COLLIMATION OF ASTROPHYSICAL MHD OUTFLOWS

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Abstract. We explain in simple terms why a rotating and magnetized outflow forms a core with a jet and show numerical simulations which substantiate this argument. The outflow from a solar-type inefficient magnetic rotator is found to be very weakly collimated while the outflow from a ten times faster rotating YSO is shown to produce a tightly collimated jet. This gives rise to an evolutionary scenario for stellar outflows. We also propose a two-component model consisting of a wind outflow from a central object and a faster rotating outflow launched from a surrounding accretion disk which plays the role of the flow collimator.

Keywords: MHD – solar wind – ISM / Stars: jets and outflows – galaxies: jets

1. MHD Modelling of Jets and Outflows

The starting point in the modelling of cosmical outflows is the set of the classical MHD equations, while two approaches can be followed. The *first* and simplest one is to consider steady states wherein all physical quantities are independent of time. An advantage of this approach is that an analytical treatment is possible (Tsinganos, 1982). Via a nonlinear separation of the variables we have thus obtained the only available exact solutions which correspond to the three classes of meridionally (Sauty et al., 1999, Vlahakis and Tsinganos, 1999), radially (Vlahakis et al., 2000) and planarly (Petrie et al., 2002) self-similar solutions. The main difficulty in solving this problem is the known nonlinearity of the formidable full set of the coupled MHD equations together with the problem of causality. Specifically,

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in the solution domain appear some separatrices, or limiting characteristics, which play the role of the MHD signal horizon separating causally areas which cannot communicate with each other via an MHD signal. On these separatrices appear the MHD critical points and a physically accepted solution is determined by the requirement that it should pass through these critical points which are not known *a priori* but they are only determined *a posteriori* simultaneously with the complete solution. Alternatively, we may also solve the time-dependent set of the MHD equations (Ouyed and Pudritz, 1997; Casse and Keppens, 2002). However, in this case only numerical simulations can be performed which also follow the temporal evolution of the solution and also incorporate non-ideal MHD effects.

In this volume, Sauty et al. (2003) presented results from the analytical axisymmetric modelling of jets from the coronae of young stars, while here we complement this study by presenting numerical simulations which support the analytical results.

2. Why is a MHD Outflow Collimated?

As is well known from Parker's (1963) classical treatment of the solar wind, the unavoidable result of a hot stellar atmosphere is expansion of the plasma to the ISM with supersonic speeds. This basic result can be understood by the following simple facts. First, in a million degree corona the plasma has a high thermal conductivity, $\kappa(T) \approx 10^{-13} T^{5/2}$cal/cm sec K $\approx$ 1 cal/cm sec K, similar to the value of the conductivity of a good conductor, such as Copper. Second, because of this high thermal conductivity, the temperature tends to be homogenised. As a matter of fact, the energy equation, $\nabla \cdot [\kappa(T)\nabla T] = 0$ has the solution $T = T_o/R^{2/7}$, which means that at the distances of the ISM ($R \approx 10^4$) the temperature is much higher than the temperature of the ISM ($\approx 100K$). The transfer of thermal energy (enthalpy) to kinetic energy of the plasma follows immediately from Bernoulli's law and the atmosphere expands in what is known as the solar wind. In this treatment the effects of magnetic fields and rotation are neglected. However, what happens when magnetic fields and rotation play a dominant role? To illustrate the effects of rotation and magnetic fields in the outflow of a plasma from a central gravitating object, consider a monopole-type magnetic field, $B_R = B_o/R^2$, where B_o is the magnetic field at the base $R = r/r_o = 1$. Assume that the plasma flows with a constant speed V_o along these radial magnetic field lines. The Alfvén number of this outflow is, $M(R) = R/R_a$, where R_a is the Alfvén radial distance. Let us assume that the base of the outflow rotates with an angular velocity Ω. From the steady MHD equations the induced azimuthal magnetic field B_ϕ is $B_\varphi/B_R = -\{\Omega\varpi_a^2/[\varpi(B_R/\Psi_A)]\}\{(\varpi^2/\varpi_a^2 - 1)/(M^2 - 1)\}$, where Ψ_A is the mass flux per unit of magnetic flux. Then, at distances much larger than the corresponding Alfvén scales, $\varpi >> \varpi_a$, $R >> R_a$, $M \approx \varpi/\varpi_a$, it follows that $B_\varphi/B_R \approx -\Omega\varpi/V_o$, i.e., the azimuthal magnetic field grows with the cylindrical distance ϖ in relation to the poloidal magnetic field B_R. Thus, although at the rotation axis the magnetic tension is negligible, the azimuthal magnetic field grows with distance from the axis of rotation and eventually it will dominate over the poloidal magnetic field B_p. The magnetic pressure and tension then exert a net force towards the axis of rotation and one may wonder for what might balance this inwards force. The outward inertial force $\rho V_\varphi^2/\varpi$ is negligible since the azimuthal flow speed is negligible in the same approximation. The last available means to balance the inwards hoop stress would be some suitable pressure gradient. However, the magnetic pressure drops with the cylindrical distance ϖ like $1/\varpi^2$ and is negligible. The thermal gas pressure on the other hand, should drop like $1/\varpi^3$ in an atmosphere where $V = V_o$ ($\rho \sim \varpi^{-2}$) in order that the thermal pressure gradient balances gravity. It follows that the unavoidable result is that magnetic tension will bend the poloidal magnetic field lines towards the axis, forming a cylindrical core, as it may be seen in Figures 1. However, outside the core the fieldlines are bent inwards rather slowly.

3. Numerical Simulation of Jet Formation and an Evolutionary Scenario for the Transition from a Jet to a Wind

To illustrate the effect of magnetic self-collimation of an outflow, we show the results of a numerical simulation in Figure 1 (for details see, Tsinganos and Bogovalov 2000). Initially, we have a radial outflow and magnetic field in a nonrotating atmosphere with a polytropic index $\gamma = 1.1$. In this initial configuration, the sonic radius of the star at the equator is $R_{s,eq}$, the sound speed at the equator is $V_{s,eq}$, while the Alfvén speed at the equator is $V_{A,eq}$. At t=0 the star starts rotating with an angular velocity Ω. Then, two crucial parameters that affect the obtained final state are the dimensionless Alfvén speed V_a and the magnetic rotator parameter β, $V_a = V_{A,eq}/V_{s,eq}$, $\beta = \Omega R_{s,eq}/V_{s,eq}$. In Figure 1 is shown the shape of the poloidal magnetic field lines for the case of a slow magnetic rotator with $\gamma = 1.1$, $V_a = 6.15$ and $\beta = 0.165$, (i.e., parameters appropriate to the solar wind) while in the right column the case of a fast magnetic rotator with $\gamma = 1.1$, $V_a = 6.15$ and $\beta = 1.65$ (i.e., with parameters appropriate to a young stellar object that rotates ten times faster than the sun). In the first row the solution is shown in the near zone that contains the Alfvén and fast magnetic critical surfaces, while in the second row it is shown in the far zone. The axis is in units of the radius of the slow point at $8.4 R_\odot$. Finally, in the last third row the scales are logarithmic in order to clearly show collimation at large distances. Very weak collimation can be seen in the case of the solar wind while a tightly collimated jet from a rapidly rotating stellar object. The situation is analogous to results of the analytical solutions (Sauty et al., 1999, 2002) wherein outflows from efficient magnetic rotators obtain cylindrical asymptotics while outflows from inefficient magnetic rotators obtain radial asymptotics.

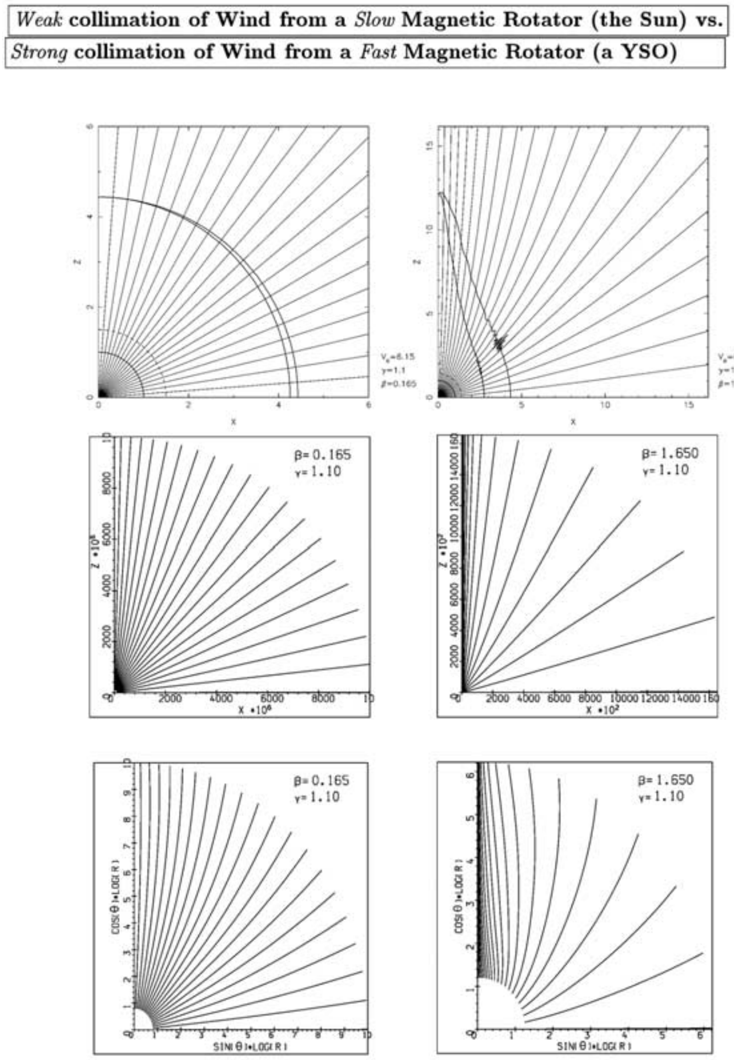

Figure 1. Left column: shape of poloidal magnetic field lines for the case of a slow magnetic rotator similar to the solar wind. Right column: same for the case of a fast magnetic rotator similar to a young stellar object rotating ten times faster than the sun. See text for more details.

According to the above results, the following simple evolutionary scenario for the shape of a plasma outflow from a central gravitating object can be proposed. Initially, the formation of a star with a surrounding accretion disk is associated with a tightly collimated outflow (jet), since the system corresponds to an efficient magnetic rotator. Subsequently however, as the star ages and by loosing angular momentum it gradually slows down, the system may gradually shift to reach the stage of an inefficient magnetic rotator with small values of the parameter β and a

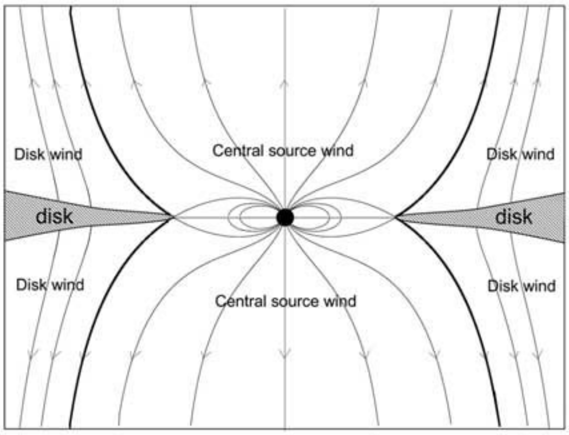

Figure 2. Illustration of the proposed model. A slowly rotating central source emits a roughly radially expanding at the base outflow which is forced to collimate by the wind from the fast rotating inner edges of the surrounding accretion disk.

rather loosely collimated wind. This conjecture may then explain the dichotomy of noncollimated outflows from solar-type stars and collimated outflows from YSO.

4. A Two Component Model for Jets from a System of a Central Source and a Disk

A serious limitation however of the previous simulations of magnetic collimation is that only a tiny fraction of order $\sim 1\%$ of the mass and magnetic flux of the originally radial wind ends up collimated inside the jet (Bogovalov and Tsinganos 2001). Similarly, in analytical models if the source of the wind is a stellar surface and the disk does not feed the outflow with mass and magnetic flux, very low wind- and jet-mass loss rates ($\dot{M}_{wind}$, $\dot{M}_j$) are obtained. However, in outflows associated with YSO current estimates place $\dot{M}_{\rm jet}$ in the limits $\dot{M}_{\rm jet} \sim 10^{-6} - 10^{-8} M_{\odot}/yr$ (Ray 1996). And, the inferred from observations mass loss rates of bipolar outflows indicate wind mass loss rates also in the range of $\dot{M}_{\rm wind} \sim 10^{-6} - 10^{-8} M_{\odot}/yr$, depending largely on the luminosity of the YSO's. Therefore, the mass loss rate in the jet has to be a large fraction of the mass loss rate in the surrounding wind.

The idea that the source of the jet rotates rather slowly may be quite reasonable, at least in relation to YSO's. It is evident that a protostar should rotate more slowly than the inner edges of its Keplerian accretion disk and observations indeed confirm this prediction. We do not intend to argue here that the matter in the jet is ejected from the protostar. The close disk-jet connection (Hartigan et al., 1995) shows that the matter in the jet is supplied by the accretion disk (Livio, 1999). But it is reasonable to assume that this matter penetrates in the magnetic field of the central star, partially falls down on the surface of the star and partially is ejected outwards

(Shu et al., 1991; Ferreira and Pelletier, 1995). In this case only the magnetic field of the jet is connected with the central star. Schematically this picture of the outflow is presented in Figure 2. According to this scheme the disk not only supplies the plasma of the jet, but also it produces the magnetized wind which collimates the outflow from the central source into a jet. A similar idea has been proposed for AGN jets (Sol et al., 1989).

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References

Bogovalov, S.V. and Tsinganos, K.: 2001, *MNRAS* **325**, 249.
Casse, F. and Keppens, R.: 2002, *ApJ* **581**, 988.
Ferreira, J. and Pelletier, G.: 1995, *A&A* **295**, 807.
Hartigan, P., Edwards, S. and Ghandour, L.: 1995, *ApJ* **452**, 736.
Livio, M.: 1999, *Physics Reports* **311**, 225.
Ouyed, R. and Pudritz, R.E.: 1997, *ApJ* **484**, 794.
Parker, E.N.: 1963, *Interplanetary Dynamical Processes*, Interscience Publishers, New York.
Petrie, G.J.D., Vlahakis, N. and Tsinganos, K.: 2002, *A&A* **382**, 1081.
Ray, T.P.: 1996, in: K. Tsinganos (ed.), *Solar and Astrophysical MHD Flows*, Kluwer Academic Publishers, p. 539.
Sauty, C., Tsinganos, K. and Trussoni, E.: 1999, *A&A* **348**, 327.
Sauty, C., Trussoni, E. and Tsinganos, K.: 2002, *A&A* **564**, 853.
Sauty, C., Tsinganos, K., Trussoni, E. and Meliani, Z.: 2003, this volume.
Shu, F., Ruden, S.P., Lada, C.J. and Lizano, S.: 1991, *ApJ* **370**, L31.
Sol, H., Pelletier, G. and Asseo, E.: 1989, *MNRAS* **237**, 411.
Tsinganos, K.: 1982, *ApJ* **252**, 775.
Tsinganos, K. and Bogovalov, S.V.: 2000, *A&A* **356**, 989.
Vlahakis, N. and Tsinganos, K.: 1999, *MNRAS* **307**, 279.
Vlahakis, N., Tsinganos, K., Sauty, C. and Trussoni, E.: 2000, *MNRAS* **318**, 417.