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# Is the disc thermal state controlling the Blandford & Znajek/Blandford & Payne jet dichotomy?

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**Abstract.** It is generally assumed that Blandford & Payne jets can carry a significant fraction of the accretion power released in the underlying disc. But this fraction actually strongly depends on the disc aspect ratio $h/r$, hence on the disc thermal properties. In fact, Jet Emitting discs (JEDs) cannot power BP-like jets if they are thicker than $h/r \simeq 0.2$. On the other hand, the power of Blandford & Znajek jets depends mostly on the magnitude of the vertical magnetic field $B_z$. If this magnetic field is dragged in by the accretion flow, then its magnitude depends also on the disc aspect ratio and the BZ jet maximum power is achieved with Magnetically Arrested Discs (MADs).
If the innermost disc regions are geometrically thin or slim, they are in a JED state with both BP and BZ jets launched. It is shown that the BZ jet acts only as a highly relativistic and shinning spine, carrying a tiny fraction of the overall jet power. If the innermost disc regions are geometrically thick, they are in a MAD state where only BZ jets are allowed. We expect quite different jet morphologies in the two cases.

## 1 Introduction

It is now commonly admitted that a large scale vertical magnetic field $B_z$ must be present in accretion discs in order to launch jets that will stay collimated up to observable distances. This holds for both young stars and compact objets (X-ray binaries and extragalactic sources). This vertical magnetic field is anchored onto a rotating object and its role is threefold:
(1) Rotation gives rise to a toroidal magnetic field and leads to a spin down of the rotating object (Lenz's law). The magnetic field extracts thereby angular momentum and rotational energy;
(2) These are then transfered to the plasma that is attached to the field lines: two oppositely directed jets are launched;
(3) The twisted magnetic field structure provides the correct configuration to allow for a self-confinement of these jets, at least for their most central parts.

There are in the literature two kinds of *self-confined* MHD jets that differ only from the nature of the rotating object:

- Blandford & Znajek (hereafter BZ) jets [1], where the magnetic field is expected to be important only at the vicinity of the rotating black hole. Here, the energy and angular momentum are extracted from the black hole's ergosphere.
- Blandford & Payne (hereafter BP) jets [2], where the magnetic field is threading the accretion disc over a large extent. Here, angular momentum and mass are directly extracted from the underlying disc, allowing accretion to proceed.

Although many critical issues remain open, these two mechanisms have been globally confirmed by many authors and numerical magnetohydrodynamic (MHD) simulations. Now, the key issue is of course the origin of this $B_z$ field. Is there a minimum field strength for a jet to be launched? Must this field be distributed over a large radial extent of the accretion disc (as in BP-like process) or field accumulation at the black hole's ergosphere (BZ-like) is enough? Certainly the jet properties (power, jet speed, overall morphology) do depend on this.

## 2 BZ jets and MADs

Since the seminal paper of Blandford & Znajek [1], there have been various attempts of constructing force-free solutions of the electrodynamics of rotating black hole magnetospheres (see e.g. [3] and references therein). But the complexity of the problem was such that no analytical approach has been found satisfactory. When it became feasible, 3D global GRMHD numerical simulations have been conducted and showed indeed the formation of a Poynting flux dominated region above the black hole, powered by its rotational energy ([4–8] to cite only a few).

This occurs as long as some large scale vertical $B_z$ field is introduced in the simulation box. When only a toroidal magnetic field is introduced as initial condition, the Magneto-Rotational Instability (hereafter MRI) is indeed triggered and accretion takes place, but no inner outflowing zone is found [9]. BZ jets require, as proposed by

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their authors, that the disc brings in already some vertical flux. Despite some theoretical expectations, no *large scale* dynamo seems to be at work in these simulations. If some large scale vertical field is not initially put in the computational box, none is generated by the local dynamo. This is probably because of the Keplerian time shear, which forbids the establishment of large correlation lengths required to build a large scale field from small scales.

So, current 3D global simulations show the development of a turbulent accretion flow, the plunging region and, above it, a BZ jet. No powerful BP-type jet is observed launched from the surrounding disc [10, 11]. The power that feeds the BZ jet is satisfactorily following the estimate [1, 12]

$$P_{BZ} \simeq 10^{42} \mathbf{a}^2 \left(\frac{B_z}{10^4 G}\right)^2 M_8^2 \text{ erg /s} \tag{1}$$

where $a$ is the black hole spin, $M_8$ its mass normalized to $10^8 M_\odot$. In this formula, clearly what limits the jet power is the strength of the vertical field $B_z$ present in the plunging region. So the question is: what limits $B_z$?

There have been several analytical attempts to answer this question (see e.g. [13]) but, again, clear answers are directly obtained by numerical experiments. Since the magnetic field is being dragged in by the accretion flow, Tchekhovskoy et al [10] allowed the inner magnetic field to freely increase in time by providing a huge magnetic flux reservoir (ie. much larger than in previous simulations). They found that the field energy increased until it reached a value close to the gravitational energy: the inner disc reached the configuration of a Magnetically Arrested Disc or MAD [14–16]. This is the maximum limit: if more flux is being carried in, it just piles up at the outer edge of the MAD increasing thereby its radius (A. Tchekhovskoy, private communication).

The power of BZ jets therefore depends on the magnetic flux available in accretion discs and their capability to advect and accumulate it around the black hole. And one gets the maximum jet power when MADs are present. Note that the maximum jet speed is not known from these simulations. In the funnel above the hole, the density decreases in time and reaches a floor level that is arbitrarily set (for code stability), hence imposing the maximum Lorentz factor.

However, if the BZ process is the main jet formation mechanism, why do we observe very similar jets also from neutron stars [17]?

## 3 BP jets and JEDs

Since the seminal paper of Blandford & Payne [2], it is well known that magneto-centrifugally driven jets exert a torque on the underlying accretion disc. However, most of the studies devoted to the launching of such jets assumed either a platform[1] or an underlying disc unaffected by the presence of the wind, namely where the dominant torque remains the "viscous" one (as in the Standard Accretion Disc [18], hereafter SAD). Here, we focus instead on Jet Emitting Discs (hereafter JED), which is a class of accretion solutions where all the local disc angular momentum is transported vertically via two jets.

In a series of papers, the full set of dynamical equations describing both the resistive accretion disc and ideal MHD jets were simultaneously solved thanks to a self-similar Ansatz (see eg. [19–21] and references therein). It was shown that once a large scale magnetic field reaches a value smaller than but close to the equipartition value, its torque become dominant with respect to the usual viscous (turbulent) torque and accretion reaches almost sonic speeds. As a consequence, for a given accretion rate $\dot{M}_a$, a JED is much less dense than a SAD. The radial distribution of the magnetic field and the disc accretion rate are a power law, respectively $B_z \propto r^{-\delta}$ and $\dot{M}_a \propto r^{\xi}$, that must be related by

$$\delta = \frac{5}{4} - \frac{\xi}{2} \tag{2}$$

and where the exponent $\xi > 0$ is a measure of the local disc ejection efficiency [22] (note that BP jet solutions [2] where computed with $\xi = 0$). The jet magnetization $\sigma$, ratio of the MHD Poynting flux to the jet kinetic energy flux, writes $\sigma \simeq \xi^{-1}$. Thus, its value has a direct impact on the jet asymptotic speed, as it scales $u_{p,\infty} = V_{K,o}\sqrt{2\lambda - 3}$, where $V_{K,o}$ is the Keplerian speed at the disc midplane and $\lambda \simeq 1 + 1/2\xi$ is the BP magnetic lever arm parameter. The ejection index is found to lie typically around 0.01 for "cold" magnetic surfaces (isothermal [20] or adiabatic [23]) and may reach $\sim$ 0.5 when there is a sudden rise in the plasma temperature at the disc surface layers [24]. Thus, *BP-like jets from JEDs are non or only mildly relativistic*, with a mass loss to accretion rate ratio

$$\frac{2\dot{M}_j}{\dot{M}_a} \simeq \xi \ln \frac{r_{out}}{r_{in}} \tag{3}$$

where $r_{out}$ and $r_{in}$ are respectively the outer and inner radii where the JED is established. Since such a structure requires a vertical field close to equipartition with the thermal pressure [19, 20], the radial extent of a JED relies on the available magnetic flux in the accretion disc. Note that contrary to ADIOS models [25], $\xi$ is computed here and not a free parameter.

Figure (1) shows a close up of several vertical profiles in a thin disc with $\varepsilon = h/r = 0.05$, where $h(r)$ is the local vertical disc scale height. These profiles are quite typical of those found within a JED (see [19] for more details). The flow is accreting at a sonic speed (because of the quite strong magnetic field), with a slightly converging motion (ie $u_z < 0$). Only the disc upper layers are being deviated into the jet. The angular velocity $\Omega$ is slightly sub-keplerian at low altitude and becomes super-Keplerian above, a consequence of the change in sign of the dominant magnetic torque $F_\phi$. The magnetic torque changes its sign roughly at the disc surface. When this occurs, the projection of the Lorentz force along a magnetic surface becomes also positive [20]. The jet is thus accelerated by magnetic means in both directions (azimuthally and in the poloidal plane). However, within the disc, the poloidal

[1] The disc structure is not considered and equations are solved above the disc surface where ideal MHD applies.

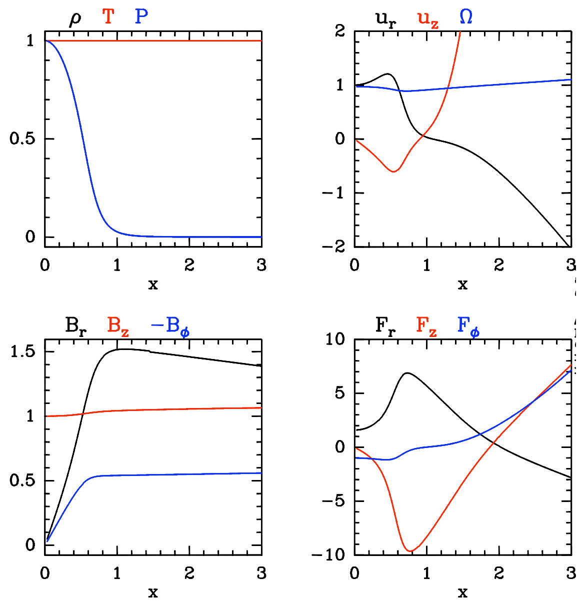


**Figure 1.** Vertical profiles of various quantities in the disc for a representative isothermal cold BP-like solution with $\xi = 0.009$ and a disc aspect ratio $\varepsilon = h/r = 0.05$. The density $\rho$, pressure $P$, temperature $T$ (isothermal) and vertical field $B_z$ are normalized to their midplane values. The poloidal components of the velocity are normalized to $u_o$ (midplane accretion speed), the angular velocity $\Omega$ to the Keplerian one and magnetic field components to $B_o$ (vertical field at equatorial plane). The components of the Lorentz force are normalized to the torque ($|F_\phi|$) at the equatorial plane. This solution goes smoothly at $x = z/h = 1.46$ from the resistive disc to ideal MHD jet and becomes super-slow magnetosonic at $x = 2$.

Lorentz force is acting against the flow. Note also that the disc is being vertically pinched by a strong magnetic compression $F_z < 0$. This is the main reason why the magnetic field cannot be too strong in JEDs. While accretion is favored for stronger fields (larger torque $F_\phi$), the disc vertical balance forbids $B_z$ to be too large. In practice, solutions are able to smoothly cross the slow-magnetosonic point only for $\mu = B_z^2/\mu_o P < 1$ (here $P = \rho c_s^2$ is the plasma thermal pressure, $\rho$ its density and $B_z$ the magnetic field at the disc midplane).

Figure (2) shows the same solution on the whole domain. The first panel shows the poloidal magnetic surface with its characteristic recollimating shape, due to the overwhelming effect of the hoop-stress [20]. The solution is mathematically terminated but, physically, a fast oblique shock would deviate the super-fast magnetosonic flow in the Z-direction. Note that this is intrinsic to the MHD solution. The bottom panels show that non-relativistic BP-like jets are very efficient accelerators, as most of the angular momentum initially stored in the magnetic field is transferred to the plasma, allowing it thereby to reach its maximum speed $u_{p,\infty}$.

Remarkably, *these works are still the only ones available in the literature that compute the disc-jet interrelations by including all dynamical terms*[2]. Since the disc is turbulent, three quantities must be specified [22]: the anomalous magnetic diffusivity in the poloidal $\nu_m$ and toroidal $\nu'_m$ directions and the anomalous viscosity $\nu_v$. This has been done by using the same gaussian vertical profile and specifying the following dimensionless turbulence midplane parameters:

$$\alpha_m = \frac{\nu_m}{V_A h} \qquad \mathcal{P}_m = \frac{\nu_v}{\nu_m} \qquad \chi_m = \frac{\nu_m}{\nu'_m} \tag{4}$$

where $V_A = B_z/\sqrt{\mu_o \rho}$ is the Alfvén speed. In addition to these unavoidably free turbulence parameters, the disc aspect ratio $\varepsilon = h/r$ is also freely specified. Then, the regularity conditions from the smooth crossing of the MHD critical points determine other parameters such as the disc magnetization $\mu$ and the ejection index $\xi$. Note that there is no thin disc approximation done: the JED can be either thin $\varepsilon \ll 1$ or thick $\varepsilon = 1$.

The outcome of this parametric study is that only a tiny interval of JED physical conditions allows for *steady-state, cold* ejection, namely $0.1 < \mu < 1$ (near equipartition field), $0.2 < \alpha_m, \chi_m \sim 1/3$ and $\mathcal{P}_m$ of order unity or less (see [23] for more details). Note that a slight anisotropy of the magnetic diffusivities is required in these stationary models. A larger level of magnetic diffusion in the toroidal direction is necessary so that the magnetic structure has comparable components at the disc surface (namely $B_z^+ \sim B_r^+ \sim -B_\phi^+$), despite the strong anisotropy of the velocity field inside the disc ($u_\phi \gg u_r \gg u_z$). Although these solutions are *exact solutions to the full set of MHD equations*, they suffer of course from two caveats:
(1) There are self-similar (power-laws of the cylindrical radius), so that no radial boundary condition can be im-

[2] Dynamo, disc self-gravity and radiation pressure have been however neglected.

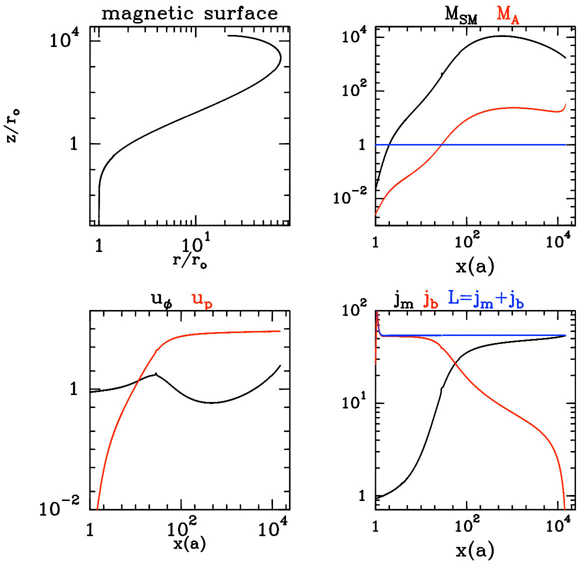


**Figure 2.** Same solution as in Fig.(1), shown in the whole domain. Top left: shape of the poloidal magnetic surface ($a = Cst$), showing the characteristic recollimating property. Top right: slow-magnetosonic $M_{SM}$ and Alfvenic $M_A$ Mach numbers along this surface. The jet becomes super-Alfvenic at $x(a) = z/h(a) = 28.9$. Bottom left: toroidal and poloidal velocities, normalized to the Keplerian speed $V_{K,o}$ at the jet footpoint $r_o$. Specific angular momentum carried by the mass $j_m$, the magnetic field $j_b$ and the jet $L = j_m + j_b$, normalized to $V_{K,o} r_o$.

posed;
(2) Local $\alpha$ prescriptions for the turbulent torque and magnetic field transport have been made.

The first caveat is actually not too serious: while astrophysical jets are definitely not self similar, the underlying physics revealed by these exact solutions remains valid, as far as the jet launching is concerned. When it comes to jet propagation and asymptotic behavior, then the mathematical bias comes into play [20, 21]. The second caveat, namely the use of an $\alpha$-prescription, is more problematic. It assumes that a full 3D magnetized turbulence is established but that, nevertheless, the effective anomalous transport of magnetic field (diffusivities) and angular momentum (viscosity) remain local (ie, involving scales smaller than the local disc scale height $h$). This is far from being obvious, especially in discs with strong magnetic fields where MRI itself seems to be actually the jet launching mechanism [26].

In a disc with no mass loss, the energy budget is simply $P_{acc} = P_{rad} + P_{adv}$, where the released accretion power is shared between the radiation losses $P_{rad}$ (disc luminosity) and the advected power $P_{adv}$ carried in by the accreting flow and feeding the black hole. Since $P_{adv}/P_{rad} \sim \varepsilon^2$, geometrically thin (cold) discs are quite dissipative and luminous [18] whereas geometrically thick (warm) discs are non luminous [27, 28]. It is well known that, for a given accretion rate and at a given radius, the thermal equilibrium of non-ejecting discs has basically three branches: an optically thick cold branch, an optically thin warm branch and an intermediate, thermally unstable branch (see [29] and references therein). The same has been shown to hold for JEDs [30]. However, the energy budget in JEDs writes

$$P_{acc} = 2P_{rad} + P_{adv} + 2P_{jet} \tag{5}$$

since jets carry away kinetic, thermal and magnetic energy. This total jet power can be written

$$P_{BP} = 2P_{jet} = b\,P_{acc} = b\,\frac{GM\dot{M}_a}{2r_i} \tag{6}$$

and the question is how does the fraction $b$ depend on the disc parameters ?

This is shown in Fig. (3). It appears that BP-like jet power strongly depends on the underlying disc aspect ratio $\varepsilon$, regardless of $\xi$. The fraction $b$ goes from roughly unity (dissipationless thin discs) to roughly 0.3-0.5 for slim discs with $\varepsilon = 0.2$. For thicker discs, no steady-state cold BP solutions has been found. This is contrary to the common sense that states that ADAF-like discs would give rise to collimated jets [31]. Of course, thick discs are warm so that thermal driving can help/supersede magnetic driving. But in any case, the jet power would be less than that from thinner discs. This important result can be easily understood. The jet power is mainly due to the MHD Poynting flux which, for each magnetic surface, scales as $\Omega_* r B_\phi B_p$, where $\Omega_*$ is the angular velocity of the surface (an MHD invariant). As shown in Fig. (3), it decreases with $\varepsilon$, explaining the decrease in $b$. Now, $\Omega_* \simeq \Omega^+$ the angular velocity of the plasma at the disc surface (in ideal MHD regime). Thus, the decrease in $\Omega_*$ is just the consequence of the decrease of the plasma angular velocity $\Omega$, which occurs when the disc thickness increases (Ferreira et al, to be submitted).

## 4 BP versus BZ jets: JEDs vs MADs ?

Since the magnetic field in BZ jets must be brought in by the outer accretion disc, there is *a priori* no reason for forbidding BP jets to be launched as well from the latter. This

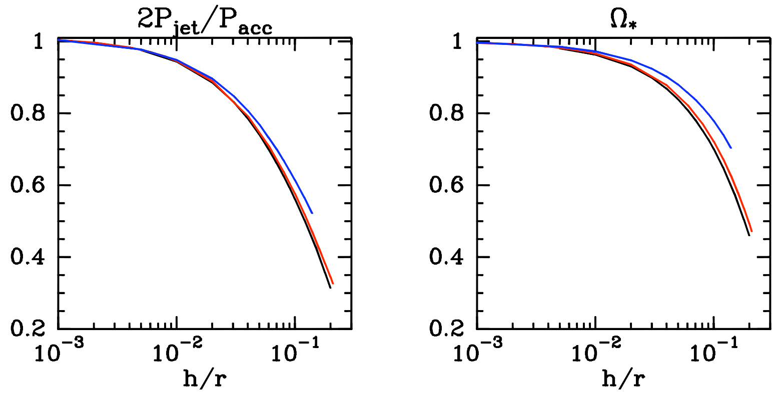


**Figure 3.** Left: Total power carried in by BP-like jets normalized to the released accretion power as a function of the disc aspect ratio $h/r$. Right: Angular velocity of the magnetic surfaces $\Omega_*$ normalized to the midplane Keplerian value as function of $h/r$. The blue (top) curves are for $\xi = 0.07$, the red (middle) for $\xi = 0.01$ and the black (bottom) for $\xi = 0.005$ (Ferreira et al, to be submitted).

allows a direct comparison between the two jet formation mechanisms. Indeed, as seen before the power of cold BP jets is directly controlled by the disc accretion rate, once the threshold in the disc magnetization $\mu$ has been reached. But on the other hand, the power of BZ jets depends on the magnetic field strength in the plunging region which is of the order of the magnetic field in the innermost disc orbit. Expressing this field as

$$\frac{B_z^2}{\mu_o} = \mu P = \frac{\mu}{m_s}\frac{\dot{M}_a\Omega_K}{4\pi r} \quad (7)$$

where $m_s = u_o/C_s$ around unity is the accretion sonic Mach number in JEDs, one gets

$$\frac{P_{BZ}}{P_{BP}} \simeq 3\,10^{-3}\,\frac{a^2}{b}\,\frac{\mu}{m_s}\left(\frac{r_i}{r_g}\right)^{-3/2} \quad (8)$$

For typical values (and most favorable situation) $a \sim m_s \sim \mu \sim 1$, $r_i \sim r_g$, one obtains a fraction $P_{BZ}/P_{BP} \sim 3\,10^{-3}/b$ which is mainly dependent on $b$. As seen before, as long as a JED is established, $b$ ranges from unity for a thin disc ($\varepsilon = h/r \ll 1$) to a minimum value of 0.3-0.5 for a slim disc ($\varepsilon \simeq 0.2$). In that case, even if BZ jets are launched above the plunging region (and there is no reason why they should not be), they remain an epiphenomenon in terms of power.

On the other hand, if the disc becomes thicker with $0.3 < h/r \sim 1$ and with $\mu \sim 1$, it is in a typical MAD configuration with no BP jets at all (although a massive thermally-driven outflow is always possible). It appears therefore that the disc thermal state is actually the main parameter controlling the kind of jets the disc can afford:

- If the innermost regions are geometrically thin or slim, they are in a JED state with both BP and BZ jets launched. But the BZ jet acts only as a highly relativistic and shinning spine, carrying a tiny fraction of the overall jet power.
- If the innermost regions are geometrically thick, they are in a MAD state where only BZ jets are allowed.

Note that while the propagation and collimation properties of BP jets have been already extensively studied (albeit in the absence of the relativistic spine), less is known about relativistic BZ jets. BP jets are non-relativistic and achieve a very good collimation. It has been shown that recollimation towards the jet axis is even a characteristic feature of such jets [20]. The presence of the spine may provide however a radial pressure support allowing almost cylindrical jets. On the other hand, the huge electric field that develops in relativistic jets balances the toroidal field responsible for the hoop stress and leads to a much less collimation degree. It is therefore quite natural to expect very different morphologies and power in jets from JEDs or from MADs.

Note finally that both disc configurations require a vertical $B_z$ field close to equipartition $\mu \sim 1$. This field is probably arising from magnetic flux accumulation due to a predominant advection with respect to field diffusion. This field advection is itself strongly dependent on the disc aspect ratio. A simple order of magnitude argument can help to understand that. As long as the field does not lead to significant ejection from the disc surface, it can be grossly described by a potential field [32]. In such a field, the steep radial decrease of $B_z$ (signature of field advection) goes along with a large inclination of the field lines. This translates into a radial field at the disc surface $B_r^+$ comparable to the vertical field $B_z$. If field diffusion is due to a turbulent magnetic diffusivity $\nu_m$, then $B_r^+/B_z \sim 1$ requires a magnetic Reynolds number $\mathcal{R}_m = ru_o/\nu_m \sim r/h$. Now, in a turbulent accretion disc described by an anomalous viscosity $\nu_v$, angular momentum transport by turbulence leads to $\mathcal{R}_e = ru_o/\nu_v \sim 1$. Therefore, strongly inclined fields would be possible only for a magnetic Prandtl number $\mathcal{P}_m = \nu_v/\nu_m \sim r/h$ [32]. However, our current understanding of (and conventional wisdom on) MHD turbulence favors $\mathcal{P}_m$ around unity [33, 34]. Thus, according to this simple argument, any large scale $B_z$ field would just diffuse outwardly in a thin accretion disc. MADs would therefore be achieved only if the whole accretion disc is thick (or slim). JEDs would maintain their own magnetic field (since they have $\mathcal{R}_m \sim r/h$ [19]) even if they are thin, but how such a field could be present at first place must rely on the magnetic history of each particular object (initial condition).

## 5 Concluding remarks

(1) Since the seminal paper of Blandford & Payne [2], there have been a lot of studies devoted to the launching of jets from near Keplerian accretion discs. In a series of papers, the full set of MHD equations describing self-consistently the transition from the resistive MHD accretion flow to the ideal MHD jet have been solved (see e.g. [20, 21]). While well known in the star formation community, these works remain poorly known in the present community.

(2) BP jets deeply affect the underlying disc structure as they carry away the disc angular momentum. This new class of discs, with a large scale magnetic field close to equipartition, has been labelled JEDs. It is shown here that JEDs cannot be too geometrically thick. Optically thin discs with an aspect ratio $\varepsilon = h/r > 0.2$ are unable to maintain a steady outflow structure. *ADAF-like solutions [27, 28] cannot drive powerful self-confined jets.* We therefore propose that discs switch instead to the MAD configuration. This analytical result provides a natural explanation for the non existence of powerful self-confined BP-like ejection in 3D GRMHD numerical simulations.

(3) Blandford & Znajek jets are probably present (though affected by radiative effects) but are energetically an epiphenomenon whenever BP jets are launched from a JED. This inner BZ jet would provide a relativistic and shining spine to the outer non or mildly relativistic BP jet. This situation is very much alike the two-flow model [35–37]. One challenging question to observers is therefore to probe the ratio $P_{jets}/P_{rad}$, where $P_{rad}$ is the disc luminosity (see for instance [30] for Cygnus X-1).

(4) How is $B_z$ distributed in accretion discs is strongly dependent on the interplay between advection by the accretion flow and turbulent diffusion. Whether or not the inner regions of discs resemble a MAD or a JED is therefore strongly dependent on the magnetic field history. This offers a possible scenario for explaining the long term variability and hysteresis cycles seen in X-ray Binaries [38, 39].

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