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# A NEW YSO OUTFLOW MODEL, JET SIMULATIONS, AND THEIR EMISSION

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RESUMEN

En el esquema teórico común de la formación estelar, el jet es eyectado de un disco de acreción magnetizado, y el flujo molecular es impulsado por el jet o por un viento más abierto proveniente del disco. Proponemos un modelo unificado alterno para los flujos alrededor de YSOs (siglas en inglés: Young Stellar Objects; Objetos Estelares Jóvenes). Además de un motor de acreción-eyección que mueve al jet, el flujo molecular es impulsado por la materia que cae y sigue un patrón de circulación alrededor del objeto central sin ser absorbido por el flujo que proviene del interior. Soluciones para jets que parten de este modelo han sido utilizadas como condiciones iniciales para simulaciones de propagación de jets pulsados. Se presentan mapas sintéticos de las simulaciones de jets.

ABSTRACT

In the usual theoretical picture of star formation a jet is ejected from a magnetized accretion disk, with a molecular outflow being driven either by the jet or by a wider wind coming from the disk. We propose an alternative unified model for the flows surrounding YSOs. In addition to a central accretion-ejection engine driving the jet, the molecular outflow is powered by the infalling matter and follows a circulation pattern around the central object without being entrained by an outflow. Jets solutions from this model have been used as initial conditions for simulations of the propagation of pulsed jets. Synthetic maps from the jet simulations are presented.

*Key Words:* **ISM: JETS AND OUTFLOWS — MAGNETOHYDRODYNAMICS — STARS: PRE-MAIN-SEQUENCE**

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## 1. INTRODUCTION

Star formation occurs in molecular clouds, and observations have shown that the accretion phase, during which the central object builds up its mass, is very often accompanied by the powerful ejection of prominent bipolar outflows, which correspond to fast jets and molecular outflows. A consensus seems to prevail on the magneto-centrifugal origin of jets, either launched from the accretion disk (*disk wind*) or from the location of the interaction of the protostar's magnetosphere with the disk (*X-wind*). On the other hand, the precise mechanism generating molecular outflows is poorly understood. The latter are generally believed to be driven by the jet or by a wide-angle wind, but both possibilities present some difficulties (Cabrit, Raga, & Gueth 1997). Instead of the usual mechanisms invoked for the origin of the molecular outflows, we propose a global model, where, in addition to a central accretion-ejection engine driving the jet, the molecular outflow is powered by the infalling matter and follows a circulation pattern around the central object. Ultimately the molecular outflow may still undergo entrainment from the fast jet but only in polar regions.

## 2. THE CIRCULATION MODEL

We suggest that the molecular gas that circulates around the source can be described by the self-similar, heated, quadrupolar and axisymmetric magnetohydrodynamic model (Henriksen & Valls-Gabaud 1994; Fiege & Henriksen 1996; Lery et al. 1999a). In the infall region, the flow is slowed down by the increasing radial pressure gradients due to heating by the central source, by the increase in the centrifugal barrier resulting from the magnetic field with proximity to the central object, and due to the increasing rotational speed. This pressure 'barrier' deflects and accelerates, by means of its poloidal gradient, much of the infalling matter into an axial outflow. The Poynting flux included in the model increases both the velocity and collimation of the outflows by helping to transport mass and energy from the equatorial regions. The solutions are developed within the context of radial self-similarity

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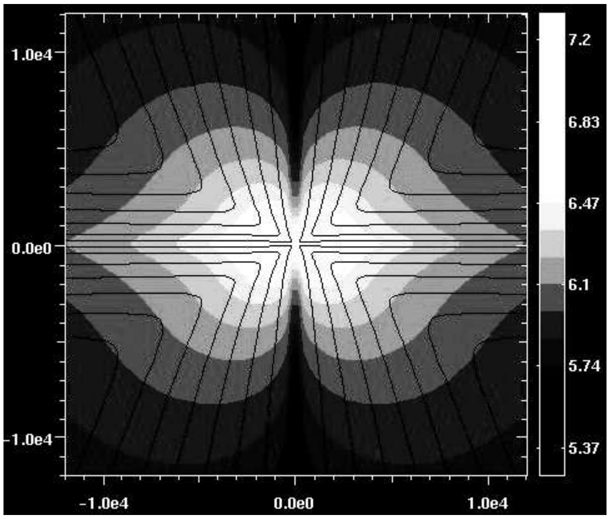



Fig. 1. Streamlines and density contours of the hydrogen number density (in logarithmic scale) for the circulation model with $\alpha = -0.2$. The density levels shown are between $10^5$ to $10^7$ cm$^{-3}$. Length scales are in AU.

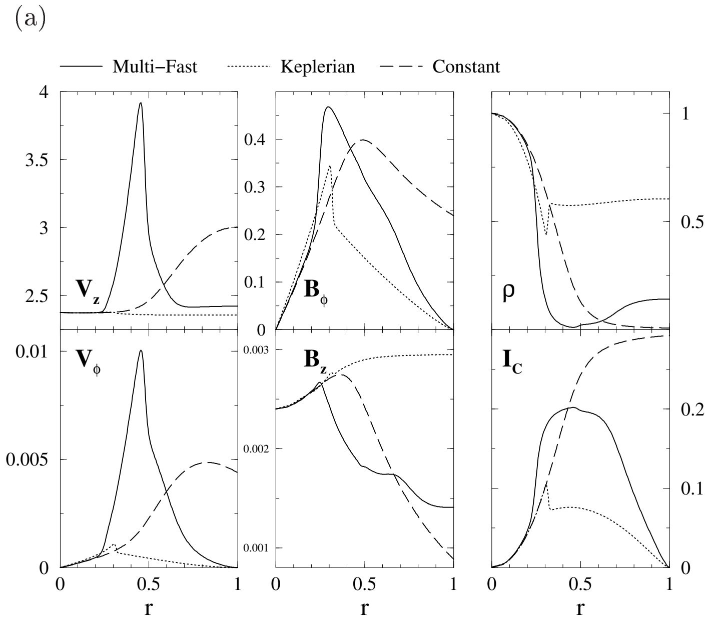
wherein a power of $r$ multiplies an unknown function of $\theta$; the spherical coordinates $r$, $\theta$ and $\phi$ being used. The power laws of the self-similar symmetry are determined, up to a single parameter $\alpha$, if we assume that the local gravitational field is dominated by a fixed central mass. In terms of a fiducial radial distance, $r_0$, the self-similar symmetry is sought as a function of two scale invariants, $r/r_0$ and $\theta$, in a separated power-law form. The self-similar index $\alpha$ is a free parameter of the solution, but it is constrained by boundary conditions to lie in the range $1/4 \geq \alpha > -1/2$ (Lery et al. 1999a).

The calculations produce solutions (see Figure 1) where the outflow can have large opening angles, and where massive protostars produce faster and less collimated outflows. Larger opening angles are associated with smaller magnetic fields. Consequently, a gradual evolutionary loss of magnetic flux may result in outflows that widen as they age. Synthetic spectral lines from $^{13}$CO ($J = 1 \rightarrow 0$) allow direct comparison with observational results via channel maps, maps of total emission, position-velocity and intensity-velocity diagrams. The model is now at a stage where synthetic CO spectra reproduce very well the observational features. The results strengthen the idea that the Poynting flux and the radiative heating are ultimately the energy sources driving the outflow. This new picture of the accretion/outflow phase provides a possible explanation for asymmetric outflows, molecular cavities and jet collimation. Self-similar models cannot of course be globally consistent in time even if they are non-stationary, since they are ignorant of initial conditions. The self-similar circulation model is intermediate in space in that regions such as the axis and the equator are strictly excluded from the domain of self-similarity although they may be approached asymptotically. The axial region is therefore modeled by a jet model that is not self-similar as described in the next section.

## 3. THE JET MODEL

The jet model is based on a simple model that proposes asymptotic MHD jet equilibria that account for the properties of the emitting source (Lery et al. 1998; Lery et al. 1999b; Lery & Frank 2000). The model is axisymmetric and stationary. It assumes the magnetic surfaces possess a shape which is known a priori inside the fast critical surface. As a first approximation, the magnetic surfaces were taken to be cones in this region. Since the jet behaviour can be directly related to the properties of the emitting source, the model can provide a better understanding of jet interactions with their surrounding medium, their propagation and instabilities, with respect to the source itself.

The MHD flow properties must be determined by solving for the equilibrium of forces parallel and perpendicular to the magnetic surfaces (the former is described by using the Bernoulli equation for a polytropic equation of state and the latter is solved via the Grad-Shafranov equation). The balance of forces perpendicular to magnetic surfaces is accounted for on the Alfvén surface and at the base of the flow. The equilibrium parallel to the surfaces takes the form of criticality conditions at the two other (fast and slow) MHD critical points. This corresponds to the differential form of the Bernoulli equation on constant $a$ with respect to $\rho$ and $r$ vanishing at the critical points. We further assume the density $\rho$ to be related to the pressure $p$ by a polytropic equation of state, $p = Q(a)\rho^\gamma$ where $\gamma$ is the polytropic index. In the general case, the model yields five integrals of motion that are preserved on any axisymmetric magnetic surface $a$. Two of the integrals are given as boundary conditions in the model. These are the angular velocity $\Omega(a)$ and an entropy factor $Q(a)$. These are supplied as a model for the source rotator. The Alfvén regularity condition together with the criticality conditions then determine the three other unknown integrals: namely the specific energy, $E(a)$; the specific angular momentum, $L(a)$; the mass to magnetic flux ratio, $\alpha(a)$. Far from the source (large $z$) the flow becomes cylindrically collimated. In this asymptotic regime the jet is



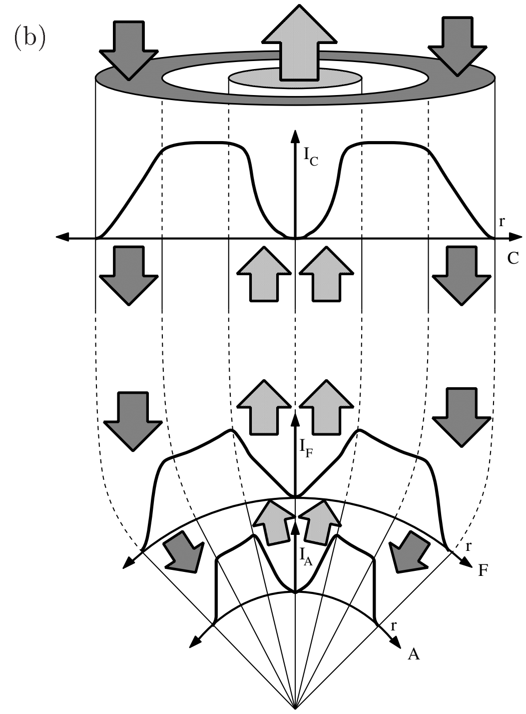




Fig. 2. (a) Example of solutions. Variations with fractional radius of components of the velocity, $V$, and magnetic field, $B$, of the density, $\rho$, and of the net electric current, $I_{\rm C}$. Constant (dotted lines), Keplerian (dashed), and multi-component (solid) rotation laws are considered. (b) Schematic representation of the net electric current along the jet (heavy solid lines), and its direction (arrows), at the Alfvénic (A), and the fast (F) surfaces, and in the cylindrically collimated regime (C).

assumed to be in pressure equilibrium with an external medium. The pressure matching condition along with with the Grad-Shafranov and Bernoulli equations are all solved in the asymptotic cylindrically collimated regime. Three different types of rotation have been studied, namely, rigid, Keplerian and multi-component rotations. The multi-component case starts with a rigid rotation. The angular velocity then doubles its value in order to model a jet rotating more rapidly than the central object before reaching a Keplerian rotation.

An example of asymptotic solution of the jet model is given for the different types of rotators in Fig. 2. There, the $z$ and $\phi$ components of velocity and magnetic field are represented together with the density $\rho$ and the net electric current $I_{\rm C}$, as functions of the relative radius (normalized to the jet radius). The density is normalized to its value on the jet axis $\rho_0$, and the non-dimensional velocities refer to the fast magnetosonic velocity $v_{\rm f}^2 = c_{\rm s}^2 + v_{\rm A}^2$ on the axis, $c_{\rm s}$ being the sound speed. The magnetic field is normalized to $\sqrt{\rho_0}\ v_{\rm f}$. In Figure 2, we also present the net electric current on the Alfvénic and fast surfaces and in the cylindrically collimated region. The current decreases from the source to the asymptotic region. Its profile is globally independent of the distance from the source. The current first increases outwards from the axis, then reaches a plateau where the magnetic pressure dominates. Finally, it decreases in the outer part of the jet. There exist a strong current in the core and a returning current in the collar, the intermediate part of the jet being almost current-free. Thus rotating MHD jets are characterized by a dense, current-carrying core, having most of the momentum, that is surrounded by a collar with an internal return current.

## 4. THE JET SIMULATIONS AND THEIR EMISSION

By using the jet model previously developed, it is possible to obtain jet equilibria whose properties directly depend on the source. These equilibria have been used to model the propagation of MHD jets into the interstellar medium. This work differs from previous studies in that the cross-sectional distributions of state variables are derived from an analytical model for magneto-centrifugal launching from a source rotator. The jets in these simulations are considerably more complex than "top-hat" profiles.

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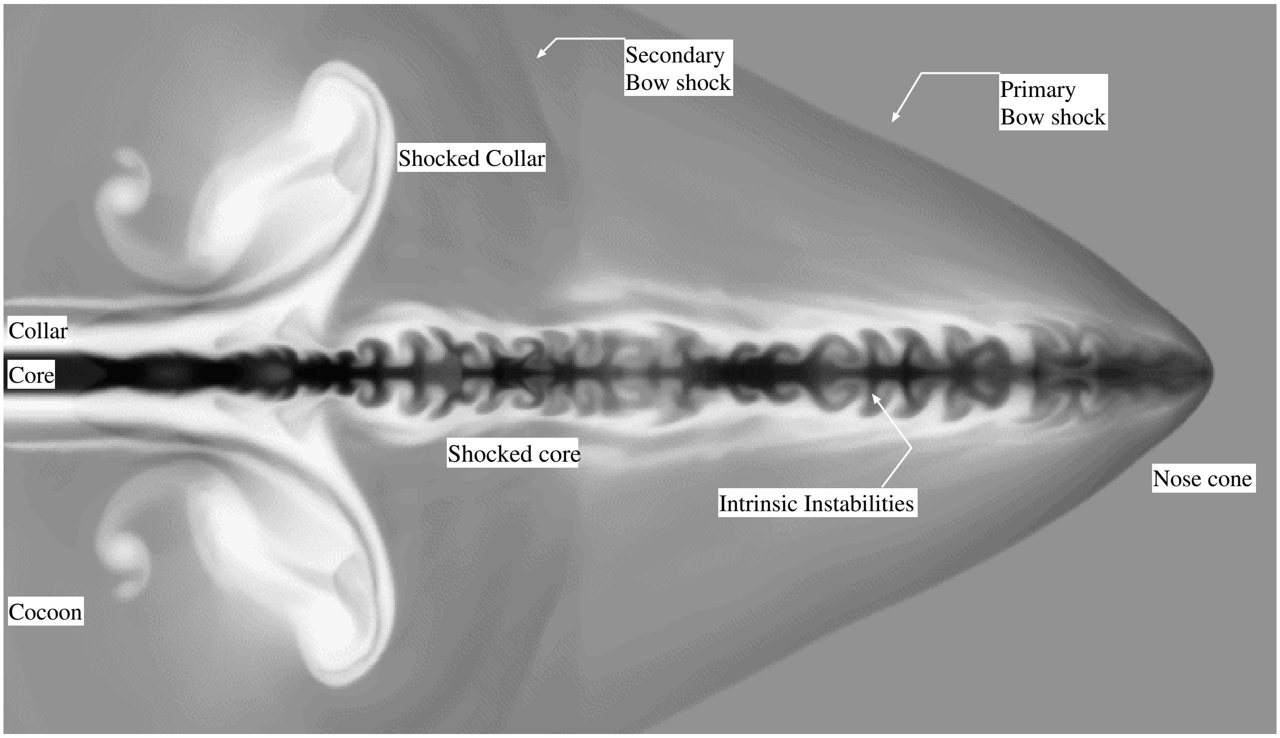


Fig. 3. Annotated grey-scale map of the density for an adiabatic simulation of the propagation of a *Multi-component* jet given by the Given Geometry model.

A multi-dimensional (2.5-D) simulation of a multi-component MHD jet have been performed using a MHD TVD code in cylindrical symmetry. The simulations are initiated with the cylindrically collimated jet equilibrium which traverses the length of the computational domain ($256 \times 1024$ zones), the jet radius being 64 zones. The equilibrium is then continuously injected at $z = 0$ boundary of the grid. The pressure outside the jet was imposed by the model through the pressure balance at the outer boundary. The jet is surrounded, in the present simulation, by a magnetized medium that has a small poloidal field and no toroidal component. We find that density and magnetic field stratification (with radius) in the jet leads to new behavior including the separation of an inner jet core from a low density collar. We find this *jet within a jet* structure, along with the magnetic stresses, leads to propagation behaviors not observed in previous simulation studies. Indeed, when the equilibrium encounters the external medium, the various elements of the equilibrium are shocked. This creates two bow shocks and a cocoon. The furthermost bow shock takes the form of a nose cone. Intrinsic instabilities develop in the inner part of the shocked core, as well as in the cocoon, as shown in Fig. 3. The most important aspect of the flow behavior seen in the simulation can be traced back to the annular stratification of the jet. In particular, the radial distributions of density velocity, and toroidal magnetic field appear to be the principle causes of the new behavior seen in the simulations. The jet exhibits a core/collar structure such that a high density core region exits near the axis surrounded by one or more lower density annuli (collars) extending out to the jet boundary. The strongest toroidal fields exist at the boundary between the core and collar. Since the momentum in the core is higher than that in the collar the propagation characteristics of the jet are dominated by the core pulling ahead of the collar. The strong field surrounding the core ensures that the two regions remain fairly distinct in terms of their dynamics. As the jet propagates we see the core acting as a *jet within a jet*. There exists a extremely low density inner collar (which also has higher velocity than the surrounding regions) and this leads to a complete separation of core and collar. The "peel-off" of the collar is quite dramatic.

Our methodology also allows us to compare MHD jets from different types of sources whose properties could ultimately be derived from the behavior of the propagating jets. By varying the properties of the

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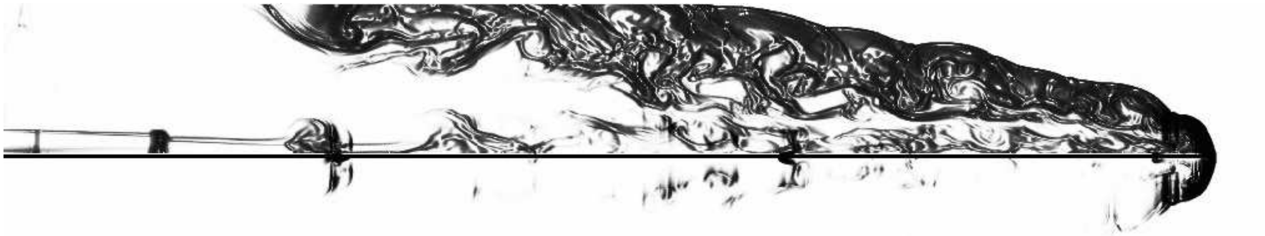

Fig. 4. Composite of the logarithm of the hydrogen number density (upper panel) and the H$\alpha$ emission (lower panel) for pulsed molecular jets propagating in an inhomogeneous medium (Courtesy S. O'Sullivan).

source, it is also possible to vary the properties of the jet itself. This introduces non-ad-hoc variations of the jet and gives rise to more complex behavior of the propagating jet, and also of the interaction with the ambient medium. We present such simulations for molecular jets in Figure 4 where the density (in the upper panel) is represented with the H$\alpha$ emission (in the lower panel) In this case, many features of the simulation are in good agreement with observations, such as the molecular cavities, the location and shape of the shocks, as well as the variation with distance of the ionization fraction and density along the jet.

Our results have bearing on a number of issues. The simplest conclusion that can be drawn is that the structure imposed on a YSO jet by the launching and collimation process can lead to fairly complex propagation characteristics. Thus our model builds on and extends previous work that utilized only "top-hat" jets as initial conditions. It does however point to the fact that the jets produced by magnetized rotators are likely to be more complex in their structure and, furthermore, that this complexity will be reflected in the observed jet morphologies. In recent observations of molecular outflows, small linear structures placed just ahead of bow shape shocks have been observed. These structures are almost exactly pointing away from the protostellar condensation position. These precursors of the bow-shock show a conical shape. It could be the trace of an underlying jet in which the shock is propagating. As the central, fast, "core" jetis propagating, it entrains the surrounding molecular outflow and forms the conical shape structure, while the outer "collar" participates in the entrainment of the larger bow-shock. These molecular emissions reveal a linear "precursor" to the bow-shocks, and may be a signature of the jet-driven entrainment of the molecular outflows at the head of the jet.

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