The power of the jets accelerated by the coronal magnetic field

Xinwu Cao

1 Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai, 200030, China; E-mail: cxw@shao.ac.cn
2 Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, 210008 Nanjing, China
3 University of Chinese Academy of Sciences, Beijing 100049, China

Accepted 2017 October 11. Received 2017 October 11; in original form 2017 January 01

ABSTRACT

It was suggested that the large scale magnetic field can be dragged inwards efficiently by the corona above the disc; i.e., the so called “coronal mechanism” (Beckwith, Hawley, & Krolik 2009), which provides a way to solve the difficulty of field advection in a geometrically thin accretion disc. In this case, the magnetic pressure should be lower than the gas pressure in the corona. We estimate the maximal power of the jets accelerated by the magnetic field advected by the corona. The Blandford-Payne (BP) jet power is found always to be higher than the Blandford-Znajek (BZ) jet power, except for a rapidly spinning black hole with a ≥ 0.8. The maximal jet power is always low, less than 0.05 Eddington luminosity, even for an extreme Kerr black hole, which is insufficient for the observed strong jets in some blazars with jet power ~ 0.1 – 1 Eddington luminosity (or even higher). It implies that these powerful jets cannot be accelerated by the coronal field. We suggest that, the magnetic field dragged inward by the accretion disc with magnetically outflows may accelerate the jets (at least for the most powerful jets, if not all) in the blazars.

Key words: accretion, accretion discs—black hole physics—quasars: general—galaxies: jets—magnetic fields.

1 INTRODUCTION

Jets are believed to be accelerated by the large scale magnetic field through either the Blandford-Znajek (BZ) or the Blandford-Payne (BP) mechanisms (Blandford & Znajek 1977, Blandford & Payne 1982). The kinetic power of a spinning black hole or the gas in the accretion disc is tapped into the jets with the co-rotating large scale magnetic field. The numerical simulations show that the net field flux is necessary for jet formation (Salvesen et al. 2010), and the large scale magnetic field accelerating jets may probably be formed by the advection of the external weak field (e.g., the field threading the interstellar medium) (Bisnovatyi-Kogan & Ruzmaikin 1974, 1976; van Ballegooijen 1989, Lubow, Papaloizou, & Pringle 1994).

Relativistic jets have been observed in radio-loud quasars. The power of the jets can be as high as the Eddington luminosity in some radio-loud quasars (e.g., Gu, Cao, & Jiang 2009; Ghisellini et al. 2014). Quasars are accreting at high rates, which may probably contain standard thin accretion discs, which implies that the weak external magnetic field should be dragged inwards by the thin accretion disc in order to form a sufficient strong field to accelerate relativistic jets near the black hole. In a steady case, the advection of the field is balanced with the magnetic diffusion in the accretion disc. The radial velocity of a conventional turbulent accretion disc is mainly regulated by the kinematic viscosity ν, and therefore the field advection in the disc is sensitive to the magnetic Prandtl number \(P_m = \eta/\nu\) (\(\eta\) is the magnetic diffusivity). Both the simple estimate of the order of magnitude (Parker 1979) and the numerical simulations show that the magnetic Prandtl number is always around unity (e.g., Yousif, Brandenburg, & Rüdiger 2003, Lesur & Longaretti 2009, Fromang & Stone 2009, Guan & Gammie 2009). It was found that the advection of the external field is rather inefficient in the geometrically thin accretion disc (\(H/R \ll 1\)) (Lubow, Papaloizou, & Pringle 1994), because of its small radial velocity. This means that the field in the inner region of the disc is not much stronger than the external weak field (Lubow, Papaloizou, & Pringle 1994), which is unable to accelerate strong jets in radio-loud quasars.

A few mechanisms were suggested to alleviate the difficulty of field advection in the thin discs (Spruit & Uzdensky 2005, Lovelace, Rothstein, & Bisnovatyi-Kogan 2009, Guilet & Oogilvie 2012, 2013, Cao & Spruit 2013). It was suggested that the external field can be dragged efficiently inwards by the hot corona above the disc, i.e., the so called “coronal mechanism” (see Beckwith, Hawley, & Krolik 2009, for the details). The radial velocity of the gas above the disc can be larger than that at the midplane of the disc, which partially solve the problem of inefficient field advection in the thin disc (Lovelace, Rothstein, & Bisnovatyi-Kogan 2009, Guilet & Oogilvie 2012, 2013). Alternatively, Cao & Spruit (2013) suggested that the radial velocity of the disc is significantly increased, if the most
angular momentum of the gas in the thin disc is removed by the magnetically driven outflows, and therefore the external field can be significantly enhanced in the inner region of the thin disc with magnetic outflows.

In this work, we estimate the maximal strength of the field dragged inwards by the hot corona, and then derive the maximal power of the jets accelerated either by the BP or BZ mechanisms. In Section 2 we estimate the strength of the large scale magnetic field dragged inwards by the corona. The maximal power of the jets accelerated by this magnetic field is derived in Section 3. The last section contains the results and discussion.

2 MAGNETIC FIELD DRAGGED INWARDS BY THE HOT CORONA

The detailed properties of the corona above the the disc is still unclear, though it has been extensively studied by many authors (e.g., Galeev, Rosner, & Vaiana 1979; Haardt & Maraschi 1991, 1993; Svensson & Zdziarski 1994; Kawaguchi, Shimura, & Mineshige 2001; Cao 2009). However, it is quite certain that the hot corona is geometrically thick and optically thin. In this paper, we use relative thickness \( \tilde{H}_c = H_c/R \) and the optical depth \( \tau_c \) to describe the corona above the accretion disc. The optical depth of the corona in the vertical direction is

\[
\tau_c = \rho_c H_c \kappa_T, \tag{1}
\]

where \( \rho_c \) is the density of the corona, \( H_c \) is the corona thickness, and \( \kappa_T = 0.4 \text{ g}^{-1} \text{cm}^2 \) is the Compton scattering opacity.

The gas pressure of the corona is

\[
p_c = \frac{\rho_c}{2} \left( \frac{H_c}{R} \right)^2 \frac{L_z^2}{R^2}, \tag{2}
\]

where \( \alpha \) is the spin parameter of the black hole, and

\[
L_z^2 = L^2 - \alpha^2 (E^2 - 1), \tag{3}
\]

(see Abramowicz, Lanza, & Percival 1997, for the details). The conserved angular momentum of the gas \( L = u_0 \alpha \), and the conserved energy \( E = -u_t \).

We use a parameter \( \beta \) to describe the magnetic field strength in the corona,

\[
p_m = \frac{B_z^2}{8\pi} = \beta p_c, \tag{4}
\]

where \( B_z \) is the strength of the vertical component of the field, and \( \beta < 1 \) is required for the field advected by the corona. The field strength of the corona is

\[
B_z = 4.37 \times 10^8 \beta^{1/2} \tau_c^{1/2} \tilde{H}_c^{1/2} m^{-1/2} \tau^{3/2} L_z^2 \text{ Gauss}, \tag{5}
\]

where

\[
\tilde{H}_c = \frac{H_c}{R}, \quad m = \frac{M_{\text{bh}}}{M_{\odot}}, \quad \text{and} \quad r = \frac{R c^2}{G M_{\text{bh}}}. \tag{6}
\]

3 JET POWER

The power of the jets driven by the field threading a spinning black hole is (MacDonald & Thorne 1982; Ghosh & Abramowicz 1997)

\[
P_{\text{BZ}} = \frac{1}{32} \omega_B^2 B_{\text{bh}}^2 R_{\text{bh}}^2 \alpha^2, \tag{7}
\]

where \( B_{\text{bh}} \) is the field strength at the black hole horizon \( R_{\text{bh}} \), and \( \omega_B^2 \) describes the effects of the angular velocity \( \Omega_B \) of the field lines relative to black hole angular velocity. The BZ jet power is maximized if \( \omega_B = 1/2 \) is adopted (MacDonald & Thorne 1982; Ghosh & Abramowicz 1997). Substituting Equation (5) into Equation (7), we have

\[
P_{\text{BZ}} = \frac{3.9 \times 10^{30} \omega_B^2 \beta \tau_c m R_{\text{bh}}^{-1} \tilde{H}_c L_z^2 (r_n) a^2 \text{ erg},} {12.51 \times 10^{38} m} = 3.12 \times 10^{-2} \omega_B^2 \beta \tau_c^{-1} \tilde{H}_c L_z^2 (r_n) a^2. \tag{8}
\]

The gas falls almost freely onto the black hole, and the angular momentum of the gas at the black hole horizon \( L(r_n) \lesssim L(r_{\text{ms}}) \) \( (r_{\text{ms}} \) is the radius of the marginal stable circular orbits). The conserved energy \( |E| \) does not deviate much from the unity, so the second term in Equation (3) is always negligible. The solution of a relativistic accretion flow surrounding a Kerr black hole shows that the angular momentum of the gas at the black hole horizon is slightly lower than that at the radius of the marginal stable circular orbits (e.g., Abramowicz et al. 1999; Gammie & Popham 1999, Mannheim 2000). As we intend to estimate the maximal jet power, we conservatively adopt \( L_* = \xi_0 (r_{\text{ms}}) \) in the estimate of the strength of the field at the black hole horizon.

The power of the jets launched by the BP mechanism is estimated as (Livio, Ogilvie, & Pringle 1999)

\[
P_{\text{BP}} \sim \frac{B_z B_{\alpha}^2}{2\pi} R_i \Omega \pi R_i^2, \tag{9}
\]

where \( R_i \) is the typical radius of the jet formation region in the corona, \( \Omega \) is the angular velocity of the gas in the corona, \( B_{\alpha}^2 \) is the azimuthal component of the field at the corona surface, and \( B_{\alpha}^2 = \xi_0 B_z \). The ratio \( \xi_0 \lesssim 1 \) is required (see Livio, Ogilvie, & Pringle 1999, for the detailed discussion). Substituting Equation (5) into Equation (10), we derive the BP power of the jets as

\[
P_{\text{BP}} \sim 3.13 \times 10^{37} \xi_0 \Omega r_i^{-1/2} m \beta \tau_c \tilde{H}_c \text{ erg s}^{-1}, \tag{11}
\]

or

\[
\frac{P_{\text{BP}}}{L_{\text{Edd}}} = \frac{P_{\text{BP}}}{1.251 \times 10^{38} m} \sim 0.25 \xi_0 \Omega r_i^{-1/2} \beta \tau_c \tilde{H}_c. \tag{12}
\]

As the most gravitational power is released in the inner region of the accretion disc within the radius of \( 2R_{\text{ms}} \) (Shakura & Sunyaev 1973), we adopt \( R_i = 2R_{\text{ms}} \) in all the estimates of the BP power

\[
P_{\text{BP}}. \tag{13}
\]

4 RESULTS AND DISCUSSION

In the case of the magnetic field dragged inwards by the corona, the magnetic pressure is required to be lower than the gas pressure in the corona, i.e., \( \beta < 1 \). In order to estimate the maximal power of the jets driven by the BP or BZ mechanisms, we adopt \( \omega_B = 1/2 \) (Ghosh & Abramowicz 1997), \( \beta = 1, \xi_0 = 1, \xi_{\text{pl}} = (r_{\text{ms}}/r_n)^2 \), and \( \Omega = 1 \), while the typical values of the corona parameters, \( \tau_c = 0.5, \) and \( \tilde{H}_c = 0.5 \) are adopted in the estimates (e.g., Cao 2009). The maximal jet powers as functions of the black spin parameter \( \alpha \) are plotted in Figure 1.

The maximal BZ power for the corona with prograde orbits surrounding the spinning black hole is significantly less than 0.01 Eddington luminosity, which is always lower than the BP power for any value of \( \alpha \). This is similar to the accretion disc case (see the discussion in Livio, Ogilvie, & Pringle 1999). The situation is
quite different in the retrograde orbit case. For the corona with retrograde orbits, the maximal BP power is higher than the BZ power except for a rapidly spinning black hole \((a \gtrsim 0.8)\) (see Figure 1). The maximal BZ power for the retrograde orbit case is higher than that for the prograde case, which is qualitatively consistent with recent numerical simulations, though based on different assumptions [Parfrey, Giannios, & Beloborodov 2013]. The maximal jet power increases with the spin parameter \(a\), which is found to be less than \(\sim 0.05\) \(L_{\text{Edd}}\) even for an extreme Kerr black hole. However, it is still insufficient for the observed strong jets with power around the Eddington luminosity in some blazars (e.g., Gu, Cao, & Jiang 2003; Ghisellini et al. 2014; Kang, Chen, & Wu 2014; Zhang et al. 2015). It implies that these powerful jets cannot be accelerated by the coronal field. We suggest that, the magnetic field dragged inwards by the accretion disc with magnetically outflows may accelerate the jets (at least for the most powerful jets, if not all) in the blazars (Cao & Spruit 2013; Li 2014; Cao 2016). In this case, hot gas/corona above the thin disc may help launching outflows/jets (Wu et al. 2013; Cao 2014), though the field is not formed through “coronal mechanism”. For those less powerful jets in radio galaxies, there is evidence that the field may be closely related to the ADAFs surrounding spinning black holes (e.g., Wu, Yan, & Yi 2013; Feng & Wu 2017).

The accretion disc may be vertically compressed by the advected large scale magnetic field [Cao & Spruit 1999; Cao 2010]. This may also be the case for the corona case discussed in this paper. If this effect is properly considered, the maximal magnetic field strength, and then the maximal jet power (either the BZ or the BP power), will be lower than the values derived in this paper, when the relative corona thickness \(H_c\) is decreased (see Equation 5).

In the strong magnetic field case, the accretion disc may be magnetically arrested by the advected field (Narayan, Igumenshchev, & Abramowicz 2003; Igumenshchev 2008; Cao 2011; Tchekhovskoy, Narayan, & McKinney 2011; Cao, Liang, & Yuan 2014). The numerical simulations were carried out for the geometically thick accretion flows, i.e., the advection dominated accretion flows (ADAFs) (Narayan, Igumenshchev 2008; Tchekhovskoy, Narayan, & McKinney 2011; Tchekhovskoy & McKinney 2012), which show that the jet efficiency \(\eta_{\text{jet}}\) can be higher than 100% under the certain circumstances (the jet efficiency \(\eta_{\text{jet}} = P_{\text{jet}}/M^2c^2\), and \(M\) is the mass accretion rate of the accretion flow). The ADAF is suppressed when the dimensionless mass accretion rate \(\dot{m}\) is greater than a critical value \(\dot{m}_{\text{crit}} (\dot{m} = \dot{M}/M_{\text{Edd}})\), which is suggested to be around 0.01 (Narayan & Yi 1994). This implies that the maximal jet power for an ADAF should be \(\sim 0.1 L_{\text{Edd}}\).

The advection of the external large scale magnetic field is efficient in the ADAF due to its large radial velocity, and a very strong magnetic field is formed near the black to arrest the accretion flow (Narayan, Igumenshchev, & Abramowicz 2003; Igumenshchev 2008; Cao 2011; Tchekhovskoy, Narayan, & McKinney 2011; Cao, Liang, & Yuan 2014). This is different from the accretion disc-corona case considered in this paper. In the accretion disc-corona system, the external large scale field is dragged inward by the hot corona above/below the disc. Similar to an ADAF, the radial velocity of the hot corona is much higher than that of the thin disc, and the field is advected inward efficiently. However, the dragged field lines will have to pass through the geometrically thin disc located between the coronae. The field dragged by the corona may be diffused in the thin disc, and therefore it is sceptical whether the field can be developed to be so strong to arrest the accretion disc-corona. In this case, the maximal strength of the field advected by the corona is still limited by the condition \(\beta \lesssim 1\).

**ACKNOWLEDGMENTS**

I thank the referee for his/her helpful comments/suggestions. This work is supported by the NSFC (grants 11233006 and 11773050), the CAS grant (QYZDJ-SSW-SYS023), and Shanghai Municipality.

**REFERENCES**

Abramowicz M. A., Chen X.-M., Granath M., Lasota J.-P., 1996, ApJ, 471, 762

Abramowicz M. A., Lanza A., Percival M. J., 1997, ApJ, 479, 179

Beckwith K., Hawley J. F., Krolik J. H., 2009, ApJ, 707, 428

Bisnovatyi-Kogan G. S., Ruzmaikin A. A., 1974, Ap&SS, 28, 45

Bisnovatyi-Kogan G. S., Ruzmaikin A. A., 1976, Ap&SS, 42, 401

Blandford R. D., Payne D. G., 1982, MNRAS, 199, 883

Blandford R. D., Znajek R. L., 1977, MNRAS, 179, 433

Cao X., 2009, MNRAS, 394, 207

Cao X., 2011, ApJ, 737, 94

Cao X., 2014, ApJ, 783, 51

Cao X., 2016, ApJ, 833, 30

Cao X., Liang E.-W., Yuan Y.-F., 2014, ApJ, 789, 129

Cao X., Spruit H. C., 2002, A&A, 385, 289

Cao X., Spruit H. C., 2013, ApJ, 765, 149

Feng J., Wu Q., 2017, MNRAS, 470, 612

Fromang S., Stone J. M., 2009, A&A, 507, 19

Galeev A. A., Rosner R., Vaiana G. S., 1979, ApJ, 229, 318

Gammie C. F., Popham R., 1998, ApJ, 498, 313

Ghisellini G., Tavecchio F., Maraschi L., Celotti A., Szylinski T., 2014, Natur, 515, 376

Ghosh P., Abramowicz M. A., 1997, MNRAS, 292, 887

Gu M., Cao X., Jiang D. R., 2009, MNRAS, 396, 984

Guo X., Gammie C. F., 2009, ApJ, 697, 1901

Guillet J., Ogilvie G. I., 2012, MNRAS, 424, 2097
Guilet J., Ogilvie G. I., 2013, MNRAS, 430, 822
Lubow S. H., Papaloizou J. C. B., Pringle J. E., 1994, MNRAS, 267, 235
MacDonald D., Thorne K. S., 1982, MNRAS, 198, 345
Manmoto T., 2000, ApJ, 534, 734
Haardt F., Maraschi L., 1991, ApJ, 380, L51
Haardt F., Maraschi L., 1993, ApJ, 413, 507
Igumenshchev I. V., 2008, ApJ, 677, 317-326
Kang S.-J., Chen L., Wu Q., 2014, ApJS, 215, 5
Kawaguchi T., Shimura T., Mineshige S., 2001, ApJ, 546, 966
Lesur G., Longaretti P.-Y., 2009, A&A, 504, 309
Li S.-L., 2014, ApJ, 788, 71
Livio M., Ogilvie G. I., Pringle J. E., 1999, ApJ, 512, 100
Lovelace R. V. E., Rothstein D. M., Bisnovatyi-Kogan G. S., 2009, ApJ, 701, 885
Manmoto T., 2000, ApJ, 534, 734
Narayan R., Igumenshchev I. V., Abramowicz M. A., 2003, PASJ, 55, L69
Narayan R., Yi I., 1995, ApJ, 452, 710
Parfrey K., Giannios D., Beloborodov A. M., 2015, MNRAS, 446, L61
Parker, E. N. 1979, in Chapter 17, Cosmical Magnetic Fields (Oxford:Clarendon Press)
Salvesen G., Armitage P. J., Simon J. B., Begelman M. C., 2016, MNRAS, 460, 3488
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Spruit H. C., Uzdensky D. A., 2005, ApJ, 629, 960
Svensson R., Zdziarski A. A., 1994, ApJ, 436, 599
Tchekhovskoy A., McKinney J. C., 2012, MNRAS, 423, L55
Tchekhovskoy A., Narayan R., McKinney J. C., 2011, MNRAS, 418, L79
van Ballegooijen, A. A. 1989, in Accretion Disks and Magnetic Fields in Astrophysics, ed. G. Belvedere (ASSL Vol. 156; Dordrecht: Kluwer), 99
Wu Q., Cao X., Ho L. C., Wang D.-X., 2013, ApJ, 770, 31
Wu Q., Yan H., Yi Z., 2013, MNRAS, 436, 1278
Yousef T. A., Brandenburg A., Rüdiger G., 2003, A&A, 411, 321
Zhang J., Xue Z.-W., He J.-J., Liang E.-W., Zhang S.-N., 2015, ApJ, 807, 51

© RAS, MNRAS 000, 1–?