Magnetic fields in thin accretion disks around black holes

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ABSTRACT. We study magnetic field topologies and magnetic field strength in a thin accretion disk around a rotating black hole. The magnetic field is assumed to enter the disk at the outer edge and is amplified in the accretion process by differential rotation. This scenario seems likely for AGN, where magnetized plasma from a molecular torus flows into an inner accretion disk.
In nonideal Newtonian magnetohydrodynamics the presence of a rotating central black hole is taken into account by using the form of the Keplerian rotation law valid for Kerr geometry outside the marginally stable orbit and a boundary layer, caused by the frame dragging effect, within. In the unstable region close to the hole the turbulent timescale is much larger than the accretion timescale so that the effective magnetic diffusivity, which is large in the disk due to turbulence, is low. As a consequence the poloidal magnetic field lines cross the horizon almost radially in agreement with [1].
We present stationary axisymmetric solutions of the induction equation for vanishing α-effect. Dipolar field structures are most favourable for the generation of fast jets and can effectively contribute to the heating of a corona or some X-ray source. Quadrupolar field structures may also drive jets, however the field strength is considerably lower and therefore also the energy that can be supplied into a corona or a jet.

1. The magnetic fields

In axisymmetry, lines of constant poloidal flux $\Psi(R,z) = \int_F \mathbf{B}_\mathrm{p}\mathbf{n}dF$ are field lines of the poloidal magnetic field $\mathbf{B}_\mathrm{p} = B_R\mathbf{e}_R + B_z\mathbf{e}_z$. In analogy, lines of constant integral poloidal current $I = -\int_F \mathbf{j}_\mathrm{p}\mathbf{n}dF = -\frac{c}{2}RB_\phi$ are flux lines of the poloidal current density $\mathbf{j}_\mathrm{p}$. Therefore our solutions are represented by the two flux functions $\Psi(R,z)$ and $T(R,z) = RB_\phi(R,z) = -2I(R,z)/c$.

1.1 STATIONARY SOLUTIONS

The magnetic field in the disk is determined by Maxwell's equations supplemented by Ohm's law. The equations can be combined to two scalar equations, which describe advection and diffusion of the poloidal flux Ψ and RB_ϕ respectively, as well as the amplification of RB_ϕ by differential rotation of the disk plasma (Ω-effect). We give the equations for the stationary case in the thin disk approximation

$$\frac{\partial\Psi}{\partial R} + D(R)\frac{\partial^2\Psi}{\partial\zeta^2} = 0 \tag{1.a}$$

$$\frac{\partial}{\partial R}\left[\left(u + \frac{\eta}{R}\right)B_\phi\right] + \frac{\partial\eta}{\partial R}\frac{\partial B_\phi}{\partial R} + u(R)D(R)\frac{\partial^2 B_\phi}{\partial\zeta^2} = \frac{d\Omega}{dR}\frac{1}{H(R)}\frac{\partial\Psi}{\partial\zeta}\,. \tag{1.b}$$

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Here $\zeta = z/H(R)$ is the dimensionless scaleheight of the disk, $D(R)$ is the diffusion coefficient, $u(R)$ is the accretion velocity and $\eta(R)$ is the magnetic diffusivity. Separating radial and vertical parts of Ψ and B_ϕ, respectively, yields ordinary first order differential equations for the radial parts and $\chi(\zeta) = a\, sin(k\,\zeta) + b\, cos(k\,\zeta)$ in vertical direction. We study the special cases of even ($b = 0$) or odd ($a = 0$) symmetry of $\Psi(R, z)$ (B_ϕ has opposite symmetry).

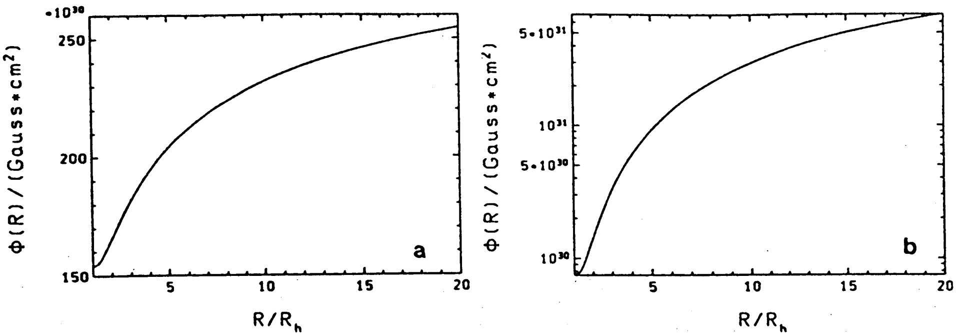

Fig. 1. Radial dependence $\Phi(R)$ of the poloidal flux $\Psi(R, z)$ for a) dipolar and b) quadrupolar field topology; $R_h = R_{horizon}$. Flux at outer edge ($1000\ R_h$) $\Psi_{out} = 3 \times 10^{32}$ Gauss cm^2.

The amount of poloidal flux and current that leave the disk surface are determined by the separation parameter k. For a physically motivated choice of k (see [2]) the flux of poloidal field lines into a magnetosphere above the inner region of the disk would be much higher for even symmetry of $\chi(z)$ (corresponding to dipolar field topology) than for odd symmetry of $\chi(z)$ (quadrupole) (Fig. 1). For a given wind rate of a jet formed in the magnetosphere, the magnetization in the dipole would be much higher as well and thus the final velocity in the jet [3].

For a jet to be produced by centrifugally accelerating particles along magnetic field lines, the disk solution has to smoothly fit to a wind solution. Figure 2 shows the calculated dipole solution for B_p and j_p in combination with a schematic view of a possible jet solution. In the disk solution itself we find $j_p || B_p$ at the disk surface, so that a jet could start of as a force-free configuration. The shape of the current field lines in the disk allow the current to flow out in the jet envelope and to come back along the jet axis. The current can be closed in the disk at one end and somewhere in the jet at the other end (in the hot spot e.g.). Furthermore, our Newtonian solution suggests that the current can be closed in a region where relativistic effects are important. This result gives support to the idea of Blandford and Znajek [4] to extract rotational energy from the black hole by some kind of magnetic braking.

The quadrupole topology is not suitable for the production of a force-free jet (Fig. 3 a). Moreover, since the currents turn quite far away from the hole, the

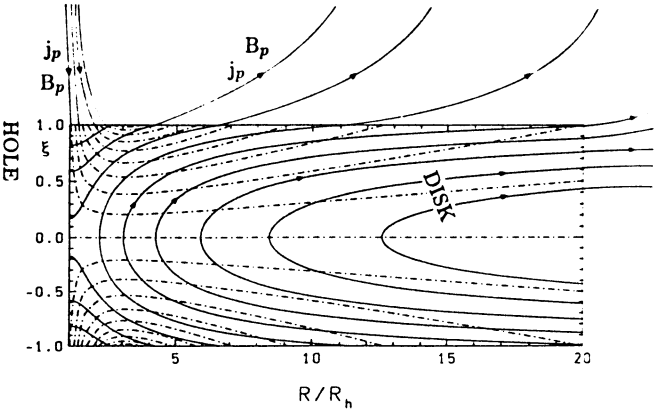

Fig. 2. $\mathbf{B_p}$ (solid lines) and $\mathbf{j_p}$ (dashed lines) - topology in disk (calculated) and jet (schematically) for a dipole.

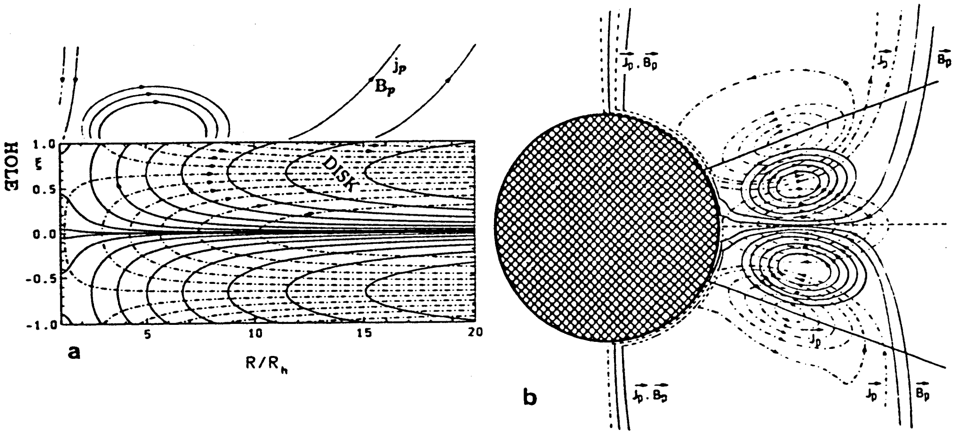

Fig. 3. a) $\mathbf{B_p}$ (solid lines) and $\mathbf{j_p}$ (dashed lines) -topology in disk (calculated) and jet (schematically) for a quadrupole. b) Suggested topology, that could produce a fast jet.

outflow is not connected to the disk by strong currents and thus the Blandford-Znajek process could not be very effective.
However, it should be possible to produce fast jets in a quadrupolar field topology [5]. This requires a maximum of Ψ and $|T|$ near the hole. In Fig. 3 b) we suggest a possible disk solution. The maximum in Ψ in the disk could be produced by the α-effect peaked at the very site where $R\frac{d\Omega}{dR}$ has its extremum. This can be seen from the coupled source terms for $\frac{\partial\Psi}{\partial t}$ and $\frac{\partial B_\phi}{\partial t}$, which are $\alpha_D R B_\phi$ and $R\frac{d\Omega}{dR}\frac{\partial\Psi}{\partial z}$, respectively (see [2]).

2. Coronal heating

The magnetic power L_{cor} that is available to heat a disk corona, is given by the integral of the vertical Poynting flux $S_z(R) \approx -R\Omega B_\phi B_Z/4\pi$.

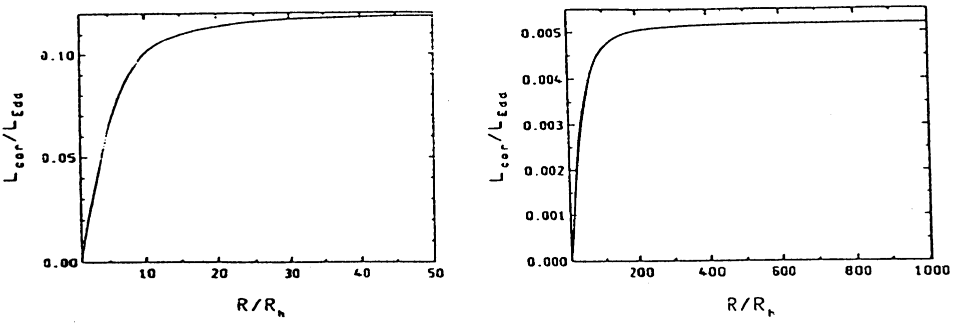

Fig. 4. The integral coronal heating power L_{cor} within a distance R in units of the Eddington luminosity for $M_{hole} = 10^9\,M_\odot$; $\eta_{accr} = 0.1$. a) Dipole structure, b) quadrupole structure.

For our dipole case solutions we find that S_z carries a magnetic energy equivalent to a luminosity of $L_{cor,tot} \approx 3 \times 10^{46}$ergs^{-1}, which is ≈ 12 per cent of the Eddington luminosity of an AGN with a central hole of $10^9\,M_\odot$, if the accretion efficiency is assumed to be 10%. This energy might power an X – ray emitting region somewhere above the disk, as required by recent models (see e.g. [6]) to illuminate outer parts of the accretion disk in an AGN. In Fig. 4 a) we see that practically all the Poynting flux is radiated from the disk in the innermost region. In the quadrupole case $L_{cor,\,tot}$ is smaller by a factor 25. Here the bulk of the Poynting flux is radiated away within $\approx 200R_{in}$ (Fig. 4 b)).

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