Jet production in black-hole X-ray binaries and active galactic nuclei: mass feeding and advection of magnetic fields

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ABSTRACT

Relativistic jets are observed only in the low/hard and intermediate states of X-ray binaries (XRBs), and are switched off in the thermal state, but they appear to be present in both low-luminosity and luminous active galactic nuclei (AGNs). It is widely believed that strong large-scale magnetic fields is a crucial ingredient in jet production: such fields can be attained only through efficient advection from the outer disc. We suggest that geometrically thin accretion discs with magnetic outflows are present in luminous radio-loud AGNs; this is likely because the interstellar medium provides both mass and sufficient magnetic flux to the outer disc. Most angular momentum of such disc is removed by the outflows, and the radial velocity of the disc is significantly increased compared to viscous drift velocity. This facilitates efficient magnetic field advection through the disc to produce a strong field near the black hole in luminous AGNs, which helps launch relativistic jets. In XRBs, the magnetic fields of the gas from companion stars are too weak to drive outflows from outer discs. Jets are therefore switched off in the thermal state due to inefficient magnetic field advection in the disc.

Key words: accretion, accretion discs—black hole physics—galaxies: active—galaxies: jets—magnetic fields—X-rays: binaries

\section{1 INTRODUCTION}

Accretion discs are present both in black hole X-ray binaries (XRBs) and active galactic nuclei (AGNs), with the black hole (BH) masses ranging from \(\lesssim 10M_{\odot}\) in XRBs to \(\gtrsim 10^9M_{\odot}\) in AGNs. In XRBs, discs are fed by mass transfer from a companion star, while in AGNs circumnuclear gas in the host galaxy is accreted onto a central supermassive BH. The physics of accretion discs in these two types of sources is almost same, and observations show that they indeed share many common properties.

Although both XRBs and AGNs produce relativistic jets, a direct mapping between the disc-jet phenomenologies of XRBs and AGNs is unclear (e.g., Körding, Jester, & Fender 2004; Fender 2010). In XRBs, X-ray outbursts are known to occur in cycles of several distinct spectral states (Belloni et al. 2005). Steady compact jets are always associated with the low/hard state, characterized by high power law in the X-ray spectrum. Powerful episodic jets are produced in the intermediate state, containing both high power law component and soft spectral component. In the high-soft (thermal) state, radio jets are switched off (Fender et al. 1999; Corbel et al. 2001; Fender, Gallo, & Jonker 2003; Gallo, Fender, & Pooley 2003; Fender & Belloni 2004; Fender, Belloni, & Galli 2004), although non-relativistic winds/outflows have been observed in some X-ray binaries (Neilsen & Lee 2009; Ueda, Yamaoka, & Remillard 2009; King et al. 2013; Miller et al. 2012). The origin of such winds/outflows is unclear (Neilsen & Lee 2009). It is believed that the spectral states of BH XRBs correspond to different accretion modes. In the low/hard state, the standard thin disc is truncated at a large distance from the BH, and is replaced in the inner region by a geometrically thick, radiatively inefficient flow (e.g., Esin, McClintock, & Narayan 1997; Meyer, Liu, & Meyer-Hofmeister 2000; Zdziarski et al. 2004; Wu & Gu 2008; Belloni 2010).

In the thermal state, the thin disc extends to the innermost stable orbit around the BH. It is clear that the production of relativistic jets is regulated by accretion mode. The role of magnetic field in state transition and jet formation in XRBs has been explored in some previous works (e.g., Kylafis et al. 2012; Kylafis & Belloni 2015; Li & Yaqing 2014; Cao 2016). The phe-
nomenclature of state transition and jet production in AGNs is less clear. Low-luminosity AGNs may contain radiatively inefficient flows, which correspond to the low/hard state of XRBs, while standard thin accretion discs are present in luminous AGNs (thermal state) (Colbert & Mushotzky 1999; Zdziarski, Lubinski, & Smith 1999; Jester 2003; Hj 2005; Vasisht & Fabian 2007). The observed jets in AGNs always exhibit a flat-spectrum radio core, which are similar to the steady jets observed in the low/hard state of XRBs. Otherwise, one may expect that a compact radio core is present only in a fraction of radio AGNs, if they contain episodic jets as those in the intermediate state of XRBs. By analogy with XRBs, one might expect that relativistic jets preferentially appear in low-luminosity AGNs. However, several lines of evidence suggest that jets are also produced in luminous AGNs (analogy of thermal state of XRBs). (i) The Eddington ratios of many radio-loud quasars are $\sim 0.1 - 1$ (e.g., Sikora, Stawarz, & Lasota 2007; Wu 2009). For some radio-loud narrow-line Seyfert 1 galaxies, the Eddington ratios can be as high as $\gtrsim 1$ (Zhou et al. 2003; Komossa et al. 2006b; Yuan et al. 2008; Calderone et al. 2013). Relativistic jets have been observed in radio-loud narrow-line Seyfert 1 galaxies (Doi et al. 2007; Gu & Chen 2010). These indicate that both radio-loud quasars and narrow-line Seyfert 1 galaxies with jets contain radiatively efficient accretion discs, either standard thin discs or slim discs (Shakura & Sunyaev 1973; Abramowicz et al. 1988). (ii) IR I radio galaxies have lower radio power than FR II galaxies, and they have different radio morphologies (Fanaroff & Riley 1974). Using a sample of FR galaxies, Ghisellini & Celotti (2001) suggested that FR I galaxies can be separated from FR II galaxies by the Eddington ratio $\sim 0.001 - 0.01$, which implies different accretion modes in these two types of sources. (iii) In the unification scheme for radio-loud AGNs, BL Lacertae (BL Lac) objects are believed to be FR I radio galaxies with the jets aligned to our line of sight, while radio quasars correspond to FR II galaxies viewed at small angles with respect to the jet orientation. The Eddington ratio distributions of BL Lac objects/quasars are separated (see Figure 2 in Xu, Cao, & Wu 2009), which implies that radio quasars may contain radiatively efficient accretion discs, while radiatively inefficient flows may be in BL Lac objects. For most BL Lac objects in the Xu et al. (2009) sample, the BH masses are estimated from the host galaxy luminosities by using the $M_{bh} - L_{*}$ relation derived by McLure & Dunlop (2004). For a few BL Lac objects with measured stellar dispersion velocity $\sigma$, the BH masses are estimated with the empirical $M_{bh} - \sigma$ relation. The bolometric luminosity of BL Lac objects is derived from their broad/narrow line emission, because the continuum emission may be dominated by Doppler beamed jet emission (see Xu, Cao, & Wu 2009, for the details). (iv) A big blue bump in continuum spectra has been detected in some radio quasars, which is taken as a characteristics of standard thin accretion discs surrounding supermassive BHs (Jolley et al. 2006). (v) The observation of a broad ionized Fe K$\alpha$ line shows that a thin accretion disc extends to the innermost region near the black hole in the broad-line radio galaxy 4C 74.26 (Ballantyne & Fabian 2005). Overall, it appears that jet formation in AGNs is not strongly regulated with the accretion mode, contrary to the case of XRBs.

The production of relativistic jets in accreting BH systems (XRBs and AGNs) relies on extracting the rotational energies of the inner accretion discs and/or BHs through large-scale magnetic fields (see, e.g., Hawley et al. 2013, for a recent review). In the Blandford-Payne (BP) mechanism (Blandford & Payne 1982), a small fraction of gas in the accretion disc is accelerated by the magnetic field lines co-rotating with the disc. The final velocity of the driven gas is only a few times the rotational velocity of the disc (e.g., Padurariu, Rogers, & Ouyed 2006), which implies that the BP mechanism is likely responsible for accelerating outflows. In the Blandford-Znajek (BZ) mechanism, the jets are powered by spinning BHs (Blandford & Znajek 1977), which is realized by the numerical simulations (e.g., Komissarov 2001, 2003; McKinney & Gammie 2004; De Villiers et al. 2008). It is found that magnetic forces play a key role in jet acceleration (e.g., Tchekhovskoy, Narayan, & McKinney 2011; McKinney, Tchekhovskoy, & Blandford 2012). Other mechanisms that do not rely on relativistic discs or BH spins may also operate (e.g., Yuan et al. 2009). Regardless of the details, large-scale magnetic fields is a key ingredient of all jet production mechanisms. Such large-scale fields are unlikely to be a result of local MHD dynamo process, even for geometrically thick discs (see, e.g., simulations by McKinney, Tchekhovskoy, & Blandford 2012). Thus it is natural to expect that jet formation requires efficient advection of large-scale magnetic fields in the disc from large distances to the inner region (e.g., Sikora & Begelman 2011; Sikora et al. 2013; Cao 2016b).

The origin of large-scale magnetic fields in BH accretion discs is directly linked to the issue of mass feeding in the outer discs. As the external large-scale poloidal fields (e.g., the fields in the interstellar medium in AGNs, or the fields of companion stars in XRBs) are dragged inward by the plasma in the discs, the fields in the inner regions of the discs can be significantly enhanced (Bisnovatyi-Kogan & Ruzmaikin 1974, 1976). However, the enhancement of magnetic fields is reduced by the magnetic diffusion (e.g., van Baller (1982); Lubow, Papaloizou, & Pringle 1994; Ogilvie & Livio 2001). For isotropic turbulence, the effective magnetic Prandtl number $Pm = \nu / \eta \sim 1$ (where $\nu$ is the viscosity, and $\eta$ is magnetic diffusivity) is expected (Parker 1979), which is consistent with numerical simulations (e.g., Yousef, Brandenburg, & Rüdiger 2003; Lesur & Longaretti 2009; Fromang & Stone 2009; Guan & Gammie 2009). It was found that field advection in a conventional turbulence-driven thin disc is rather inefficient due to its low radial velocity (Lubow, Papaloizou, & Pringle 1994). There are several possible ways to resolve this difficulty of field advection in thin discs (e.g., Spruit & Uzdensky 2003; Lovelace, Rothstein, & Bisnovatyi-Kogan 2009; Beckwith, Hawley, & Krolik 2008; Cao & Spruit 2013; Zhu & Stone 2017). Spruit & Uzdensky (2005) suggested that large-scale magnetic fields threading the disc could be in the form of discrete, asymmetric patches, which can efficiently remove disc angular momentum through magnetic winds, leading to more efficient inward drift of the field. Lovelace et al. (2009) (see also Guil et & Ogilvie 2012, 2013) suggested that the radial velocity of the gas in the disc upper layer could be larger than that in the disc midplane, which may also help field advection in thin discs. Cao & Spruit (2013) constructed a disc-outflow model, in which the angular momentum of the disc removed by a magnetically accelerated outflow dominates over that caused by turbulence in the disc. The radial velocity of the disc is therefore significantly increased, and a weak external magnetic field can be captured to form a strongly magnetized inner disc.

In this work, we explore the difference of jet production between XRBs and AGNs. As noted above, the presence of large-scale magnetic fields in the inner disc is a necessary condition for jet formation. We compare the differences of mass/field supplies in the outer disc boundaries and field advection through accretion discs in these two types of sources. We suggest that jets are
switched off in the thermal state of XRBs due to inefficient field advection in thin discs.

2 MODEL

As noted in Section 1, observations are consistent with the picture that jet production is similar for XRBs and AGNs accreting at low rates, while it is different at high rates – Jets are switched off in the thermal state of XRBs, but are observed in luminous AGNs accreting at high rates (thermal state). Jets can be magnetically driven by a spinning BH (BZ mechanism) or/and from the inner region of the accretion discs (BP mechanism). Thus, jet formation in XRBs and AGNs is closely associated with strong large-scale magnetic fields in the inner regions of the discs surrounding BHs, i.e., a strong magnetic field is a necessary condition for jet formation.

In the thermal state, a geometrically thin disc extends to the inner-most region of the BH either in XRBs or AGNs. For a pure viscous disc (i.e., angular momentum is transported only by viscous stress), the radial velocity \( v_r \propto (H/R)^2 \), and thus field advection is very inefficient for thin discs (small \( H/R \)). In this work, we assume that most angular momentum of the thin disc is removed via magnetic outflows, and the radial velocity of the disc is significantly increased (see Cao & Spruit [2013] for the details). Strong magnetic field can be formed near the BH (which then leads to jet production) only if the condition for launching outflows from a thin disc is satisfied.

2.1 Condition for magnetically driven outflows

We consider an accretion disc driven by magnetic outflows, i.e., the angular momentum of the disc is predominantly removed by the outflow accelerated by the field lines threading the disc. The field lines threading the disc are co-rotating with the disc, and a fraction of tenuous gas at the disc surface moves along the field line rotating with angular frequency \( \Omega \), if the field line is inclined at an angle \( \leq 60^\circ \) to the disc surface (Blandford & Payne [1982]). In this case, the azimuthal velocity of the co-rotating gas changes with \( R \) in the outflow till it moves beyond the Alfven radius (roughly). Therefore, the angular momentum of the gas in the disc is carried away by the outflows, which is equivalent to a magnetic torque exerting on the disc. The magnetic torque exerted by the outflow per unit area of the disc surface is

\[
T_m = \frac{B_zB_\phi^2}{2\pi R},
\]

where \( B_\phi^2 \) is azimuthal component of the large scale magnetic field at the upper disc surface, which is caused by the mass loaded in the outflows. The radial velocity of the disc driven by the outflows is

\[
v_r \simeq \frac{2T_m}{\Sigma R \Omega},
\]

where \( \Omega \simeq \Omega_K \) is assumed for weak field cases, i.e., \( \beta = 8\pi P_{\text{kin}}/B^2 \gg 1 \) (see Equation 11 in Cao & Spruit [2013]). The mass accretion rate of the disc is

\[
\dot{M} = -2\pi R \Sigma v_r \simeq -4\pi T_m \Omega_K \frac{B_z B_\phi^2 R}{\Omega_K},
\]

where Equations (1) and (2) are used. We can therefore derive a relation of the magnetic field strength with the mass accretion rate,

\[
B_z = \frac{1}{\sqrt{2}} \xi_\phi^{-1/2} \tilde{\xi}_m^{1/2} \Omega_K^{1/2} R^{-1/2}
\]

\[= 9.77 \times 10^8 \xi_\phi^{-1/2} \tilde{\xi}_m^{1/2} m^{-1/2} \rho^{-5/4} \text{ Gauss}, \tag{4}\]

where \( \xi_\phi = -B_\phi^2/B_z \). The minus sign indicates the azimuthal component of the field being in the counter-direction of the disc rotation (for \( B_z > 0 \)). The dimensionless quantities are defined as

\[
m = \frac{M}{M_\odot}, \quad \dot{m} = \frac{\dot{M}}{M_{\dot{Edd}}}, \quad M_{\dot{Edd}} = \frac{L_{\dot{Edd}}}{0.1 c^2}, \quad r = \frac{R}{R_\odot},
\]

where \( R_\odot = G M/c^2 \).

Since the ratio \( \xi_\phi \lesssim 1 \) is required to avoid the instability (or reconnection) of toroidal field (Biskamp [1993], Livio, Ogilvie, & Pringle [1999]), the condition

\[
B_z \gtrsim B_\phi^\text{min} = 9.77 \times 10^8 m^{-1/2} \rho^{-5/4} \text{ Gauss}, \tag{5}\]

must be satisfied for accretion discs driven by magnetic outflows. This result is plotted in Figure 1 for different disc parameters.

2.2 Magnetic field advection of thin accretion discs driven by outflows

The field dragged by the accretion disc is described by the induction equation (e.g., see Eq. 14 in Lubow, Papaloizou, & Pringle [1994]). In the steady state, the left side of the equation equals zero (\( \partial / \partial t = 0 \)). This implies that the sum of the field evolution due to field advection and diffusion vanishes. We note that the magnetic diffusion is sensitive to the field curvature in the disc, so the field inclination at the disc surface can be derived from the advection/diffusion balance at all radii. In this work, we consider the steady case, i.e., \( \tau_{\text{adv}} = \tau_{\text{diff}} \), which are estimated as

\[
\tau_{\text{adv}} \sim -\frac{R}{v_r}, \tag{6}\]

and

\[
\tau_{\text{diff}} \sim \frac{R \kappa_0 \eta}{\eta}, \tag{7}\]

where \( \eta \) is the magnetic diffusivity, and \( \kappa_0 \equiv B_z/B_\phi^2 \) at the disc surface. The radial velocity of the gas in the disc is then

\[
v_r = -\frac{\alpha \kappa_0}{\kappa_0 P_m}, \tag{8}\]

where \( P_m = \nu/\eta \), and \( \nu = \alpha \kappa_0 H \).

The field inclination is crucial in accelerating outflows. The cold gas can be magnetically driven from the mid-plane of a Keplerian disc only if the field line is inclined with an angle \( \leq 60^\circ \) (i.e., \( \kappa_0 \leq \sqrt{3} \)) with respect to the mid-plane of the disc (Blandford & Payne [1982]). The situation is slightly different for more realistic cases (e.g., a sub-Keplerian disc) (see Ogilvie & Livid [2001], Cao & Spruit [2002]). In this work, we adopt a necessary condition to drive magneto-centrifugal outflow as \( \kappa_0 \lesssim 1 \) (approximately). With Equation (8), we derive the required radial advection velocity to be \( |v_r| \gtrsim 2 \kappa_0 P_m \). For a conventional viscous accretion disc without magnetically driven outflows, the radial velocity is

\[
|v_r| = -\frac{3\nu}{2 R} = -3 \kappa_0 H \frac{P_m}{2R}, \tag{9}\]

Thus, we have

\[
|v_r| = \frac{2}{3 \kappa_0 H P_m}, \tag{10}\]

where \( H = H/R \). Numerical simulations indicate that Prandtl number \( P_m \sim 1 \) (Yousef, Brandenburg, & Rüdiger [2003]).
Fromang & Stone (2009), Guan & Gammie (2009), or $P_{in} \sim 2 - 5$
Lesur & Longaretti (2009). In this work, we conservatively adopt
$P_{in} = 1$ in most of our calculations. The ratio $v_r/v_r^\infty \sim 1/\dot{M}$ for
$P_{in} = 1$ if the field line is inclined at $60^\circ$ with respect to the disc
plane at the disc surface. This indicates that the radial velocity
of the disc driven by the outflows can be much higher than that of
a viscous thin disc. In principle, we can calculate the global accretion
disc structure with a suitable outflow solution, and then the large-
field configuration can be calculated by solving the induction equa-
tion (ξ parameter
disc structure with a suitable outflow solution, and then the large-
viscous thin disc. In principle, we can calculate the globalaccretion
plane at the disc surface. This indicates that the radial velocity of
due to the presence of magnetically driven outflows. W e note t hat
the external field strength
the field strength at the outer radius of the disc is even lower than
the disc, which means that the local emission of the discs with outflows
as a radio-loud one only if the angular velocity of the circum nuclear
gas is lower than a critical value at the Bondi radius (see the detailed
discussion in Cao 2016b). If the external field is not ordered or if it
is misaligned with the axis of the disc, the field enhancement may
not be so efficient as estimated. In this case, a luminous AGN will
also appear as a radio-quiet one. As the gas with a small angular
velocity falls almost freely from the Bondi radius onto the outer
radius of the disc, we suggest that the reconnection of the field in
this region is inefficient. Numerical simulations show that shocks in
a quasi-spherical slow-rotating flow may form very close to the BH
(at tens of gravitational radii) (see Suková & Janík 2015, for the
details). In our model, the thin discs are formed at $\sim 10^{-3} - 10^{-4} R_g$
in bright AGNs, and we believe that the flows from the Bondi radius
to the circularization radius are shock-free.

Strong outflows driven magnetically from accretion discs are
required in RL AGNs (Cao (2016b), which may alter the structure
of the discs. We found that the disc remains optically thick even if
its radial velocity increases ten times that of a conventional viscous
disc, which means that the local emission of the discs with outflows
in RL AGNs are still nearly blackbody. Thus emergent spectra of
accretion discs with outflows should have similar characteristics
in UV/optical wavebands as those of standard thin discs, which
is verified by the detailed calculations of the spectra of accretion
discs with outflows (You et al. 2016). This is consistent with similar
UV/optical continuum spectra observed in both RL and RQ AGNs
(e.g., Elvis et al. 1994; Richards et al. 2006; Shang et al. 2011).

For X-ray binaries in thermal state, the external magnetic fields
threading the gas from companion stars are advected inward by
thin accretion discs. If the external magnetic field strength is
weaker than the minimal field strength required to drive outflows
from the outer region of the disc, the advection of the field would
be very inefficient. We conjecture that this is the case for X-ray
binaries, and therefore no jets are observed in thermal state. Most
BH-XRBs have low-mass (solar-type) stellar companions. There is
no measurement of magnetic fields in these companions as far as
we are aware. However, it is safe to assume that they have solar-
type magnetic fields of order 1 G. The physics of the magnetic field
enhancement during the mass transfer from the companion star to
the outer radius of the disc is complicated, and no detailed calculation
is available till now. We suggest that during mass transfer, the magnetic field is amplified somewhat. On the other hand, the
required field at $10^7 R_g$ is $\sim 100$ G (see Figure 1). So for most BH-
LMXBs, outflows around $R_{out}$ are unlikely driven from the discs.
Therefore magnetic fields cannot efficiently be advected inward in
most cases.
For Cyg X-1, there is a claimed measurement by Karitskaya et al. (2009): 300 G at the companion star, 500 G at the outer disc boundary. However, the field detected in this star is very near the reliable detection limit of the instrument (Bagnulo et al. 2012), and thus further observations would be desirable. It is well known that Cyg X-1 is unique among BH-XRBs in that the companion is a massive star with $\sim 20 M_\odot$ (Grosz et al. 2011). There is evidence that the mass is transferred through stellar wind instead of Roche lobe overflow in Cyg X-1, which indicates that the size of the disc in this source is likely smaller than that of the Roche lobe of the BH (e.g., Shinohara & Ishimaru 1974; Zdziarski, Kamauta, & Mineshige 2000; Comptat, Fender, & Dubus 2012). A small size of the disc implies higher magnetic field strength at the outer radius of the disc required to drive outflows (see Fig. 1). The field in this source may still be too weak to drive outflows, even if the field of the companion star is indeed as high as claimed.

As noted in Section 1, jets are observed in the low/hard state of X-ray binaries, and it is believed that an ADAF is present in such state. As the luminosity increases, the ADAF is probably truncated at a smaller radius (e.g., Plant et al. 2013; De Marco et al. 2018; Basuk & Zdziarski 2018; Bernardi et al. 2018; Poutanen, Vedelina, & Zdziarski 2018; Tucker et al. 2018), and then connects to a thin disc in the region beyond the transition radius. Steady jets in this state indicate a strong magnetic field in the ADAF surrounding the BH, which implies sufficiently strong field strength at the outer radius of the ADAF. The detailed processes responsible for the field advection in the thin disc between the transition radius and outer disc radius are still unclear. It was suggested that the radial velocity of the hot gas above the disc can be higher than that at the midplane of the thin disk, which can increase the inward field advection efficiency (Lovelace, Rothstein, & Bisnovatyi-Kogan 2006; Beckwith, Hawley, & Krolik 2009; Guillemet & Ogilvie 2011, 2013). In this picture, the weak field of the gas from the companion star is advectioned by the hot corona (hot gas) above the disc in the outer region, and the enhanced magnetic field at the transition radius is further dragged inwards by the inner ADAF. This may lead to a strong magnetic field accelerating jet near the BH even for an ADAF surrounded by a thin disc with corona in the outer region.

Although there is no clear observational evidence for a corona in the outer region of the disc (but also see Gilfanov & Arfiev 2005; Gilfanov 2010), observations are also unable to rule out such an outer corona, because the X-ray emission from the outer region of the corona can be overwhelmed by the inner ADAF radiation (e.g., less than 10 per cent of total gravitational energy is released in the disc region with $R > 100 R g$, and only a small fraction of it is radiated from the corona). Formation of the corona may be related to the disc instability (Dubus, Hamer, & Lasota 2001), which is beyond the scope of this work. In the high/soft state, the spectrum is dominated by the thermal radiation, and a power-law spectral component may also be present but very weak (see, e.g., Fender & Belloni 2012). External magnetic fields cannot be advected inwards efficiently by a thin disc or a very weak corona (if it is indeed present above the disc in thermal state).

Jets are probably accelerated by the magnetic field of the ADAF in low/hard state, and we can estimate how the jets are switched off when the XRB transits from the hard to soft state. The ADAF will transit to a standard thin disc when the mass accretion rate rises above a critical value, the duration of the transition from an ADAF to a thin disc is roughly the cooling timescale of the ADAF, which can be estimated by

$$t_{\text{cool}} \sim \frac{H u}{F_{\text{rad}}},$$

where the radiation flux from the unit surface area of the ADAF, $F_{\text{rad}} = (1 - f_{\text{adv}}) Q_d$ (with $Q_d$ the gravitational energy dissipation rate), and $f_{\text{adv}}$ is the fraction of the dissipated energy advected in the flow. The internal energy of the gas is

$$u = \frac{3}{2} n_i k T_i + \frac{3}{2} \alpha_\kappa k T_c \simeq \frac{3}{2} n_i k T_i,$$

because the internal energy of the electrons is negligible in ADAFs. Equation (11) can be re-written as

$$t_{\text{cool}} \sim \frac{H u}{(1 - f_{\text{adv}}) Q_d} = \frac{3}{2} \alpha_\kappa k T_i,$$

where $\alpha_\kappa = H \Omega_K, f_\sigma = \Omega/\Omega_K$, and we have used

$$Q_d = \frac{1}{2} \sigma T^4 \left( \frac{d \Omega}{d R} \right)^2 \simeq \frac{1}{2} \alpha_\kappa H \Sigma \Omega^2.$$

If the outer thin disc is covered with a hot corona, the cooling timescale is the corona

$$t_{\text{cool}} \sim \frac{H u}{F_{\text{rad}}} = \frac{3 \tau_{\text{cor}} k T_i}{2 \sigma T_{\text{cor}} F_{\text{disc}}}.$$

Thus Equation (15) reduces to

$$t_{\text{cool}} \sim 1.9 \times 10^{-12} f_{\text{cor}}^{-1} \tau_{\text{cor}} m_{\text{n}}^{-1} \tau_r^{-1} \text{ day},$$

where the temperature of ions in the corona is assumed to be around virial temperature, $T_i \sim T_{\text{vir}} = G M m_{\text{n}}/3 k R$ (see Can 2009, and the references therein). The cooling timescale of the corona is around ten seconds at $r \equiv R/R_R = 100$ (or around ten minutes at $r = 10^5$), while it can be ~ 100 days at $r = 10^5$, if typical values of the parameters, $f_{\text{cor}} = 0.1$, $\tau_{\text{cor}} = 0.5$, $m_{\text{n}} = 10$, and $\tau_r = 0.01$ are adopted. This means that the corona in the inner region of the disc is suppressed soon after the hard to soft state transition, while only the corona near the outer edge of the disc may still survive after such a state transition. It is obvious that the external field cannot be dragged inwards efficiently, even if the field can be enhanced to some extent by the outer corona, because a barely thin disc is present in the inner region preventing further field enhancement. As discussed above, the X-ray emission from the outer corona should be very weak, which is consistent with the observational features of the thermal state.

Steady jets are present in low/hard state of XRBs. After such an accretion mode transition, the strong magnetic field formed in the ADAF decays at the magnetic diffusion timescale of the thin disc, which is

$$t_{\text{diff,TD}} \sim \frac{R_{R_R}}{\eta} = \frac{P_{\text{rotd}} R}{\alpha \Omega K H_{\text{TD}}}.$$
diffusion timescale of the field in the thin disc is roughly comparable to the duration of accretion mode transition for a typical value of $P_{\text{in}} \sim 1$. This indicates that strong jets will be switched off in the thermal state soon after the state transition (Cao 2016a). For bright AGNs, the field is dragged inwards by the gas falling onto the BH. The strong field near the BH is formed almost simultaneously with the accretion disc, which implies that jets can be formed soon after the appearance of a bright AGN at the center of a galaxy if the condition for magnetically driven outflows is satisfied.

An ADAF may probably exist relatively close to the BH in hard state (e.g., Plant et al. 2013; De Marco et al. 2013; Basak & Zdziarski 2016; Bernardini et al. 2016; Poutanen, Veledina, & Zdziarski 2018; Tucker et al. 2018), and therefore sufficiently strong field strength at the outer radius of the ADAF is required for jet formation. The hot corona above the thin disc between the transition radius and the outer radius with relative thickness $H/R \sim 1$ may help field advection in this region. However, it seems to be inconsistent with the optically thin corona with $H/R \sim 0.1$ inferred from the observations of XRBs (see Gilfanov & Arefev 2003; Gilfanov 2010, for the details). The corona scenario is also challenged by the observations of radio jets re-appearing almost immediately after transitions from the soft to hard state (Islam & Zdziarski 2018), because the soft-to-hard transitions start in the inner regions extending to the inner stable circular orbits, and the corona is therefore required to be generated instantly, which seems impossible. Thus, it seems that the corona scenario may not work in this case. The actual mechanism of the field advection in the accretion discs in hard state remains unknown, which would be an interesting issue for future investigation.

3 SUMMARY

We have examined the possibility that different physical conditions (magnetic fields in particular) in the outer discs may give rise to qualitatively different phenomenologies of jet productions in AGNs and XRBs. Current observations are consistent with, although do not require, the picture that while relativistic jets are observed only in the low/hard state and intermediate state of XRBs, they are produced in most accretion states of AGNs, including the luminous thermal state. We suggest that this difference arise from the different efficiencies of magnetic field advection in AGN and XRB discs. The production of relativistic jets requires sufficiently strong large-scale magnetic field to build up in the inner disc, and this in turn requires efficient field advection from the outer disc boundary.

For geometrically thin discs that describe the thermal state of accreting BHs, magnetic field advection is inefficient unless the radial drift velocity in the disc is significantly larger than viscous accretion. Magnetically driven outflow is a natural mechanism for the enhanced radial drift, provided that the field strength is larger than a minimum value (see Equation 5).

In XRBs, the thin disc extends to $\sim 10^5 R_g$, and the magnetic field strength of the gas from the companion star is typically lower than the minimum field required to maintain an outflow-driven accretion disc. Therefore magnetic field advection in the thin disc of XRBs is rather inefficient, and no jets are produced from the inner disc in the thermal state.

For radio-loud luminous AGNs, the outer radius of the thin disc is $\sim 10^{3–4} R_g$. The magnetic field in the ISM is substantially enhanced when the gas inflows from the $\sim$ pc scale to the outer radius of the accretion disc. The magnetic field strength at $R_{\text{out}}$ is higher than the minimum strength required to maintain an outflow-driven thin disc. Thus magnetic fields can be efficiently advected in the thin disc, and jets can be accelerated by the strong fields accumulated in the inner discs.

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