The kinetic power of jets magnetically accelerated from advection dominated accretion flows in radio galaxies

Shuang-Liang Li*, Xinwu Cao†

Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan RD, Shanghai, 200030, China

ABSTRACT

There is a significant nonlinear correlation between the Eddington ratio ($L_{\text{bol}}/L_{\text{Edd}}$) and the Eddington-scaled kinetic power ($L_{\text{kin}}/L_{\text{Edd}}$) of jets in low luminosity active galactic nuclei (AGNs) (Merloni & Heinz). It is believed that these low luminosity AGNs contain advection dominated accretion flows (ADAFs). We adopt the ADAF model developed by Li & Cao, in which the global dynamics of ADAFs with magnetically driven outflows is derived numerically, to explore the relation between bolometric luminosity and kinetic power of jets. We find that the observed relation, $L_{\text{kin}}/L_{\text{Edd}} \propto (L_{\text{bol}}/L_{\text{Edd}})^{0.49}$, can be well reproduced by the model calculations with reasonable parameters for ADAFs with magnetically driven outflows. Our model calculations is always consistent with the slope of the correlation independent of the values of the parameters adopted. Compared with the observations, our results show that over 60% of the accreted gas at the outer radius escapes from the accretion disc in a wind before the gas falls into the black holes. The observed correlation between Eddington-scaled kinetic power and Bondi power can also be qualitatively reproduced by our model calculations. Our results show that the mechanical efficiency $\varepsilon$ ($L_{\text{kin}} = \varepsilon M_{\text{Bondi}} c^2$) varies from $10^{-2} \sim 10^{-3}$, which is roughly consistent with that required in AGN feedback simulations.

Key words: accretion, accretion discs – black hole physics – magnetohydrodynamics: MHD – ISM: jets and outflow – quasars: general – X-rays: galaxies.

1 INTRODUCTION

It was found that the mass of the black holes in the centre of galaxies is tightly correlated with galaxy properties (e.g., Tremaine et al. 2002; Bandara et al. 2009). The co-evolution of massive black holes and galaxies is usually ascribed to the so-called AGN feedback (Silk & Rees 1998). There are two ways of the AGN feedback on the ambient gas, i.e., radiative feedback and mechanical feedback, which correspond to the cases of high and low Eddington-scaled accretion rate respectively (Fabian et al. 2001; Croton et al. 2006). The mechanical feedback is in the form of powerful outflows/jets produced in the most central small region, which can spread to a large region. The X-ray cavities and bubbles in the galaxies and clusters are believed to be blown up through the interaction between the outflows/jets and the intra-cluster medium (ICM), which are carefully studied owing to the high resolution observations of Chandra and XMM-Newton (e.g., Birzan et al. 2004; Allen et al. 2004; 2006; Rafferty et al. 2004; Merloni & Heinz 2007). Search the literature for the data of X-ray cavities, Merloni & Heinz (2007) compiled a sample of 15 objects containing the data of mechanical power, the black hole mass and the nuclear luminosity both in the radio (5 GHz) band and in the 2-10 kev band. They found a strong correlation between Eddington-scaled kinetic power and bolometric luminosity. A similar correlation between Eddington-scaled kinetic power and Bondi power was also present for this sample (see also Allen et al. 2006).

ADAFs are optically thin, geometrically thick and very hot as most releasing gravitational energy being stored in the gas instead of radiating away, which are believed to be present in most of low-luminosity AGNs (e.g., Narayan & Yi 1994, 1995). Due to their high temperature and positive Bernoulli parameter, ADAFs are prone to be associated by outflows (Blandford & Begelman 1999), which are consistent with numerical simulations and observations (e.g., Stone & Pringle 2001; Gammie et al. 1999; Yuan et al. 2003). Merloni & Heinz (2007) adopted a simple self-similar model for ADAFs coupled with outflows developed by Kuncic & Bicknell (2004) to explore the correlations between Eddington-scaled kinetic power, bolometric luminosity and Bondi power. They found that the correlations can be qualitatively reproduced by the model calculations (see Merloni & Heinz 2007, for the details).

The outflows may probably be accelerated from the accretion flow by the large-scale ordered magnetic fields threading the accretion flow (e.g., Blandford & Payne 1982; Cao 2002; Spruit...
2 Model

In this work, we adopt the model of ADAFs with magnetically driven outflows (Li & Cao 2009) to explore the above-mentioned correlations given by Merloni & Heinz (2007).

We summarize this model briefly in this section. The basic equations, i.e., the continuity equation, radial momentum equation, angular momentum equation and the energy equations are given as follows.

In the presence of magnetically driven outflows, we need to add some additional terms related with outflows to the dynamical equations for a classic ADAF (see Cao & Spruit 2002; Li & Cao 2009, for the details). The continuity equation describing such an ADAF+outflow system is

$$\frac{d}{dR}(2\pi R\Sigma n_t) + 4\pi R\dot{m}_w = 0,$$

where all the physical quantities denote their common meanings, $\dot{m}_w$ is the mass loss rate from unit surface area of accretion flow due to the outflow.

The radial momentum equation is

$$\frac{d\rho}{dR} = -\rho\Omega^2 - \rho \frac{dP}{dR} - g_m = 0,$$

where $\Omega$ is the angular velocity of the accretion flow at $R$, the radial magnetic force $g_m = B_r^2 B_t / 2\pi \Sigma$ ($B_r$ and $B_t$ are the radial and vertical components of the magnetic fields at the disc surface).

The angular momentum equation reads

$$\frac{d(\rho R^2)}{dR} - \frac{1}{\rho H R} \frac{d}{dR}(R^2 H \tau_{\phi}) + T_m = 0,$$

where $T_m$ is the magnetic torque exerted on the unit surface area of the disc due to the presence of the outflows $L_{\text{obs}}$, Papaloizou, & Pringle (1994b). A fraction of the energy and angular momentum of the accretion flow is carried away by the outflows, which is equivalent to a torque exerted on the accretion flow. We can calculate the magnetic torque $T_m$ with energy conservation law, provided the power of the outflow from unit surface area of the accretion disc is known, which leads to

$$T_m = \frac{2}{\Omega} \left[ \frac{\dot{m}_w}{2} \Omega^2 R^2 - \dot{m}_w (e_i + e_e) \right],$$

where $\dot{m}_w$ and $\dot{m}_w$ are the kinetic power and the mass loss rate of the outflow from unit surface area of the accretion disc, $e_e$ and $e_i$ are the specific internal energy of electrons and ions respectively. The main difference between our calculation of $T_m$ and that in Lubow, Papaloizou, & Pringle (1994b)'s work is that the internal energy of the gas is properly included in our calculation, while theirs is only for cold outflows.

The energy equation for ions and electrons are given by

$$\rho \frac{d\epsilon_i}{dR} - \frac{P_i}{\rho^2} \frac{dP}{dR} - \delta \dot{q}_i^+ - \dot{q}_w + \frac{2\dot{m}_w \epsilon_i}{2H} = 0,$$

and

$$\rho \frac{d\epsilon_e}{dR} - \frac{P_e}{\rho^2} \frac{dP}{dR} - (1 - \delta) \dot{q}_e^+ + \dot{q}_w + \frac{2\dot{m}_w \epsilon_e}{2H} = 0,$$

where, the parameter $\delta$ describes the fraction of the viscously dissipated energy that goes directly into electrons in the accretion flow, $q^+ = -\alpha P R d\Omega / dR$ is the energy dissipation rate per unit volume, and the radiative cooling rate $q^-$ consists of synchrotron, bremsstrahlung, and Compton coolings (see, Mannucci 2004, for details). The last terms in Eqs. (5) and (6) represent the internal energy of the gas in the accretion flow carried away in the outflows. The effects of bulk kinetic part of the outflows are included in the angular momentum equation (4), and the structure of the ADAF is altered, which leads to changes of $q^+$ and $q^-$ in Eqs. (5) and (6). The energy transfer rate $q_w$ from ions to electrons through Coulomb collisions is

$$q_w = \frac{3}{2} \frac{\dot{m}_w}{\rho} \frac{n_i n_e \sigma T_c}{c} \frac{(kT - kT_e)}{K_2(1/kT_e) K_2(1/kT)} \ln \Lambda$$

$$\times \left[ 2\left( \theta_e + \theta_i \right)^2 + 1 \right] K_1 \left( \theta_e + \theta_i \right) + 2K_0 \left( \theta_e + \theta_i \right),$$

where the Coulomb logarithm $\ln \Lambda = 20$ (Stephew & Gilburt 1983).

For simplicity, the large-scale magnetic field lines are assumed to thread the accretion disc, and the strength of the magnetic fields far from the disc surface along the field line to be roughly self-similar (Lubow, Papaloizou, & Pringle 1994b),

$$B_{p}(R) \sim B_{p0}(R_i) \left( \frac{R}{R_i} \right)^{-\zeta},$$

where $B_{p0}$ is the strength of the poloidal component of the field at the disc surface, $B_{p}(R)$ is the field strength at $R$ along the field line threading the disc surface at $R_i$. The self-similar index $\zeta \geq 1$ is required, because the configuration of any magnetic fields of the disc being able to accelerate outflows should have an expanding shape above the disc. In our model calculations, we have not adopted a detailed configuration of magnetic fields threading the disc, instead, we use the parameter $\zeta$ to describe how the poloidal field strength decline along the field line for simplicity as that adopted by Lubow, Papaloizou, & Pringle (1994b). In the calculations of Lubow, Papaloizou, & Pringle (1994b), $\zeta = 4$ is adopted.

For a relativistic jet accelerated by the magnetic field of the disc, the Alfvén velocity at the Alfvén point is (Camenzind 1986)
The kinetic power of jets from ADAFs in radio galaxies

\[ v_A = \frac{B_0^a}{(4\pi \rho_A \gamma_A^a)} \]  

where \( B_0^a \) and \( \rho_A \) are the poloidal field strength and the density of the outflow/jet at Alfvén point, and \( \gamma_A^a \) is the Lorentz factor of the bulk motion of the outflows/jets at the Alfvén point.

The mass and magnetic flux conservation along the field line requires

\[ \frac{\dot{m}_w}{B_0^a} = \frac{\rho_A v_A}{B_0^a} \]  

The outflow/jet can be magnetically accelerated over the Alfvén point all along until the modified fast magnetosonic point as those done in the previous works (e.g., Li, Chueh, & Begelman 1992; Cao & Spruit 1994; Vlahakis & Königl 2003, 2004). The Lorentz factor of the outflow/jet is

\[ \gamma_A^a \simeq \left[ 1 - \left( \frac{v_A}{c} \right)^2 \right]^{-\frac{1}{2}}. \]  

Combining equations (9)–(11), the mass loss rate in the outflow/jet from the unit surface area of the disc is

\[ \dot{m}_w = \frac{B_0^2}{4\pi c} \left[ \frac{R_d \omega(R_d)}{c} \right] \frac{\gamma_A^a}{(\gamma_A^a - 1)^{(1+\gamma_A^a)/2}}. \]  

As described in Sect. 2, the structure of the accretion flow and the outflows is calculated, and then the kinetic power of outflows and the bolometric luminosity of the accretion flow are available. Changing the mass accretion rate, the relation between Eddington-scaled bolometric luminosity \( \lambda = L_{\text{bol}}/L_{\text{Edd}} \) and kinetic power of the outflows is plotted in Fig. 1 for different values of \( \zeta \) with \( \beta = 0.92 \), i.e., \( P_{\text{in}} = 0.087P_{\text{gas}} \), in which the results are compared with the correlation between \( L_{\text{bol}}/L_{\text{Edd}} \) and \( L_{\text{kin}}/L_{\text{Edd}} \) given by Merloni & Heinz (2003). The Eddington-scaled kinetic power as functions of Eddington-scaled bolometric luminosity of the accretion disc is plotted in Fig. 2 for different values of \( \beta \) (\( \zeta = 2 \) is adopted). The observed correlation can be well reproduced by our model calculations by tuning the values of two parameters, \( \beta \) and \( \zeta \). In Fig. 3 the best fitted model parameters in \( \zeta-\beta \) space are plotted. We plot the mass accretion rate as functions of radius for different values of \( \zeta \). The Bondi power is defined as (Merloni & Heinz 2007):

\[ P_{\text{bondi}} = 0.1M_{\text{bondi}}c^2, \]  

where \( M_{\text{bondi}} \) is the Bondi accretion rate. The Bondi accretion rates of the sources in the sample of Merloni & Heinz (2007) were estimated with the X-ray luminosity and the accretion rate at the outer radius. We can therefore plot the dependence of the kinetic powers as functions of Bondi power in Fig. 5 for different values of \( \beta \) and \( \zeta \).

4 DISCUSSION

Merloni & Heinz (2007)’s sample are limited to low luminosity radio galaxies, which are supposed to be accreting at low rates, probably through a radiatively inefficient ADAF. In this work, we show that the ADAF model developed by Li & Cai (2008a) can explain the correlation between Eddington-scaled kinetic power and bolometric luminosity found by Merloni & Heinz (2007).
Figure 1. The Eddington-scaled kinetic power as functions of Eddington-scaled bolometric luminosity ($\lambda = L_{\text{bol}}/L_{\text{Edd}}$) for different values of $\zeta$. The bold solid line is the best fitted result of on the correlation given in Merloni & Heinz (2007), i.e., $\log(L_{\text{kin}}/L_{\text{Edd}}) = 0.49\log(L_{\text{bol}}/L_{\text{Edd}}) - 0.78$. The dashed line, solid line and dotted line are for $\zeta = 1$, $\zeta = 2$ and $\zeta = 4$ respectively.

Figure 2. The Eddington-scaled kinetic power as functions of Eddington-scaled bolometric luminosity ($\lambda = L_{\text{bol}}/L_{\text{Edd}}$) for different values of $\beta$. The bold solid line is the best fitted result of on the correlation given in Merloni & Heinz (2007). The dashed line, solid line and dotted line are for $\beta = 0.9$, $\beta = 0.92$ and $\beta = 0.94$ respectively.

Figure 3. The best fitted results to the observed correlation in the $\zeta$-$\beta$ space.

Figure 4. The mass accretion rate as functions of radius for different values of $\zeta$, where $\beta = 0.92$ and the accretion rate at outer radius $\dot{m}_0 = 10^{-5}$ ($\dot{m}_0 = \dot{M}_0/\dot{M}_{\text{Edd}}$) are adopted.

Figure 5. The Eddington-scaled kinetic power as a function of Eddington-scaled Bondi power for different values of $\beta$ and $\zeta$. luminosity for different values of $\zeta$, which describes the distribution of the magnetic field in the space above the disc. It is found that the slopes of the model calculations with different values of $\zeta$ are almost constant, which is in good consistent with the observed correlation (see Fig. 1). The slope changes very little with different values of $\beta$ (see Fig. 2). This means that the slope of the observed correlation between $L_{\text{bol}}/L_{\text{Edd}}$ and $L_{\text{kin}}/L_{\text{Edd}}$ is always consistent with our model calculations independent of the values of parameters adopted. Figure 3 shows that a relatively high $\zeta$ is required for low-$\beta$, which means that field lines diverse rapidly if the field strength is relative high, in order to explain the observed correlation between $\lambda$ and $L_{\text{kin}}/L_{\text{Edd}}$. This provides useful clues to constructing detailed accretion disc/outflow models, which is beyond the scope of this work.

We find that the internal energy is not important compared with other terms in Eq. (15). The jet power is mainly related to the strength of the magnetic fields threading the disc and then to the disc properties. The bolometric power of the accretion flow is also related with the disc properties (e.g., density and temperature). Thus, the observed correlation between the kinetic power of the outflow and the bolometric power of the accretion flow can be naturally reproduced by our model calculations. The solid line in Fig. 4 corresponds to the best fitted model calculation on the observed
The kinetic power of jets from ADAFs in radio galaxies

5

correlation between Eddington-scaled kinetic power and bolometric luminosity, which implies that over 60% of the accreted gas at the outer radius escapes from the accretion disc in a wind before the gas falls into the black holes in these low luminosity AGNs. We find that best fitted model parameters $\zeta$ and $\beta$ are somewhat degenerated, i.e., they cannot be uniquely determined from the comparison with the observation, which may be caused by the simplified outflow model adopted in this work. The observed correlation can be used to constrain the model if the physics of the origin and the configuration of the magnetic fields is included, which is beyond the scope of this work.

The results of our ADAF model with outflows can be qualitatively explained in the frame of the self-similar ADAF model (Narayan & Yi 1995). The radiative efficiency of an ADAF varies with mass accretion rate. Narayan & Yi (1995)'s results showed that the bolometric luminosity of an ADAF $L_{\text{ADAF}} \propto m^s$, where $s \sim 2$ for an ADAF due to the effects of energy advection in the accretion flow. Based on their self-similar solution for an ADAF, $B^2 \propto P_{\text{gas}} \propto \dot{m}$ and then $L_1 \propto \dot{m}$, which leads to $L_1 \propto L_{\text{ADAF}}^{1/2} \propto L_{Edd}^{0.5}$. Instead of ADAFs discussed above, one may wonder whether the standard thin accretion disc model can explain this correlation between $\lambda$ and $L_{\text{kin}}/L_{\text{Edd}}$, though these sources are accreting at very low rates. The dependence of jet power on dimensionless mass accretion rate for standard accretion discs with different scaling laws for magnetic field strength on the disc properties were explored in some previous works (e.g., Moderski & Sikora 1996, Ghosh & Abramowicz 1997, Livio, Ogilvie, & Pringle 1999, Cao 2002). Most of them suggested that $L_{\text{kin}}/L_{\text{Edd}} \propto \lambda$ (e.g., see Livio, Ogilvie, & Pringle 1999, Cao 2002, for the details), and no theoretical model calculations can reproduce the observed correlation: $L_{\text{kin}}/L_{\text{Edd}} \propto \lambda^{0.5}$, based on thin accretion disc models (e.g., Moderski & Sikora 1996, Ghosh & Abramowicz 1997).

Our calculations also show that the kinetic power increases with Bondi power when we set the mass accretion rate at the outer radius $\dot{M}_0 = \dot{M}_{\text{Bondi}}$ (see Fig. 5). This is roughly consistent with the correlation between $P_{\text{Bondi}}/L_{\text{Edd}}$ and $L_{\text{kin}}/L_{\text{Edd}}$ found in Merloni & Heinz (2007) (see Fig. 1 in their paper). The mechanical efficiency $\varepsilon \left( L_{\text{kin}} = \varepsilon \dot{M}_{\text{Bondi}} c^2 \right)$ varies from $10^{-1}$ to $10^{-5}$ in the AGN feedback simulations according to the complicated environments and outflows/jets mechanism, etc (Gaspari et al. 2005, Hopkins & Elvis 2010). In our calculations, the value of $\varepsilon$ is about $10^{-2} \sim 10^{-3}$, which may be useful for future AGN feedback simulations.

ACKNOWLEDGEMENTS

We thank the anonymous referee for her/his constructive suggestions and comments. This work is supported by the NSFC (grants 10903021, 10773020, 10821302 and 10833002), the CAS (grant KJCX2-YW-T03), the Science and Technology Commission of Shanghai Municipality (10XD1405000), and the National Basic Research Program of China (grant 2009CB824800). S.-L. Li thanks the support from the Knowledge Innovation Program of Chinese Academy of Sciences.

REFERENCES

Allen S. W., Schmidt R. W., Ebeling H., Fabian A. C., van Speybroeck L., 2004, MNRAS, 353, 457

Allen S. W., Dunn R. J. H., Fabian A. C., Taylor G. B., Reynolds C. S., 2006, MNRAS, 372, 21

Armitage P. J., 1998, ApJ, 501, L189

Bandara, K., Crampton, D., Simard, L., 2009, ApJ, 704, 1135

Birzan L., Rafferty D. A., McNamara B. R., Wise M. W., Nulsen P. E. J., 2004, ApJ, 607, 800

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

Blandford, R. D., & Begelman, M. C. 1999, MNRAS, 303, L1

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

Camenzind M. 1986, A&A, 156, 137

Cao, X., 2002, MNRAS, 332, 999

Cao X., Spruit H. C., 1994, A&A, 287, 80

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

Croton, D. et al. 2006, MNRAS, 365, 11

Fabian A. C., Mushotzky R. F., Nulsen P. E. J., Peterson J. R., 2001, MNRAS, 321, L20

Gammie C., Narayan, R., & Blandford, R. D. 1999, ApJ, 516, 177

Gaspari M., Melioli C., Brighteni F., & D'rcole A., 2009, arXiv:0909.1282

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

Hopkins, P. F., & Elvis, M., 2010, MNRAS, 404, 7

Kuncic Z., & Bicknell G. V., 2004, ApJ, 616, 669

Li S.-L., & Cao, X., 2009, MNRAS, 400, 1734

Li Y., Gan Z. M., Wang D. X., 2010, New Astron., 15, 102

Li, Z.-Y., Chiueh, T., & Begelman, M. C. 1992, ApJ, 394, 459

Livio M., Ogilvie G. I., Pringle J. E., 1999, ApJ, 512, 100

Lubow S. H., Papaloizou J. C. B., Pringle J. E., 1994a, MNRAS, 267, 235

Lubow S. H., Papaloizou J. C. B., Pringle J. E., 1994b, MNRAS, 268, 1010

Mannino T. 2000, ApJ, 534, 734

Merloni A., Heinz S., 2007, MNRAS, 381, 589

Moderski R., Sikora M., 1996, MNRAS, 283, 854

Narayan, R., & Yi, I. 1994, ApJ, 428, L13

Narayan, R., & Yi, I. 1995, ApJ, 444, 231

Narayan R., Yi I., 1995, ApJ, 452, 710

Rafferty D. A., McNamara B. R., Nulsen P. E. J., Wise M. W., 2006, ApJ, 652, 216

Romanova M. M., Ustyugova G. V., Koldoba A. V., Chechetsk V. M., Lovelace R. E. V., 1998, ApJ, 500, 703

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 331, L1

Spruit H. C., 2008, in Belloni T., ed., The Jet Paradigm C From Microquasars to Quasars. Lecture Notes in Physics. Springer, New York, preprint (arXiv:0804.3096)

Spruit H. C., Uzdensky D. A., 2005, ApJ, 629, 960

Stepney, S., & Guilbert, P. W. 1983, MNRAS, 204, 1269

Stone, J. M., & Pringle, J. E. 2002, ApJ, 574, 554

Tremaine S. et al., 2002, ApJ, 574, 554

Spruit H. C., Uzdensky D. A., 2005, ApJ, 629, 960

Vlahakis, N., & Königl, A. 2003, ApJ, 596, 1080

Vlahakis, N., & Königl, A. 2004, ApJ, 605, 656

Yuan, F., Quataert, E., & Narayan, R. 2003, ApJ, 598, 301