Star-Driven Wind and Jet Models *

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Abstract. We outline some main results from recent analytical modelling of axisymmetric jets from the coronae of young stars and compare them to disk-wind and X-wind models. We emphazise the roles of the magnetic rotator and the disk in the formation and the evolution of the jet. We conjecture that with time both the efficiency of the magnetic rotator and the role of the disk as a primary source for the wind decline.

Keywords: MHD – solar wind – ISM / stars: jets and outflows

1. Introduction

Jets and outflows seem to be necessary ingredients of the process of low mass star formation. Such outflows may be modelled by solving the classical MHD equations for an ionized gas which emerges from the gravitational potential well of a central stellar condensation during the process of star formation and subsequent collimation of the outflow to form a jet. Three key questions arise. Is the magnetic field or the total effective pressure responsible for the plasma acceleration? Is collimation due to magnetic self-confinement or is it the result of some external pressure ? Is the star, the disk, or the connecting region between the two the main source of the outflow?

The outflow can be *accelerated* by strong toroidal magnetic fields which act as an uncoiling spring, or a plasma gun. This is mainly seen in time-dependent simulations on short time scales. The most favoured magnetic process remains nevertheless the mechanism proposed by Blandford & Payne (1982). In this case, close to the base of the outflow the material is forced to corotate due to strong poloidal magnetic fields in the subAlfvénic regime. The centrifugal force in the

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corotating frame accelerates the flow as a bead on a wire. This efficient mechanism cannot be effective however close to the rotation axis of the source where the plasma needs to be driven either by thermal, or radiative and wave driving forces. In all three cases, it is the negative gradient of the total effective pressure which pushes the plasma away.

Confinement on the other hand, can be provided by toroidal magnetic fields in the superAlfvénic regime through the pinching Lorentz force, if the outflow is carrying a net outflowing current, as discussed in Heyvaerts & Norman (1989). Alternatively, the flow can be confined by the pressure of some external medium, or because of the intrinsic pressure gradient directed towards the axis.

Finally, the *source* of the wind can be the outer Keplerian region, as is the case in the Blandford & Payne (1982) special model, discussed for example by J. Ferreira in this volume [Casse & Ferreira (2000), Vlahakis et al. (2000)] and where radially self-similar disk-wind models can be used. The source of the outflow can also be in the connecting part between the disk and the star, as discussed in the X-wind models proposed by F. Shu [Shu et al. (1994), Shang et al. (2002)]. In order to give some hints to the 3 initial key questions, we shall explore here a third approach to describe axisymmetric steady outflows from a central spherical corona using a nonlinear separation of the variables which corresponds to a meridionally self-similar symmetry. The physical idea is not very different from the X-wind scheme except that solutions are consistently deduced from the full set of the MHD equations and that the magnetic topology of the outflow from the disk does not need to be fan-like; this avoids the strong instabilities the X-point is likely to undergo, as suggested in Bardou & Heyvaerts (1996). Our approach is valid to model the outflow around the axis, where thermal driving is important while collimation is mainly magnetic. More technical details can be found in Sauty et al. (1999, 2002).

2. Modelling jets from T Tauri stars

Meridionally self-similar solutions can be used to model jets from T Tauri stars. We present in panel a) and b) of Fig. 1 the morphology in the poloidal plane of the flux tubes of two models for the jet of RY Tau, where UV emission indicates the presence of a shock at 38 AU from the star (Gomez de Castro et al., 2000). The vertical axis is the polar axis and the horizontal one the equatorial axis. The two solutions depend on whether we try or not to model the shock. As the temperature seems to decrease away from the rotation axis in YSO jets, we have been using the underpressured solutions presented in Sauty et al. (2002).

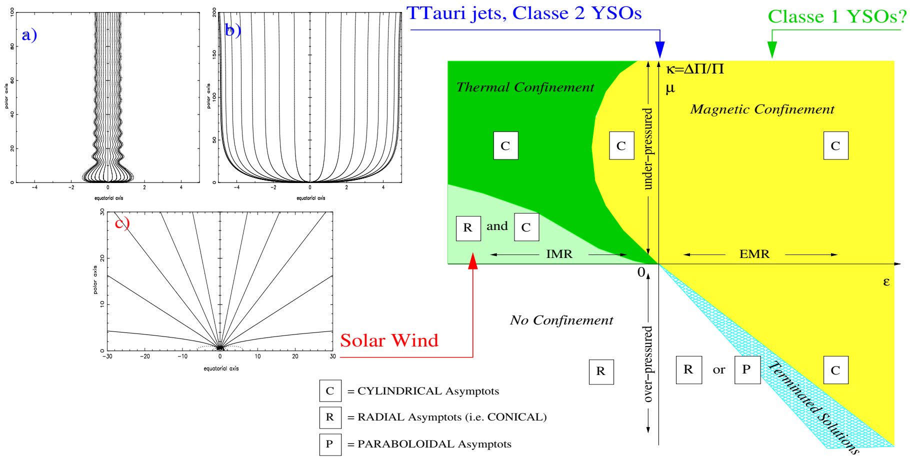

Figure 1. We plot the asymptotic morphology of different solutions (cylindrical, radial, or terminated) in the parametric space [μ,ε] (see text for details). In this space, a) and b) correspond to T Tauri jet models and c) to a model of the solar wind.

For the first solution (Fig.1a), we have used the rotation frequency of the star Ω, which corresponds also to the corotation frequency, the density before and after the shock and the asymptotic speed. We further assumed that the form and the location of the shock are related to the refocalization we obtain for some classes of solutions in Sauty et al. (2002). Although the mass loss rate is not measured for this specific jet, this solution gives a rather low value for the mass loss rate of a classical T Tauri outflow. Moreover, the asymptotic pressure is rather high, which leads to high temperatures unless the total pressure is partially due to Alfvén waves after the shock. This would imply Alfvén waves with amplitudes of the magnetic field variations of the order of the magnitude of the magnetic field itself.

Alternatively, we may use the same set of parameters but without trying to reproduce the shock, which is however not stationary. As shown in Sauty et al. (2002), for a given set of parameters there is a unique solution where the jet morphology goes without oscillations into a cylindrical shape. This is the case of the second example shown on Fig. 1b). The jet goes from an underpressured regime close to the star to an overpressured regime after 100 AU. This could account for the transition when the jet exits from the central embedding cloud. The temperature profile is more reasonable and lower, starting around 10^3 K close to the star up to 10^5 K in the maximum of the "corona" and down to 10^3K asymptotically. This solution gives a stellar mass loss rate of $10^{-10} M_\odot/yr$ compatible with the mass loss rate of a weak

T Tauri star. Moreover, we can extend the solution in the inner disk region consistently as the momentum equation is fulfilled even in the equatorial plane with a negligible accretion velocity. We then get a mass loss rate of a few $10^{-9} M_\odot/yr$, typical of classical T Tauri stars (see Hartigan, if the source of the wind extends in the disk up to 2.5 stellar radii from the star.

It is worth noting that these particular solutions or slightly different ones can be scaled to fit also observations of jets from other T Tauri stars (e.g. lkC15, DE Tau, GK Tau, DR Tau, IP Tau). Thus, this kind of solution seems to be rather generic of a wide class of jets from classical T Tauri stars (CTTS), assuming that most of the mass is ejected by the inner central part of the disk as proposed in Shu et al. (1994). Parallely, it may also model winds from weak T Tauri stars (WTTS), consistently showing that both ejections from CTTS and WTTS differ essentially by the role played by the disk as a source, as expected. This is also consistent with the results obtained in Machado (2001) where it is concluded that the star itself cannot provide the large densities and velocities observed simultaneously.

3. Classification of jets and sources

In the case of meridionally self-similar models of cosmical MHD outflows, a rather general criterion for the collimation of winds into cylindrical jets has been established [Sauty et al. (1999)]. According to this criterion, if there is an excess of volumetric energy along a non polar streamline with respect to the axis, the outflow collimates asymptotically into cylinders. This is quantified by the parameter ε',

$$\varepsilon' = \frac{\rho(r,A)\tilde{E}(A) - \rho(r,\mathrm{pole})\tilde{E}(\mathrm{pole})}{\rho(r,A)L(A)\Omega(A)}\,, \tag{1}$$

which equals to the difference of converted energy $\tilde{E}$ of a line of magnetic flux A (i.e. the total energy once we have substracted the thermal content that remains at infinity) compared to the polar line and normalized to the energy of the magnetic rotator $L\Omega$. L is the angular momentum and Ω the corotation frequency of the streamline of magnetic flux A. The parameter ε' is positive for collimated solutions and negative for non collimated winds. We notice that $\tilde{E}$ is the energy effectively used to accelerate and collimate the flow.

The parameter ε' has two contributions, one thermal μ and another magnetic ϵ, thus generalizing the usual criterion for fast vs. slow magnetic rotators, by taking into account thermal confinement as well,

$$\varepsilon' \equiv \mu + \varepsilon\,, \tag{2}$$

$$\mu \propto \frac{P(r,A) - P(r,\mathrm{pole})}{P(r,\mathrm{pole})} = \kappa\,, \tag{3}$$

where $P(r,A)$ is the pressure along the line of magnetic flux A and $P(r,\mathrm{pole})$ the pressure along the polar axis. Hence, μ measures the collimation due to the pressure gradient and in our model it is proportional to the relative variation of pressure across the outflow, κ. When μ or κ are positive (negative) the jet is underpressured (overpressured respectively) at the base of the flow. The magnetic parameter ε is

$$\varepsilon = \frac{L\Omega - E_{\mathrm{R},o} + \Delta E_{\mathrm{G}}^{*}}{L\Omega}\,, \tag{4}$$

where $E_{\mathrm{R},o}$ is the rotational energy that tends to decollimate the wind because of the centrifugal force, and

$$\Delta E_{\mathrm{G}}^{*} = -\frac{\mathcal{G}\mathcal{M}}{r_o}\left[1 - \frac{T_o(A)}{T_o(\mathrm{pole})}\right]\,, \tag{5}$$

where $\mathcal{G}$ is the gravitational constant, $\mathcal{M}$ the mass of the star and T_o the temperature at the base of the flow r_o. The quantity $\Delta E_{\mathrm{G}}^{*}$ in Eq. (5) corresponds to the gravitational potential well which is not compensated by thermal acceleration and thus must be supplied by the magnetic rotator in order to allow ejection. In other words, the parameter ε measures the quantity of energy of the magnetic rotator which is left once we have substracted the part that helps accelerating the flow. If there is an excess of such energy, the plasma is magnetically collimated. Thus, a fast magnetic rotator (large $L\Omega$) is not necessarily an **efficient magnetic rotator ($\varepsilon > 0$)** if magnetocentrifugal acceleration is important. Conversely a slow magnetic rotator (low $L\Omega$ as in T Tauri stars) can be either efficient ($\varepsilon > 0$) or inefficient ($\varepsilon < 0$) depending on the efficiency of thermal acceleration.

In the space of those 2 parameters μ and ε we have plotted in Fig. 1 the various types of outflow morphology that we obtain. Three domains exist, one with cylindrical asymptotics corresponding to jets from young stars, one with radial asymptotics if the pressure goes to zero at infinity as in the case of the solar wind and a small region where no steady physical solutions exist. It is interesting to note that in this parametric space, solutions modelling jets from Class 2 T Tauri stars, (panels a) and b) in Fig.1), correspond to marginally efficient magnetic rotator, $\varepsilon \approx 0$. Conversely, using the same model to fit observations from Ulysses on the solar wind, during solar minimum, leads to radially expanding solutions as shown on Fig. 1c) with low efficiency of the magnetic rotator, $\varepsilon = -50$. We conjecture that Class 1 objects would correspond to even more efficient magnetic rotators on the right part of the ε axis of the parametric space of (ε, μ).

4. From Class 0 to the main sequence

From the previous analysis, we may conjecture that, as the star evolves towards the main sequence, it is likely that the efficiency of the central magnetic rotator decreases. Parallely, the source of the wind should get closer and closer to the central star until the star reaches the main sequence where the disk has evaporated and the wind comes solely from the star.

In fact, in Contopoulos & Sauty (2001) it has been shown that jets from Class 0 objects may appear early in time, even before the central star is formed, because the external free falling of the plasma onto the centrifugally supported disk induces a bending of the poloidal fieldline in the external parts of the disk favorable to the formation of a magnetocentrifugally driven wind [see also Lery et al. (1999) for an alternative]. Then, for Class 1 jets, ejection is probably dominated by the disk wind, as in Casse & Ferreira (2000) and other simulations of time-dependent jets presented in this conference. Then, winds from the region connecting the disk to the star [Shang et al. (2002), Sauty et al. (2002)] may become dominant for Class 2 objects, as proposed here. Thus, once the efficiency of the magnetic rotator of the central star has lowered and the disk disappears the jet may transform itself into a solar-type radial wind.

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