_{Edd} \) are shown in Figure 1(a) and 1(b), respectively. It is shown that the ratio of the power dissipated in the corona \( f_{cor} \) increases with the increasing the spin parameter \( a_* \), but decreases with the increasing accretion rate \( \dot{m} \).

![Figure 1](image_url)

Figure 1  (a) The value of \( f_{cor} \) varying with radial parameter \( \xi \) for different values of \( a_* \): \( a_* = 0.1 \) (dotted lines), \( a_* = 0.5 \) (dashed lines), \( a_* = 0.7 \) (dot-dashed lines), \( a_* = 0.9 \) (solid lines). \( \dot{m} = 0.1 \) is adopted in the calculations. (b) The value of \( f_{cor} \) varies with \( \dot{m} \) for different values \( a_* \), \( \xi = 30 \) is adopted in the calculations.

3 Jet from disk-corona

We wish to discuss the acceleration mechanism of the jets being magnetically driven by the fields created in the corona. In this work, it is considered that the coronal power \( Q_{cor} \) can be partly dissipated locally to heat the corona and ultimately radiated away as hard X-ray radiation with power \( L = \eta Q_{cor} \). Therefore we assume that the magnetic energy density in the corona is

\[ \frac{B^2_{cor}}{8\pi} = \frac{L(r)^{1/2}P_{cor}dr}{2\pi r H_{cor}dt_0}, \tag{13} \]

where \( H_{cor} \) is the height of the corona, and \( t_0 \sim H_{cor}/v_{diss} \) is the dissipation time. The dissipation velocity \( v_{diss} \) depends on the uncertain nature of the heating process, \( v_{diss} = 0.01c \) is adopted in our calculation.

Though the origin of large-scale magnetic field is still unclear, some authors have verified that the large-scale field can be produced from the small-scale field created by
In the disk-corona system the strength of the poloidal field component depends on the typical scaleheight of a coronal magnetic flux tube and on the capability of reconnection events. In this paper, for simplicity, we assume that the poloidal component of the large-scale magnetic field is given approximately by

\[ B_{\text{cor}}^p \approx \frac{H_a}{r} B_{\text{cor}}, \]  

(14)

where \( H_a \) is the typical scaleheight of a coronal magnetic flux tube. As the height of the coronal magnetic flux tube is much larger than the disk thickness, we adopt \( H_a = 2 r_{ms} \) in our calculation.

![Figure 2](image)

**Figure 2** The value of \( B_{\text{cor}}^p \), varying with radial parameter \( \xi = r/r_{ms} \) for the different values of \( a_+ : a_+ = 0.1 \) (dotted lines), \( a_+ = 0.5 \) (dashed lines), \( a_+ = 0.9 \) (solid lines). \( \eta = 0.5 \) is adopted in the calculations.

We plot the curves of the value of \( B_{\text{cor}}^p \), varying with radial parameter \( \xi = r/r_{ms} \) for the different BH spin parameters \( a_+ \) in Figure 2. Note that the magnetic field \( B_{\text{cor}}^p \) is in units of \( B_0 = \sqrt{M/8\pi M^2} \), where \( M \) is the accretion rate, and \( r \) is the BH mass. Inspecting the Figure 2, we find that the value of the large scale poloidal magnetic field reaches a maximum as \( r = 1.3 r_{ms} \). In addition, the value of \( B_{\text{cor}}^p \) increases with the increasing BH spin parameter \( a_+ \).

Macdonald and Thorne [7] pointed that the magnetosphere anchored in a black hole and in its accretion disc should transfer much of the rotational energy of the hole and orbital energy of the disk into an intense flux of electromagnetic energy. They constructed a general relativistic version of electronic circuit theory, and derived the analytical expressions of the electromagnetic power from the disk as follow [7]

\[ \Delta P = I^2 \Delta Z_A = \Omega_F \left( \frac{I}{2\pi} \right) \Delta \Psi. \]  

(15)

where \( I \) is the equivalent current, \( \Delta \Psi \) is the magnetic flux between the two adjacent magnetic surfaces, and the quantity \( \Omega_F \) is the magnetic field line angular velocity.

Based on the work of Macdonald and Thorne, we also propose an equivalent circuit to calculate the electromagnetic power from the corona. The following equations are used in deriving jet power,

\[ \Delta Q_{\text{jet}} = (I^p)^2 \Delta Z_A, \quad I^p = \Delta e / \Delta Z_A, \quad \Delta e = (\Delta \Psi / 2\pi) \Omega_F, \]  

(16)

where \( I^p \) is the poloidal current in each loop in the corona, \( \Delta e \) is the EMF due to the rotation of the disk-corona system. \( \Delta \Psi \) and \( \Delta Z_A \) are the magnetic flux between the two adjacent magnetic surfaces and the impedance of the corresponding acceleration-region, respectively. The magnetic flux \( \Delta \Psi \) can be expressed as

\[ \Delta \Psi = B_{\text{cor}}^p 2\pi (\sigma \rho / \sqrt{A})_{\text{r=rms}} dr. \]  

(17)

The magnetic field line angular velocity \( \Omega_F \) is determined by the ratio of acceleration-region impedance to disk impedance, and if the disk impedance is very low, \( \Omega_F \approx \Omega_D \) [7]. In our disk-corona model, considering that corona impedance is also very low relative to the acceleration-region impedance, we can assume that the magnetic field line angular velocity in the corona is

\[ \Omega_F \approx \Omega_D = \frac{1}{M (\xi^{3/2} \chi_{ms} + a_+)} \]  

(18)

where the radial parameter \( \chi_{ms} \) is defined as \( \chi_{ms} = \sqrt{r_{ms}/M} \).

The load resistance \( \Delta Z_A \) between the two adjacent magnetic surfaces can be written as

\[ \Delta Z_A \sim (5/6)(\Delta r/\pi) \sim (25 \text{ ohm})(\Delta r/\pi). \]  

(19)

The concerned Kerr metric coefficients are given as follows [23],

\[ \begin{aligned}
&\Sigma^2 \equiv (r^2 + a^2)^2 - a^2 \Delta \sin^2 \theta, \\
&\rho^2 \equiv r^2 + a^2 \cos^2 \theta, \\
&\Delta \equiv r^2 - a^2 - 2Mr.
\end{aligned} \]  

(20)

incorporating eqs. (16)–(20), and integrating eq.(16) over the radial parameter \( \xi = r/r_{ms} \), we have the expression for the jet power as follows

\[ Q_{\text{jet}} = \int_1^\infty 6(B_{\text{cor}}^p M)^2 (\xi^3 \chi_{ms}^2 + \xi a_+^2 \chi_{ms} + 2 \chi_{ms} a_+^2)^{3/2} d\xi. \]  

(21)

The power arising from the BZ process by a rotating black hole with a magnetic field \( B_\perp \) normal to the horizon has been given by

\[ P_{\text{BZ}} = \frac{1}{32} B_\perp^2 \omega_F^2 r_H^2 a_+^2, \]  

(22)

where \( r_H \) is the horizon radius, and the factor \( \omega_F^2 \equiv \Omega_F (\Omega_H - \Omega_F) / \Omega_H^2 \) is a measure of the effects of the angular velocity \( \Omega_F \) of the field lines relative to that of the hole \( \Omega_H \). In the case of \( \Omega_F = 1/2 \Omega_H \), the output power of BZ process takes a maximum, we adopt \( \omega_F = 1/2 \). Considering the balance between the magnetic pressure on the horizon and the ram
pressure of the innermost part of an accretion flow, Moderski et al. [24] give the relation between the magnetic field \( B_\perp \) and the accretion rate \( \dot{M} \) as:

\[
(B_\perp)^2 / 8\pi = P_{\text{ram}} \sim \rho c^2 \sim \dot{M} (4\pi v_H^2) .
\]  

(23)

From eq.(23) the strength of magnetic field on BH horizon is given by

\[
B_\perp = \sqrt{2\dot{M} / (M^2(1 + q)^2)} , \quad q = \sqrt{1 - a_c^2} .
\]

(24)

It is evident that the jet power increases monotonically with the increasing accretion rate.

4 Comparison with observation

The method of estimating jet power is important for quantifying the power emerging from the central engine of the radio source. Willott et al. [25] used the optically thin flux density from lobes measured at 151 MHz to estimate the value of the jet power, they have given an empirical relation between the jet power and the extended radio luminosity \( L_{151} \). Recently Punsly [26] presented a theoretical derivation of an estimate for a radio source jet kinetic luminosity, which assumes that most of the energy in the lobes is in plasma thermal energy with a negligible contribution from magnetic energy. Based on the formula derived by Punsly [26], Liu et al. [27] estimated the jet powers of 146 radio-loud quasars. As the central black hole masses are given for the sources, the accretion rates of these sources can be estimated by using the bolometric luminosity \( L_{\text{bol}} \). The dimensionless accretion rate is given by

\[
\dot{m} = \dot{M} / \dot{M}_{\text{Edd}} \approx L_{\text{bol}} / L_{\text{Edd}} .
\]

(25)

The curves of the jet powers varying with the radial parameter \( \xi \) and the spin parameter \( a_c \) are shown in Figure 3(a) and Figure 3(b). From the Figure 3, we find that the jet power \( Q_{\text{jet}} \) increases with the increasing black hole spin \( a_c \), the curves of \( Q_{\text{jet}} \) turn to flat at \( \xi \ll 1 \), imply that the mostly jet power \( Q_{\text{jet}} \) concentrates in the inner region of the disk. In addition, the jet powers \( Q_{\text{jet}} \) versus the accretion rate \( \dot{m} = \dot{M} / \dot{M}_{\text{Edd}} \) for the deferent parameters are plotted in Figure 4.
BZ power) is calculated by using the eq.(22). The steep-spectrum sources and flat-spectrum sources in Figure 5 and 6 are labeled as circles and triangles, respectively.

Inspecting the above Figures, we have the following results: (I) The jet in the great majority of sources cannot be powered by the BZ process, even if the black hole spin parameter is $a_\bullet = 0.99$; (II) The jet production mechanism in our model be able to produce sufficient power observed in the 35 sources (except 0538 + 498.1828 + 487 ), if black hole spin parameter is taken into account in the calculation. In addition, we find the jet power in our model depends mainly on the black hole spin $a_\bullet$ and the accretion rate $\dot{m} \approx L_{bol}/L_{Edd}$. By using eq.(21), we stimulate the jet powers observed in these sources as shown in the column (8) of Table 1. The reason that the two sources (0538 + 498.1828 + 487 ) cannot be fitted by our model, may be these two sources have different accretion modes, for example, ADAF or adiabatic inflow-outflow solutions [31]. Furthermore, we can not anticipate that the jet powers of all quasars are explained by one kind of jet acceleration mechanism.

However some uncertainties exist in our model. One uncertainty is the geometry of the hot corona on the disk. For simplicity, we adopt a slab corona in this paper. Some authors also propose a patchy corona, which made of a number of separate active regions [17,32]. In that patchy-corona scenario, if the numbers of active regions between the two adjacent magnetic surfaces locate on the disk radius $r$ and $r + dr$ can be given, the jet power should be calculated by using the equivalent electronic circuit method in principal. Another uncertainty lies in the parameter $\eta$. Since much about the corona in the disk-corona system remains unknown, for example, the fraction of power heating the corona is unclear. To simplify, we adopt $\eta = 0.5$ in the calculations.

It should be noticed that the plunging region between the BH’s horizon and the inner edge of the disk usually be neglected in discussing the relative importance of BZ process by some author [1,8]. Li [33] proposed that the energy can be continuously extracted from the BH through this region and this may be the more efficient way for extracting energy from a Kerr BH. Reynolds et al. [34] argued that the plunging inflow can greatly enhance the trapping of large scale magnetic field on the black hole, and therefore may increase the importance of the BZ process relative to previous estimates that ignore the plunging region. Conversely, if some magnetic field lines connect the plunging region to the disk, this magnetic fields can exert stresses on the inner edge of an accretion disk around a BH [35]. This magnetic torque can considerably enhance the amount of total energy released in the disk-corona system [36]. In such case, the magnetic energy density and the large scale magnetic field would be enhanced in our model. This would in turn increase the jet power from the corona. This effect of the plunging region
on the BZ power and coronal jet power should be further investigated in the disk-corona scenario.

Finally, in this paper we focus mainly on the jet formation in the form of Poynting fluxing. We shall discuss the acceleration of jet in the hydrodynamic regime in future work.

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Table 1  Data of the sample and the values of the concerned parameter for fitting the jet power.

| Sources   | Type | Log$M_{BH}$ | Log$L_{bol}$ | $\dot{m}$ | Log$Q_{jet}$ | $a_*$ | Log$Q_{jet}$(model) |
|-----------|------|-------------|--------------|--------|-------------|------|-------------------|
| 0022-297  | SS   | 7.91        | 44.98        | 0.12   | 45.61       | 0.63 | 45.60             |
| 0056-001  | FS   | 8.71        | 46.54        | 0.68   | 45.69       | 0.72 | 45.70             |
| 0119+041  | FS   | 8.38        | 45.57        | 0.15   | 44.69       | 0.75 | 44.69             |
| 0133+207  | SS   | 9.52        | 45.83        | 0.02   | 45.50       | 0.88 | 45.49             |
| 0134+329  | SS   | 8.74        | 46.44        | 0.50   | 46.30       | 0.95 | 46.27             |
| 0135-247  | FS   | 9.13        | 46.64        | 0.32   | 44.98       | 0.18 | 45.02             |
| 0336-019  | FS   | 8.98        | 46.32        | 0.21   | 45.18       | 0.17 | 45.15             |
| 0403-132  | FS   | 9.07        | 46.47        | 0.25   | 45.60       | 0.68 | 45.62             |
| 0405-123  | FS   | 9.47        | 47.40        | 0.32   | 44.98       | 0.18 | 45.02             |
| 0518+165  | SS   | 8.53        | 46.34        | 0.65   | 46.89       | 0.78 | 46.90             |
| 0538+498  | SS   | 9.58        | 46.43        | 0.07   | 46.90       | ---  | ---               |
| 0637-752  | FS   | 9.41        | 47.16        | 0.56   | 46.48       | 0.75 | 46.50             |
| 0838+133  | FS   | 8.52        | 46.23        | 0.51   | 46.19       | 0.95 | 46.15             |
| 0923+392  | FS   | 9.28        | 46.26        | 0.10   | 45.69       | 0.85 | 45.66             |
| 0954+556  | FS   | 8.07        | 46.54        | 3.00   | 45.64       | 0.90 | 45.61             |
| 1007+417  | SS   | 8.79        | 46.74        | 0.83   | 45.77       | 0.76 | 45.80             |
| 1100+772  | SS   | 9.31        | 46.49        | 0.15   | 45.30       | 0.31 | 45.35             |
| 1136-135  | FS   | 8.78        | 46.78        | 1.00   | 46.27       | 0.91 | 46.28             |
| 1137+660  | SS   | 9.36        | 46.85        | 0.31   | 46.19       | 0.85 | 46.18             |
| 1250+568  | SS   | 8.42        | 45.61        | 0.15   | 45.50       | 0.75 | 45.50             |
| 1253-055  | FS   | 8.43        | 46.10        | 0.46   | 45.70       | 0.88 | 45.70             |
| 1354+195  | FS   | 9.44        | 47.11        | 0.47   | 45.77       | 0.28 | 45.76             |
| 1355+416  | SS   | 9.73        | 46.48        | 0.06   | 45.58       | 0.28 | 45.58             |
| 1611+343  | FS   | 9.57        | 46.99        | 0.26   | 45.63       | 0.22 | 45.63             |
| 1637+574  | FS   | 9.18        | 46.68        | 0.31   | 45.39       | 0.20 | 45.38             |
| 1641+399  | FS   | 9.42        | 46.89        | 0.30   | 45.30       | 0.18 | 45.32             |
| 1642+690  | FS   | 7.76        | 45.78        | 1.04   | 45.22       | 0.84 | 45.21             |
| 1656+053  | SS   | 9.62        | 47.21        | 0.39   | 45.02       | 0.21 | 45.07             |
| 1828+487  | SS   | 9.85        | 46.78        | 0.09   | 46.89       | ---  | ---               |
| 2135-147  | SS   | 8.94        | 46.17        | 0.17   | 44.69       | 0.30 | 44.70             |
| 2155-152  | FS   | 7.59        | 45.67        | 1.20   | 45.27       | 0.96 | 45.24             |
| 2201+315  | FS   | 8.87        | 46.62        | 0.56   | 45.29       | 0.18 | 45.28             |
| 2216-038  | FS   | 9.24        | 47.17        | 0.85   | 45.38       | 0.17 | 45.40             |
| 2251+158  | SS   | 9.17        | 47.27        | 1.26   | 45.21       | 0.21 | 45.22             |
| 2255-282  | FS   | 9.16        | 46.96        | 0.63   | 46.08       | 0.27 | 46.06             |
| 2311+469  | SS   | 9.30        | 46.55        | 0.18   | 46.15       | 0.86 | 46.18             |
| 2345-167  | FS   | 8.72        | 45.92        | 0.16   | 44.90       | 0.62 | 44.89             |

Notes: Column(1): IAU source name. Column(2): the radio type (FS: flat-spectrum sources, SS: steep-spectrum sources). Column(3): the black hole mass in the units of solar mass. Column(4): the bolometric luminosity in the units of $10^{45}$ ergs. Column(5): the accretion rate $\dot{m}$. Column(6): the jet power $Q_{jet}$ in units of $10^{45}$ erg s$^{-1}$. Column(7) is the value of the BH spin parameter. Column(8): the fitted jet power.