STATIONARY ACCRETION DISKS LAUNCHING SUPER–FAST-MAGNETOSONIC MAGNETOHYDRODYNAMIC JETS

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ABSTRACT

We present self-similar models of resistive viscous Keplerian disks driving nonrelativistic MHD jets and becoming super–fast-magnetosonic. We show that in order to obtain such solutions, the thermal pressure must be a sizeable fraction of the poloidal magnetic pressure at the Alfvén surface. These steady solutions that undergo a recollimation shock causally disconnected from the driving engine account for structures with a high-temperature plasma in the sub-Alfvénic region. We suggest that only unsteady outflows with typical timescales of several disk dynamical timescales can be produced if the suitable pressure conditions are not fulfilled.

Subject headings: accretion, accretion disks — galaxies: jets — ISM: jets and outflows — MHD — stars: pre–main-sequence

On-line material: color figures

1. INTRODUCTION

Self-collimated jets are now commonly observed originating from young stellar objects (YSOs), active galactic nuclei, and galactic binaries (Livio 1997). All these flows share common properties such as being always correlated with the accretion phenomenon (Hartigan, Edwards, & Ghandour 1995; Falcke & Biermann 1996; Serjeant et al. 1998; Gallo, Fender, & Pooley 2003). It has long been identified that jet self-confinement requires the presence of a large-scale magnetic field in order to focus the outflowing plasma (Chan & Henriksen 1980). The “universal” paradigm of jet formation relies on the occurrence of bipolar magnetic fields threading the accretion disk. As a consequence, the theory of accretion disks had to be revisited in order to take into account the mass, angular momentum, and energy transports achieved by the jet. One notorious modification to the standard picture is the necessary radial stratification of the disk accretion rate, namely, \( \dot{M}_r \propto r^\xi \) (\( \xi \) being a measure of the disk ejection efficiency). For instance, \( \xi = 0 \) describes a standard disk with no outflow, while \( 0 < \xi < 1 \) stands for an ejecting Keplerian accretion disk (Ferreira 1997). If one wishes to obtain the exact ejection efficiency, one has to solve without any approximation the full MHD two-dimensional structure of the disk.

Anomalous magnetic diffusivity must be present within the disk to allow accreting (and rotating) mass to cross the magnetic field lines whereas ejected mass becomes frozen into the field. Only self-similar solutions taking into account the underlying resistive accretion disk hitherto provided this description (Ferreira & Pelletier 1995; Ferreira 1997; Casse & Ferreira 2000a, 2000b). Within these solutions, once in ideal MHD regime, mass is magnetically accelerated along each field line and must successively cross three MHD critical points, namely, the slow and fast magnetosonic (SM and FM) ones and the Alfvénic point. So far, none of the self-similar solutions was able to obtain both disk and jet flows, the latter crossing the three critical surfaces.

Using the same framework, Vlahakis et al. (2000) solved the ideal MHD jet equations and provided new solutions crossing these three critical points. However, since these solutions were not connected to the underlying disk, the issue of super-FM jet production from the accretion disk remained. In this Letter, we present the necessary conditions to get self-similar super-FM jets (§ 2), discuss the properties of typical solutions (§ 3), and conclude with some astrophysical implications that may be put to the test of observations.

2. ROLE OF A SUB-ALFVÉNIC HEATING

Stationary jets are described by a set of axisymmetric ideal MHD equations. Thus the poloidal magnetic field writes \( \mathbf{B}_p = (\nabla \times \mathbf{e}_s)/r \), where \( a(r, z) = C s \) describes a surface of constant magnetic flux. Disk winds are produced whenever a large-scale magnetic field, close to equipartition with the disk thermal pressure (Ferreira & Pelletier 1995), is present over a range in anchoring radii \( r_0 \). The corresponding jet is made of magnetic surfaces nested one around each other with several integrals of motion. In the nonrelativistic case, one gets \( (u_p, \Omega, p, \rho) \) defined by \( \mathbf{B}_p, \rho \), \( \Omega_0 \), and \( \eta \), the angular momentum \( L_0 = \Omega_0 r_0^2 = \Omega r^2 - r B_{\|}/\eta \) transported away. Here, \( r_0 \) is the Alfvén radius where mass reaches the Alfvén poloidal velocity. In this Letter, we are interested in jets that may be heated by their surroundings so that an adiabatic description is inadequate. Instead, we assume the presence of a heat flux \( q = \nabla H - \nabla P \rho \), where \( H \) is the usual enthalpy for a perfect gas. Including this additional effect, one gets the generalized Bernoulli equation via \( \mathbf{F}[\mathcal{F}(s, a)] = (u^2/2) + H + \Phi_E - r \Omega B_z/\eta \), where \( \mathcal{F}(s, a) = \int^{s'} q \cdot \mathbf{e}_s ds \) is the heating term that depends on a curvilinear coordinate \( s \) along a given magnetic surface \( s' \) (roughly the SM point and \( \mathbf{B}_p = B_0 \mathbf{e}_z \)). The total specific energy provided at the disk surface is \( E(s) = \Omega_0 r_0^2 (\lambda - 3/2) \) for a thin disk, where \( \Omega_0 \) is the Keplerian rotation at the anchoring radius \( r_0 \), and \( \lambda = L_0/\Omega_0 r_0^2 \) is the magnetic lever arm. The shape of the magnetic surface is given by the Grad-Shafranov (GS) equation

\[
(1 - m^2) J_\theta = J_\lambda + J_r + J_\phi,
\]
Mass is being ejected. Only angles up to the angle, the larger the magnetic compression and the less
ishes at three singular points where the following numbers
the projected velocity \( \mathcal{V} \), even if the poloidal ve-
Disks were given in Ferreira (1997). Once fulfilled, a super-A
been proved to be possible from Keplerian accretion disks,
and is the disk aspect ratio. This general expression
on the transverse equilibrium, this additional heating must pro-
the Alfven critical surface. The unit vector \( \mathbf{n} \) is defined as \((\varepsilon, r')/(r^2 + \varepsilon^2)^{1/2}\).

\& Ferreira 2000a), but none of these solutions can become
super-FM.

Every super-FM solution obtained by Vlahakis et al. (2000)
exhibits Alfven surfaces closer to the equatorial plane (i.e.,
\( \Psi_A \sim 60^\circ \)), but being not connected to a resistive MHD disk,
they did not have to fulfill the requirement of a quasi-static
disk vertical equilibrium. Actually, no Keplerian disk would
probably survive the overwhelming magnetic compression im-
posed by the bending of the field lines (or allow the imposed
mass effluvium). The only possible way to have an Alfven
surface closer to the disk is to break this univocal link between
\( \Psi_A \) and \( \theta_{\text{SM}} \). This implies a change of some invariants (entropy and total specific energy) between the disk and the Alfven
surface. Physically this requires an extra force term in the GS
equation, namely, a strong outwardly directed pressure gradient
in the sub-A region. Within the self-similar framework, it means
building up a large thermal pressure, thus an additional heating
starting above the disk.

The generalized GS equation becomes \( \cos \theta_{\lambda} = R(\theta_{\lambda}; \Psi_A) + \beta_{\lambda}(\theta_{\lambda}; \Psi_A) \), where

\[
R_{\lambda}(\theta_{\lambda}; \Psi_A) = -\frac{g_{a,\lambda}}{4} \left[ \frac{2}{8_a} \cos \theta_{\lambda} + \frac{\sin \Psi_A}{\sin(\Psi_A - \theta_{\lambda})} \times \left( \frac{2 - \cos \Psi_A}{C^2_{\lambda,\lambda}} - \frac{d \ln \rho_{\lambda}}{d \nu_{\lambda}} - \frac{1}{\gamma - 1} \right) \right]
\]

is the contribution of this additional heat flux and \( \beta_{\lambda} \) is the
ratio of the plasma pressure \( P_{\lambda} = \rho_{\lambda} C^2_{\lambda,\lambda} \) to the poloidal
magnetic pressure at the Alfven point. This equation shows that \( \beta_{\lambda} \)
large enough (\( \beta_{\lambda} \ll 1 \)) and \( R_{\lambda} \) negative are two necessary condi-
tions to increase \( \Psi_A \). Indeed, since \( \theta_{\lambda} \) is always smaller than
\( \Psi_A \), any tendency to increase \( \theta_{\lambda} \) leads to a lowering of the Alfven
surface.

At the Alfven surface, \( \beta_{\lambda} = 2 \omega_{\lambda}^2 (\varepsilon^2/\lambda) (T_{\lambda}/T_0) \), where
\( \omega_{\lambda} = \Omega_{\lambda}/\mu_{\lambda,\lambda} \equiv 1 \) (Ferreira 1997; Casse \& Ferreira 2000a) and \( \epsilon = h/r \) is the disk aspect ratio. This general expression
shows that any cold jet (isothermal \( T_{\lambda} = T_0 \) or adiabatic
\( T_{\lambda} \ll T_0 \)) always displays \( \beta_{\lambda} \ll 1 \). In order to have any influence on the transverse equilibrium, this additional heating must pro-
vide a large increase in jet temperature, namely, \( T_{\lambda} \approx T_0/\lambda^2 \).

The second condition \((R_{\lambda} < 0)\) sheds light on the required heat-
The ratio is always large enough (but of the order of unity). The density profile inside the disk, where both and are negative, is very much comparable from the disk surface to the Alfvén point. Note that the FM critical point allows to determine the critical value of the adiabatic index . Further up, we allow for a continuous transition to a polytropic energy equation, . The X-type heating function is assumed to be present, starting at the disk surface but vanishing before the Alfvén point, with an already decreasing temperature (due to adiabatic cooling).

3. SELF-SIMILAR NUMERICAL SOLUTIONS

We follow basically the same integration procedure as in our previous works (see Casse & Ferreira 2000b for more details). A heating function is assumed to be present, starting at the disk surface but vanishing before the Alfvén point, with an adiabatic index . Further up, we allow for a continuous transition to a polytropic energy equation, \( P \propto \rho^5 \). The X-type FM critical point allows to determine the critical value \( \Gamma_p \) of the polytropic index: if \( \Gamma < \Gamma_p \), thermal acceleration is too inefficient (breezellelike solution), whereas if \( \Gamma > \Gamma_p \), the strong decrease in enthalpy leads to a shocklike solution. Although Vlahakis et al. (2000) used an analogous way, our solutions strongly differ by the fact that jet invariants are fixed by the disk. Therefore, we need first to drastically increase the jet enthalpy before fine-tuning the polytropic index. As in solar wind models, we are playing around with one free parameter (\( \Gamma \)) while one should solve the full energy equation.

Figure 2 shows a typical super-FM solution obtained with \( \Gamma_p = 1.45 \). The energy input required can be measured by the ratio \( f = \mathcal{F}(\chi, a) / E(a) \) since most of the heating occurs in the sub-A region. Solutions displayed here required of several \( 10^{-2} \), allowing us to get \( \Psi_\alpha \approx 65^\circ \) with \( \beta_\alpha \approx 0.1 \) (condition \( T_\alpha \approx T_\alpha / e^2 \) is verified). Note that smaller temperature values would also allow super-FM jets, but they would just be terminated much sooner as in Vlahakis et al. (2000).

In general two-dimensional flows, the “causal horizon” (here the \( M_{FM} = 1 \) surface) is the envelope of one of the two families of characteristics (Tsiganos et al. 1996) and not the surface of parabolicity \( n = 1 \) (see Fig. 3). Any perturbation occurring to the flow downstream to the \( M_{FM} = 1 \) surface is unable to cross this horizon. This result is generic to two-dimensional solutions; the only bias introduced by self-similarity is the conical shape of such surfaces, not their separate existence. This has strong consequences on numerical experiments, as already pointed out by Ustyugova et al. (1999). To ensure the absence of feedback from the imposed boundary conditions, the Mach cones (defined locally as the tangents to the characteristics) must be directed out of the computational domain at its boundaries.

4. ASTROPHYSICAL IMPLICATIONS

The present computed MHD flows are the first-ever steady state solutions describing an overall accretion-ejection structure from the resistive accretion disk to the super-FM jet region. The strict stationarity of such accretion-ejection engines depends critically on the thermal properties of the sub-A region. If the plasma pressure, measured at the Alfvén point, is a sizable fraction of the poloidal magnetic pressure, MHD jets from Keplerian accretion disks can become super-FM. In the super-FM region, the jet is always facing a recollimation that ends up as a shock. The further jet propagation requires numerical time-dependent simulations. Around a protostar, such thermal pressure gradient occurs whenever temperatures as high as several \( 10^3 \) K are reached along the inner streamline. This is compatible with recent observations of blueshifted UV emission lines (Gómez de Castro & Verdugo 2001) and some absorption features (Takami et al. 2002). Unfortunately, the heating source can only be inferred from its effects, and its origin remains a crucial issue. For instance, YSOs’ accretion disks are assumed to be highly magnetized, so one may safely expect that some accretion energy is also dissipated in the upper disk layers and...
provides coronal heating (Galeev, Rosner, & Vaiana 1979; Heyvaerts & Priest 1989). This is actually shown by both numerical simulations (Miller & Stone 2000) and some observational indication of accretion-powered corona (Kwan 1997). Moreover, since the central object has a hard surface, the shock of the infalling material provides another source of UV radiation (as well as X-rays), illuminating the disk and heating the sub-
over, since the central object has a hard surface, the shock of indication of accretion-powered coronae (Kwan 1997). Moreover, since the central object has a hard surface, the shock of the infalling material provides another source of UV radiation (as well as X-rays), illuminating the disk and heating the sub-

On the other hand, if an accretion-ejection engine cannot provide this additional heating or if there is no inner spine, then the thermal pressure is negligible at the Alfvén surface and jets remain sub-FM. Recollimation toward the axis leads to open up. In YSOs such a flow could be provided by the interaction between the protostellar magnetosphere and the disk (Ferreira, Pelletier, & Appl 2000; Matt et al. 2002; Romanova et al. 2002). Temperatures required around a compact object imply a relativistic plasma. In this case, the inner pressure could be provided by an inner beam composed of relativistic electron-positron pairs, heated and accelerated inside the hollow part of the disk wind (Renaud & Henri 1998).

The amount of large-scale poloidal magnetic flux trapped in accretion disks is completely unknown. The above astrophysical implications hold only if this flux is large enough so that an equipartition field spans at least one decade in radius in the disk. Indeed, in such circumstances, there is no physical reason for strong gradients in jets, and one may expect an almost plane Alfvén surface (Krasnopolsky, Li, & Blandford 1999; Casse & Keppens 2004). These kind of jets display dynamical properties (acceleration and collimation) that weakly depend on the radial (inner and outer) boundary conditions, as in self-similar models. On the contrary, if the flux is small and concentrated at the inner edge of the disk, one would expect an almost spherical expansion of the field lines as in X-wind models (Shu et al. 1994). Observations allowing to infer jet velocity patterns and to relate them to the source (Garcia et al. 2001; Bacciotti et al. 2002; Pesenti et al. 2003) are necessary to discriminate between these two extreme pictures.

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