Region of magnetic dominance near a rotating black hole

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Abstract

Processes of collimation of electrically charged particles near a rotating black hole are discussed. It is assumed that the black hole is immersed in a weak magnetic field aligned with rotation axis. This situation is relevant for understanding pre-collimation of astrophysical jets. Magnetic field affects motion of material and restricts validity of various scenarios which adopt the test-particle (cold plasma) approximation. A simplified criterion which estimates relevance of such approximation is discussed in connection with the mechanism of the dissipative collimation, as proposed by de Felice & Curir [19].

Keywords: Galaxies: jets — Galaxies: nuclei — Black hole physics

1 INTRODUCTION

Numerous observations confirm that collimated outflows of matter are rather generic phenomenon connected with certain types of astronomical objects [27]. These jets exist on different length-scales and they are associated with various types of sources ranging from stars to galactic nuclei—i.e. over nine orders of magnitude in the mass of the central source. The origin of jets is probably diverse but they share common properties. For example, it has been speculated about analogies between electromagnetic processes which accelerate particles near pulsars [5,39] versus processes in magnetospheres of supermassive black holes in active galactic nuclei (AGN) [10,42]. AGNs with jets show many diverse properties, but it is tempting to link the differences, at least partially, to orientation of these objects with respect to the observer. The interest in this subject has been amplified by recent discoveries of relativistic outflows in our Galaxy [26,40,59] which have their well-known counterpart in extragalactic superluminal jets [65]. Unifying schemes have been proposed for cosmic sources with jets. Useful review articles summarizing our knowledge can be found in the literature, both for stellar-scale objects in the Galaxy [45] and for extragalactic jets [4,60].

Extragalactic jets are presumably formed in the innermost regions of the source (within a few or a few tens of gravitational radii, $R_g$, from the center) and they emanate outwards along rotation axis of the central object. We assume the model with a compact rotating object in the center. Gravitational field of the central object is approximated by the Kerr metric while self-gravity of the jet material and accretion disk is neglected. It has been widely recognized that large-scale outflows can be adequately described in the magnetohydrodynamic regime but situation very close to the horizon is less understood. The initial phase of the jet formation is sometimes called pre-collimation, in distinction to the processes of successive collimation which operate in more distant regions.

Several mechanisms of the jet pre-collimation have been proposed. Mag-
Magnetic fields play most probably a major role in focusing and maintaining collimated outflows on their course. Numerous authors have studied collimation within the hydromagnetic framework [9,12,13,37,44]. It has been shown that toroidal component of the magnetic field is maintained by rotation of the accretion disk and enhances collimation [61]. We were interested in the contribution of the Kerr geometry to the resulting collimation of jets, and it appears quite natural to presume that our attention can be restricted to the region within a few tens of gravitational radii from the center. The inner region of the object is crucial for the theory of jet formation but it remains beyond current observational capabilities which are of the order of $(10^2–10^3)R_g$ for extragalactic sources (the best linear resolution, approximately $0.01\text{ pc}$, has been achieved with the radio jet in the galaxy 3C 274; [28]).

Abramowicz & Piran [1] and Sikora & Wilson [57] consider collimation inside a funnel of a luminous thick accretion disk. Material of the jet is in mutual interaction with the disk radiation which determines its terminal speed [48]. Nowadays, the idea of extremely thick disks with very narrow funnels and highly super-Eddington luminosity (e.g., [21]) is not favoured because these models suffer from several inconsistencies but the general scheme of jets flowing along the disk axis remains viable with more sophisticated models of accretion disks. The model has been advanced by detailed quantitative calculations of acceleration/deceleration of jets due to radiation pressure and losses due to cooling, both within the framework of the hydrodynamic [16,36,47] and the test-particle approximation [38,56,57,62]. These calculations impose strong limitations on radiatively driven jets because their material cannot reach Lorentz factors much greater than unity. Hydromagnetic scenario is thus currently favoured [3,44].

The above-mentioned schemes consider a massive compact object to be present in the center of the source but the Kerr geometry and the effects of general relativity are not crucial for their function. On the other hand, de Felice & Curir [19] and de Felice & Carlotto [18] have explored a special family of geodesics spiralling along the axis of the Kerr black hole (vortical geodesics; see [17,20]) and determined constraints on the rate of change of energy and angular momentum of outflowing material that may result in collimation. They did find collimation but the physical nature of dissipative processes that cause the loss of particle energy and angular momentum remains unclear. It is the aim of the present contribution to advance the latter model by systematic discussion of the parameter space of particle trajectories. We want to determine, by a simplified but systematic approach, circumstances under which the above-mentioned scheme could be relevant (rather than build up our own model). In other words, we ask whether specific features of motion in Kerr geometry are relevant for pre-collimation of astrophysical jets. Indeed, the original motivation to deal with this problem was a suspicion that even relatively weak magnetic fields impose strong limitations upon the model. (This fact has been quoted and applied in numerous works; we wish to discuss the problem in a more systematic way with the Kerr geometry.) Our arguments could be ap-
plied also to other models based on the properties of the geodesic motion [7], spin-curvature coupling (another purely general relativistic effect, [54]), and influence of magnetic fields which affect the spacetime geometry [30]. The latter process requires dimensionless product $\beta$ of magnetic intensity and the mass of the central object to be of the order of unity, which is value much higher than $\beta = 5 \times 10^{-8} B_4 M_8 \approx 10^{-8}$, where $B_4 \equiv B/(10^4 \text{ gauss})$ and $M_8 \equiv M/(10^8 M_\odot)$ denote typical values relevant for the innermost magnetosphere in AGNs. Direct interaction of the jet material with external electromagnetic fields appears more important. (Geometric units will be used hereafter, $c = G = 1$; time, mass, electric charge and [magnetic intensity]$^{-1}$ have dimension of length, i.e. cm. Next, quantities with dimension of length will be expressed in units of $M$.)

Structure of this text is as follows: First, equations for generalized energy and generalized angular momentum of electrically charged particles are given. Dimensionless parameters characterizing, locally, electromagnetic effects upon the test-particle motion are then defined and evaluated. It should be noted that in the present contribution we do not address the problem of extraction of rotational energy from a magnetized black hole which also relies on properties of the Kerr spacetime [25,43,58,64], neither we discuss purely electromagnetic collimation due to toroidal magnetic fields.

2 CHARACTERISTIC LENGTH-SCALE

2.1 Details of the model

We assumed that a weak magnetic field is generated far from the black hole, outside the region where motion of matter is studied. The spacetime is described by the Kerr metric with an asymptotically uniform magnetic test field [63]. This solution reflects the large-scale field which is generated far from the black hole. We further assumed that the field is aligned with rotation axis because non-aligned fields exert torque on the black hole, so that its rotation slows down and the black hole gets aligned with the field [33,49,51]. Typical time-scale for the black-hole alignment due to electromagnetic torques is proportional to $\beta^{-2}$ and rather long (in physical units, $\tau/(10^{10} \text{ yr}) \approx M_8^{-1} B_4^{-2}$) but tidal effects enhance alignment and decrease $\tau$ [34,52].

Structure of an asymptotically uniform magnetic field is simple and collimation by Kerr geometry is presumably easier to notice [53]. (As mentioned above, toroidal fields, $B_\phi$, contribute to purely electromagnetic collimation and to the total power-output from a black hole [46]; in time-dependent calculations, $B_\phi = 0$ is often taken as an initial configuration of the magnetic field [44]). Jets are formed near a black hole but the material which forms jets is an open question (see, e.g., [3,35] for general issues related to formation of jets). In the case of electron-positron plasma, the specific electric charge of individual particles is $|\tilde{q}| \approx 2 \times 10^{21}$ (elementary charge $q$ and mass of electron $m$).
will be assumed in numerical estimates, \( \tilde{q} \equiv q/m \). Dimensionless parameter \( \epsilon \equiv |\beta \tilde{q}| \) determines motion of charged particles.

Trajectory of individual particles is determined by Larmor gyrations around magnetic lines of force (Larmor radius \( r_L \)) and the drift motion across the field-lines (e.g., [2]). Motion of electrically charged particles near a black hole has been studied by numerous authors \([8,15,22,55]\). Prasanna \([50]\) and Karas & Vokrouhlický \([30]\) show examples of test-particle trajectories near magnetized black holes. Now we are interested in the bulk motion of the material rather than individual trajectories which can be very complicated. It is thus useful to disregard local gyrations and accept the guiding-center approximation. Damour et al. \([14]\) determined shape of the plasma flow-lines near a weakly magnetized Kerr black hole in the guiding-center approximation. Discussion has been generalized to the case of an electrically charged rotating black hole by Hanni & Valdarnini \([24]\) (with a weak magnetic field), and Karas & Vokrouhlický \([31]\) (an exact solution of the Einstein-Maxwell equations with an arbitrarily strong magnetic field). These authors verified that plasma moves along rotation axis and they concluded that asymptotically uniform magnetic field evidently contributes to collimation.

The situation becomes much less understood when mechanism proposed by de Felice & Curir \([19]\) (motion along vortical geodesics plus tiny, yet undetermined dissipation of energy and angular momentum) is taken into account. One can, however, estimate relevance of this scheme by calculating the relative change of orbital parameters due to magnetic field.

\section*{2.2 Rate of change of orbital parameters}

In this section, we will estimate the rate of change of orbital parameters (energy and angular momentum with respect to rotation axis) of individual particles and integrate the rate over particle distribution. This approach gives us a \textit{local criterion} of importance of electromagnetic forces.

The model is described by an axisymmetric stationary spacetime metric \( g_{\mu \nu} \) \((\mu, \nu = 0, \ldots, 3)\). Electromagnetic test field is characterized by the tensor of electromagnetic field, and by corresponding four-potential: \( F_{\mu \nu} \equiv A_{\nu,\mu} - A_{\mu,\nu} \). It should be emphasized that we do not have to impose further restrictions upon gravitational and electromagnetic fields, apart from the above mentioned assumption about axial symmetry and stationarity. To be specific, however, we will consider the Kerr metric \([41]\) with an aligned asymptotically uniform magnetic field. Structure of the magnetic field has been explored by several authors (e.g., \([23,49]\) in the case of aligned fields, and \([6,32,29]\) in the case of inclined fields). In Boyer-Lindquist coordinates, \( x^\mu \equiv \{t, r, \theta, \phi\} \),

\begin{align*}
A_t &= \beta a \left[ r \Sigma^{-1} \left( 1 + \cos^2 \theta \right) - 1 \right], \quad (1) \\
A_\phi &= \beta \sin^2 \theta \left[ \frac{1}{2} \left( r^2 + a^2 \right) - a^2 r \Sigma^{-1} \left( 1 + \cos^2 \theta \right) \right]. \quad (2)
\end{align*}
Here, $\Sigma \equiv r^2 + a^2 \cos^2 \theta$. Each timelike geodesic (four-momentum $p^\mu \equiv mu^\mu$) is associated with two conserved quantities—specific energy

$$\varepsilon_0 \equiv -u_t|_{q=0},$$

and specific angular momentum with respect to the symmetry axis

$$\lambda_0 \equiv u_\phi|_{q=0}.$$

Four-momentum along a trajectory of an electrically charged particle is determined by equation

$$\frac{Du^\mu}{D\tau} = \tilde{q} F^\mu_\nu u^\nu,$$

and corresponding conserved quantities are:

$$\varepsilon \equiv -(u_t + \tilde{q}A_t), \quad \lambda \equiv u_\phi + \tilde{q}A_\phi$$

(generalized energy and angular momentum component, respectively).

Any scenario which explains collimation of particles in terms of curvature effects acting upon free particles (as in Bičák, Šemerák & Hadrava [7]) or particles that are slightly perturbed by dissipative forces (as in de Felice et al. [18,19]) turns out to be astrophysically irrelevant when electromagnetic forces strongly affect motion of particles. In order to introduce a quantitative criterion for electromagnetic effects, one can define two parameters, $\delta\varepsilon(r, \theta; p^\mu)$ and $\delta\lambda(r, \theta; p^\mu)$, which characterize the relative change of $\varepsilon_0$ and $\lambda_0$:

$$1 - \varepsilon_0|_{x^\mu + u^\mu d\tau}^{x^\mu} = \tilde{q} \Lambda \frac{F^\mu_r u^r + F^\mu_\theta u^\theta}{\tilde{q}A_t + \varepsilon} d\sigma \equiv \delta\varepsilon d\sigma,$$

$$1 - \lambda_0|_{x^\mu + u^\mu d\tau}^{x^\mu} = \tilde{q} \Lambda \frac{F^\mu_r u^r + F^\mu_\phi u^\phi}{\lambda - \tilde{q}A_\phi} d\sigma \equiv \delta\lambda d\sigma.$$

Here, $d\sigma$ denotes interval of proper time scaled with the light-crossing time across the characteristic length-scale $\Lambda$: $d\sigma \equiv d\tau/\Lambda$.

It is further postulated that $\Lambda \propto r_L = \Gamma v\tilde{q}^{-1}\beta^{-1}$ (with $\Gamma = 1/\sqrt{1 - v^2} \approx 10$ denoting the Lorentz factor, $v$ velocity with respect to the locally non-rotating frame). Hence, $\langle \delta\varepsilon \rangle$ and $\langle \delta\lambda \rangle$ become independent of magnetic field strength. This fact is understandable: the Larmor radius decreases with $\beta$ increasing, which means that the characteristic length along which the change of parameters is determined in eqs. (7)–(8) decreases as well. Such a choice of $\Lambda$ is well-founded (for our purpose of an order-of-magnitude criterion) because geodesic trajectory certainly cannot approximate a real trajectory of a charged particle on a scale greater then $r_L$. (On the other hand, it is easy to evaluate $\langle \delta\varepsilon \rangle$, $\langle \delta\lambda \rangle$ also for a different choice of $\Lambda$; $\beta$ then becomes another free parameter, however.) Considering the collimation processes acting on length-scales
Fig. 1. Graphs of $\langle \delta\varepsilon \rangle$ [panels (a), (c)] and $\langle \delta\lambda \rangle$ [panels (b), (d)] as a function of radius $x \equiv 1 - R_g/r$ ($R_g = 1 + \sqrt{1 - a^2}, 0 < x < 1$) and $\theta$ ($0 < \theta < \pi$). Upper panels, (a)–(b), show mean values taken over all trajectories with $\Gamma \leq \Gamma_{\text{max}}$ while lower panels, (c)–(d), deal with vortical trajectories only (notice a narrow gap near $\theta = \pi/2$: vortical trajectories do not cross equatorial plane). Here, $a = 1, 0 \lesssim \Gamma \lesssim 3, s = 0$. See the text for details.

Fig. 2. As in Fig. 1 but for $0 \lesssim \Gamma \lesssim 2, s = 2$.

of a few $R_g$ (as in de Felice & Curir [19]), $\Lambda$ should be comparable with or greater than $R_g$; this is further restriction on the upper limit for $\beta$.

Both parameters, $\delta\varepsilon$ and $\delta\lambda$, are defined locally (i.e. $r, \theta$ given) and they also depend on particle’s $p^\mu$. We study the region outside the black-hole horizon by averaging over distribution of particles in the momentum space. We define

$$\langle \delta\varepsilon \rangle^2 \equiv \frac{1}{4\pi} \int_{4\pi} d\Omega \int_{\Gamma_{\text{min}}}^{\Gamma_{\text{max}}} d\Gamma n(\Gamma) \delta\varepsilon^2, \quad (9)$$

and analogously

$$\langle \delta\lambda \rangle^2 \equiv \frac{1}{4\pi} \int_{4\pi} d\Omega \int_{\Gamma_{\text{min}}}^{\Gamma_{\text{max}}} d\Gamma n(\Gamma) \delta\lambda^2. \quad (10)$$

Integration is taken over the particle distribution in energy, $n(\Gamma)$, and over all directions of their local velocity. Values of $\langle \delta\varepsilon \rangle \gtrsim 1, \langle \delta\lambda \rangle \gtrsim 1$ mean that approximation of geodesic motion with a small perturbation is inappropriate, while values of both parameters much less than unity, simultaneously with $\Lambda \gtrsim R_g$, indicate that this approximation might be meaningful.

3 RESULTS

We evaluated parameters $\langle \delta\varepsilon \rangle$ and $\langle \delta\lambda \rangle$ for the Kerr metric and electromagnetic test field (1)–(2). Equations (3)–(4) can be written in the explicit form:

$$\varepsilon_0 = \sqrt{\Sigma \Delta A^{-1}} \Gamma + \omega \lambda_0, \quad (11)$$

$$\lambda_0 = \sqrt{A \Sigma^{-1}} v^\phi \sin^2 \theta, \quad (12)$$

where $\Delta = r^2 - 2r + a^2, A = (r^2 + a^2)^2 - \Delta a^2 \sin^2 \theta, \omega = 2arA^{-1}$ are functions from the Kerr metric in standard notation [41]; $v^\phi$ is azimuthal component of the speed of particle with respect to LNRF. Energy distribution of particles was approximated by a power-law: $n(\Gamma) \propto \Gamma^{-s}$ in a restricted interval of
energy ($\Gamma_{\text{max}} \approx 20$, $0 \lesssim s \lesssim 2$; power-law energy distribution is motivated by astrophysically relevant situations).

Figures 1–2 illustrate our results for an isotropic distribution of particles with respect to LNRF. We assumed $\Lambda \approx r_L$ (characteristic length) for definiteness. In these two figures, $\langle \delta \varepsilon \rangle \ll 1$, $\langle \delta \lambda \rangle \ll 1$ [panels (a) and (b)], and one concludes that approximation of the close-to-geodesic motion may be relevant for modelling the jet precollimation in the given region of $(r, \theta)$. We have also examined separately the case of vortical trajectories which play a crucial role in discussion of de Felice & Curir [19] [panels (c) and (d)]. In the latter case, the assumption about isotropic distribution is supplemented by specific conditions for vortical trajectories:

\[
\hat{\Gamma} > 0, \quad |L| \leq a^2 \hat{\Gamma}, \quad L < \lambda_0^2 \leq \frac{L + a^2 \hat{\Gamma}}{4a^2 \hat{\Gamma}}
\]  

($L$ denotes the fourth constant of the Kerr metric, $\hat{\Gamma} \equiv \varepsilon_0^2 - 1$). Regions in the $(r, \theta)$ plane with $\langle \delta \varepsilon \rangle \gtrsim 1$, $\langle \delta \lambda \rangle \gtrsim 1$ have been excluded from Figures for clarity (particularly, close to the horizon and rotation axis).

Figures 1–2 represent a typical situation. Further illustrations in which the parameter space is investigated systematically can be found on World-Wide Web.\(^1\)

4 CONCLUSION

We derived an order-of-magnitude criterion for possible relevance of those models of the jet pre-collimation (at distances of few $R_g$ from the black hole) which are based upon test-particle approximation: $\langle \delta \varepsilon \rangle^2$, $\langle \delta \lambda \rangle^2 \ll 1$ (independently of $B$), and $\Lambda \gtrsim R_g$ (depends on the value of $B$: $\Lambda \propto B^{-1}$). Our estimates employ characteristic length-scales which can be shorter when collisions of particles in plasma are important or if the magnetic field is dominated by a short-scale chaotic component. This means the region of magnetic dominance can be larger than our criterion indicates. Although only rough estimates of strength of the magnetic field are currently available, it appears that the guiding-center approximation is the most relevant approach among the models based on test-particle motion. One should note that general relativity effects remain important for motion of material not only because of the presence of the black hole in the center but also because the structure of electromagnetic field itself is affected by strong gravity. It is also worth noticing that explicit formulae for non-aligned test fields are known and can be studied in a similar way.

Our present discussion has been restricted by assumptions about the large-scale structure of the magnetic field, isotropic distribution of particle velocities in LNRF, and power-law distribution of their energy. We do not expect our

\(^1\)http://otokar.troja.mff.cuni.cz/user/karas/au_www/karas/papers.htm
results to be sensitive to these assumptions unless the particle distribution is very anisotropic; it should be repeated that farther from the center hydromagnetic description is appropriate.

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