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JET COLLIMATION BY COMBINING AXISWARD MOTION AND COOLING

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ABSTRACT

A simple scheme is proposed for hydrodynamical collimation of astrophysical outflows into jets: Matter launched from a base with a ringlike topology can undergo a sticky collision at the axis and remain collimated. No ambient medium is required, though a significant fraction of the outflow could avoid strong collimation.

Subject headings: hydrodynamics — ISM: jets and outflows

The theory of hydrodynamic collimation has evolved considerably over the past two decades. Old models for jet collimation balance the pressure of an ambient medium (Sheuer 1974; Blandford & Rees 1974) against the internal pressure of the jet, leading to a sonic transition and "quasi-static" collimation. Somewhat later models (Cantó 1981; Eichler 1982) balance the ambient pressure with the inertial forces of the jet material that are associated with the collimation. They allow for inward focusing of the jet even when the ambient pressure decreases monotonically with distance from the jet source and a jet interior that may be entirely supersonic. The supersonic interior is arguably advantageous in that it can stabilize the flow against disruptive global hydrodynamic instabilities that might be expected. But these models still invoke the pressure of an ambient medium, which is dubious when the collimation occurs on very small scale. Still later models, often studied via numerical simulation (e.g., Icke et al. 1991 and references therein; Frank & Noriega-Crespo 1993; Peter & Eichler 1995) balance the inertial forces of an inner collimated flow with those of an outer, uncollimated flow (i.e., inertial confinement). The latter could be, for example, an accretion inflow in the case of newly forming stars and other compact objects, remnants of a slower wind from a prior era (e.g., in the case of a planetary nebula), or an outflow from an accretion disk or neutron star merger if there is reason to suspect a density profile that decreases with latitude from the plane of rotation. These models are motivated by observations of a variety of astrophysical systems that show collimation on very compact scales, where any ambient collimating medium is almost certainly in supersonic motion because of cooling or explosive energy release. However, it is observed (Peter & Eichler 1995) that inertial confinement is delicate in the following way: It obviously relies on a sizable density of the ambient medium relative to that of the jet material. If the flow cools rapidly on a hydrodynamical timescale, then, unless the initial density contrast is large, the pressure needed to collimate the jet material will irreversibly compress the jet material to the point where it is too dense to be influenced by the ambient medium. Even if all the material were noncooling, the permanence of dramatically good collimation, even after the jet material had left the confines of the ambient material, would be questionable because the initially confined material could reexpand away from the axis.

In this paper, we propose what could perhaps be termed "negative opening angle" confinement. It can be accomplished without an ambient medium merely by combining strong cooling with a nonsimple, ringlike topology of the source of the outflow. If the source of the wind is an accretion disk, as opposed to the central star or black hole, then an unconfined wind coming from the accretion disk probably has a substantial fraction aimed toward the axis. Effective cooling then enables this portion of the jet material to stick at the axis. Of course, one expects a comparable amount of material to emerge at a positive opening angle. The fate and observability of the latter portion of jet material are uncertain, since its dispersal may prevent it from propagating away from the source as effectively as the jet material.

Nevertheless, while making minimal demands on the wind source, the model makes some general predictions: The necessity of dissipation at the axis typically predicts a component of radiation emerging from near the source that is $\sim 10^{-1}$ of the total wind power. (This is not rigorously predicted, because in principle the dissipation could be via heat conductivity or cosmic-ray production, but we are being general.) This is to be distinguished from the energy dissipated by the accretion disk itself, which would be comparable in magnitude. Moreover, the interaction of the positive opening angle component with accreting material might be dissipated into radiation at some larger scale, where the inflowing material has not yet been flattened by its own angular momentum.

The hypothesis that matter ejection from accretion disks has a substantial axisward component differs from the rather popular model of magnetocentrifugal ejection from a Keplerian disk, which would predict outward ejection. However, some of the assumptions inherent in the latter hypothesis are questionable and in any case unproved. For example, swept-up flux that accumulates in the interior of the accretion disk eventually becomes dynamically significant unless reconnection dissipates the magnetic energy. In either case, unordered magnetic activity may spoil the picture of the highly ordered field generally invoked for centrifugal winds. Although we do not presume to anticipate all the details, it seems no less likely that the wind mostly originates from an annular region that roughly coincides with the innermost Keplerian orbit of the accretion disk (where most of the disk's energy budget is expended), and that it is sprayed every which way by small-scale coronal-type processes.

The two-dimensional axisymmetric hydrodynamic code used to simulate the jet dynamics is based on the piecewise parabolic method of Colella & Woodward (1984). The code (VH-1) is similar to the one used to model astrophysical jets in previous studies (Blondin, Fryxell, & Königl 1990, hereafter BFK; Peter & Eichler 1993, hereafter PE; Peter & Eichler 1995). The ambient gas throughout the numerical grid was initially uniform and at rest with a density ρ_a and pressure p_a. A jet with velocity $v = M_A c$ and density ρ_{jet} is injected at the origin $z = 0$. The jet is hollow, with a radius r_{jet}, a thickness of one radial cell, and an opening angle θ_0 at $z = 0$. The quantity M_A is the Mach number and c is the local speed of sound. The boundary conditions are constant inflow velocity at $z = 0$ and $r = r_{jet}$, outflow boundary conditions for $z = 0$ and $r \neq r_{jet}$, a reflecting boundary condition at $r = 0$, and enforcement of zero gradients at the downstream boundaries $z = z_{max}$ and $r = r_{max}$. The equations which are solved are

$$\partial\rho/\partial t + \nabla \cdot (\rho \boldsymbol{v}) = 0 , \quad (1a)$$

$$\partial(\rho \boldsymbol{v})/\partial t + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) + \nabla P = 0 , \quad (1b)$$

$$\partial(\rho \mathscr{E})/\partial t + \nabla \cdot (\rho \mathscr{E} \boldsymbol{v}) + \nabla \cdot (P\boldsymbol{v}) = -n^2\Lambda , \quad (1c)$$

where $\mathscr{E} = v^2/2 + (\gamma - 1)^{-1}P/\rho$ is the total specific energy, ρ is the mass density, and P is the thermal gas pressure. In addition, n is number density of nuclei and Λ is the cooling function. The jet and ambient gas are treated as a single fluid with ratio of specific heats $\gamma = 5/3$. Because the gas is assumed to be completely ionized, the average mass m per particle is constant. This assumption breaks down when the gas cools below 10^4 K, resulting in an overestimation of the thermal pressure of the gas (BFK).

The simulations were conducted for a hollow jet with a 1 grid cell thickness. The jet matter propagated into a low-density, pressure-matched, ambient medium with a *negative* opening angle of 20° (chosen with no special physical significance in mind). The simulations had a computation region with an axial length of 300 cells and a radial width varying between 150 and 300 cells. The resolution varied between 12 and 150 zones per jet radius r_{jet}.

A more realistic jet would have included the effect of a finite spread of ejected material distributed at angles about −20°. However, the important effects of the model are demonstrated unambiguously with this slightly simplified set of simulations.

In the simulations, radiative cooling was calculated using a local, time-independent cooling function $\Lambda(T) \propto T$. This scaling was chosen for simplicity and convenience; it is only a crude approximation to more detailed cooling models, e.g., the nonequilibrium ionization cooling rate of a cosmic abundance gas calculated by Kafatos (1973), which was used in the simulations of BFK. The parameter study was done by specifying a parameter $\chi = d_{cool}/r_{jet}$, where d_{cool} is the distance behind a radiative shock for the gas to cool to some low value ($\sim 10^4$ K), and r_{jet} is the radius of the jet.

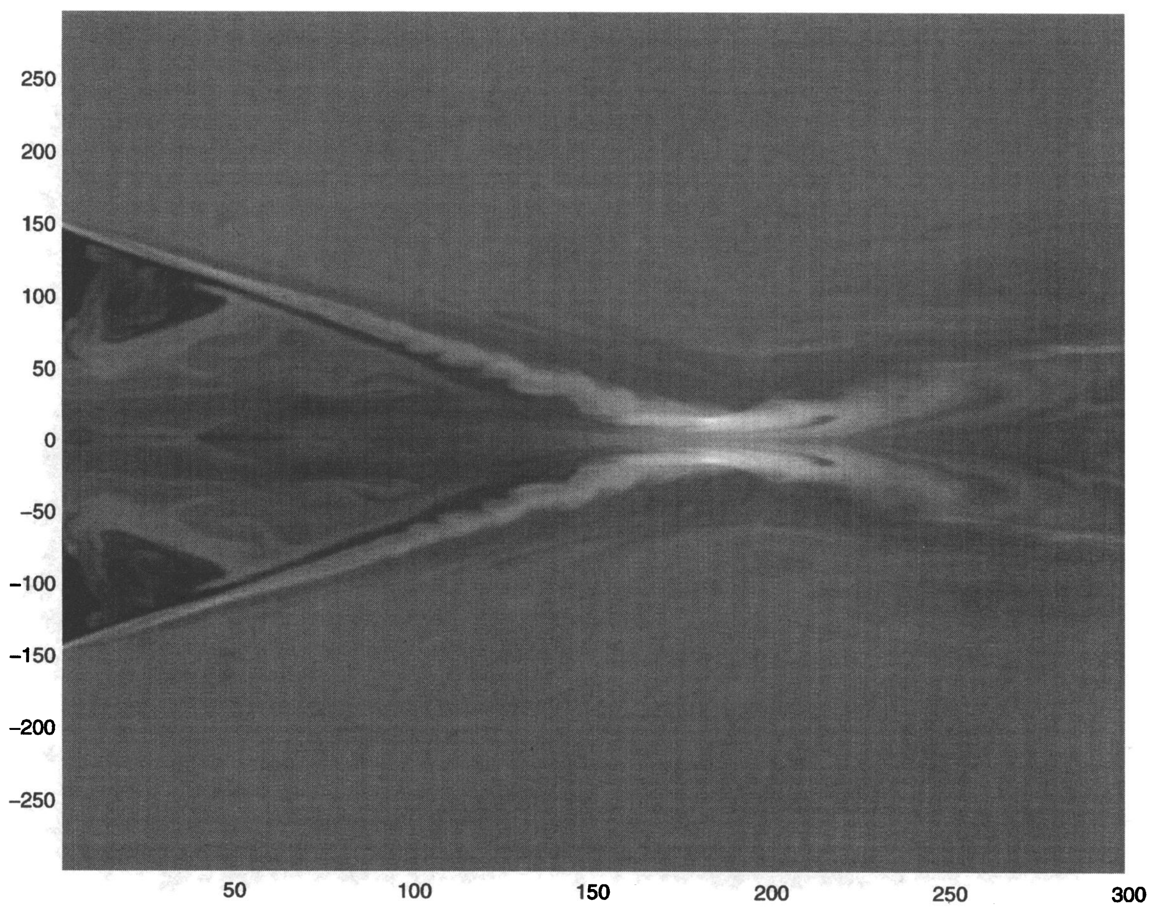

FIG. 1.—Gray-scale plot (r vs. z) of matter launched from a base with a ringlike topology. The ambient medium is pressure matched but tenuous (density contrast $\eta = 10$). The Mach number $M_A = 20$, and the opening angle is −20°. There are 150 cells per jet radius. The time of the snapshot is at $t = 350 r_{jet}/v_{jet}$. Matter collides at the axis of symmetry at $r = 0$ and then diverges. (The diverging jet is slightly more collimated because of hydrodynamic collimation of the ambient medium.)

Hence, $\chi \gg 1$ for an adiabatic jet (the shock-heated gas never appreciably cools) and $\chi \ll 1$ for an isothermal jet (the gas quickly cools to a given "floor" value for the temperature, a parameter adjustable in the code).

It was shown in BFK that $d_{\rm cool}$ can be approximated by

$$d_{\rm cool} \approx \frac{9 v_s^3 \bar{m}}{64 n_0 \Lambda(T_s)}, \quad (2)$$

where n_0 is the preshock number density of nuclei; v_s is the velocity of the radiative shock; $\bar{m}$ is the average mass per particle; Λ is the cooling rate in ergs cm^3 s^{-1}, which was assumed proportional to the temperature; and $T_s = 3\bar{m}v_s^2/16k$ is the immediate postshock temperature. In the simulations, χ instead of Λ was varied, since it is a more direct measure of radiative cooling strength. The simulations usually considered values of $\chi \lesssim 1$. In Figure 1 is a density contour plot for matter ejected with a ringlike topology into a tenuous medium. The density contrast $\eta = \rho_{\rm jet}/\rho_a = 10$ (i.e., the jet is 10 times denser than the ambient medium), and the Mach number $M_A = 20$. There is no radiative cooling. It is seen that, because of symmetry, the jet reflects off the axis of symmetry and forms a jet with a *positive* opening angle at the reflection point. Because of the presence of an (albeit tenuous) ambient medium, the reflected jet is mildly collimated by the ambient pressure (Eichler 1983; PE). In cases where the ambient medium is even more tenuous, there will be almost no collimation. In any case, the jet appears to self-disrupt at its working surface.

When radiative cooling is introduced, the picture changes. For low cooling rates (e.g., for the parameters of Fig. 1 we mean cooling ratios $\chi > 0.1$), the jet outflow may cool only *after* reflection. The resulting reflected jet (at the positive opening angle of 20°) could not collimate as well as it would in a noncooling medium because the cooling ambient medium cannot provide the usual pressure support (BFK). For large cooling rates ($\chi < 0.1$ for the jet parameters of Fig. 1), however, the incoming matter rapidly cools. When the jet material collides on the axis, it is unable to rebound with the same energy, and tends to "stick." In the cooling simulations, the matter "stuck" so closely to the axis that problems with inadequate mass advection off the singularity at $r = 0$ (Monchmeyer & Muller 1989) became more severe. This was evidenced in the simulations by a very high density spike in the first radial cell. It was necessary to modify the code according to the prescription of Blondin & Lufkin (1993) in order to deal better with the inadequate mass advection near $r = 0$. More grid cells and better resolution also seemed to ameliorate the high-density spike near $r = 0$.

Radiative cooling simulations were done using a linear cooling function χ between 0.01 and 0.1. The "floor" temperature of the cooling jet was varied between 10^{-2} and 10^{-6} of the initial jet temperature. Values of the floor temperature less than 10^{-2} cannot in principle be justified rigorously in our numerical simulations because the density of the cooling postshock gas will be orders of magnitude larger than the initial density. This should lead to large errors in

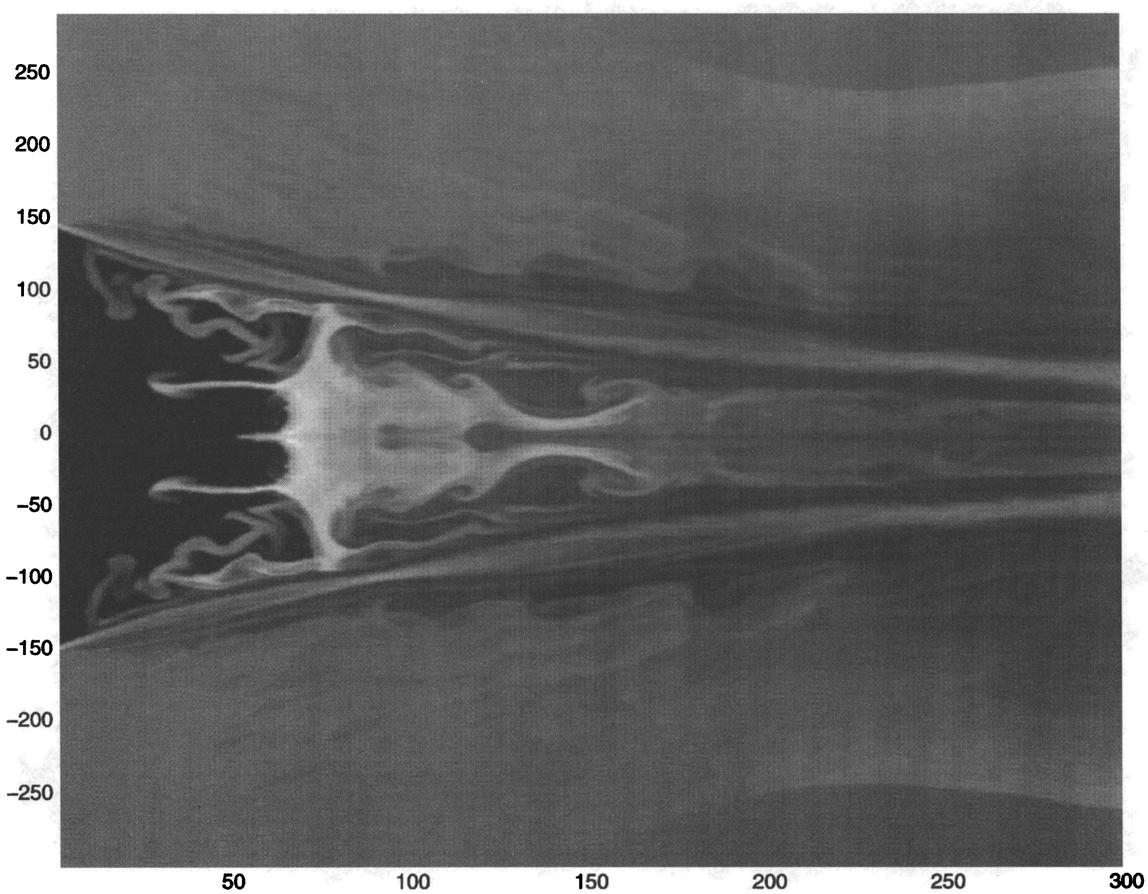

FIG. 2.—Gray-scale plot of a jet with the same parameters as in Fig. 1, except that radiative cooling is enabled ($\chi = 0.06$; the jet "floor" temperature was equal to 10^{-2} of the initial jet temperature). The time of the snapshot is at $t = 100 r_{\rm jet}/v_{\rm jet}$.

the energy loss rate of zones along the hot and cold gas interface. However, these simulations did show that, as the gas was allowed to cool to lower floor temperatures, the "stickiness" of the gas increased upon collision on axis.

In Figure 2 we give an example of a cooling jet with an opening angle of $-20°$, $\chi = 0.06$, and a floor temperature of 0.01 of the initial jet temperature. As seen in the halftone density plot, the outflowing gas material is slowly bent by oblique shocks and inner gas material, so that the flow is parallel to the cylindrical axis of symmetry. Upstream from the main shocked gas (the dense region near the axis at the origin), the gas is relatively stationary. The material downstream and inside the "hollow tube of collimated outflow" has an axial velocity along $+z$, but the magnitude of the velocity is over an order of magnitude less than that of the inflowing material on the "conical outflow surface." Because the mass of material within this conical outflow surface has a slow axial velocity, it does not accumulate with time.

The cooling parameters used in the simulation shown in Figure 2, and hence the density enhancement at the axis, are deliberately kept modest so that the latter cannot be attributed to numerical resolution issues. Rather, Figure 2 is meant to illustrate the validity of the present model in that matter launched from a base with a ringlike topology can undergo a sticky collision at the axis and remain collimated. Increased cooling was found to improve the collimation. We have also run lower resolution simulations with less zones per jet radius, in order to follow the jets farther downstream to verify that the cooling jet remained collimated at large z while the noncooling jet did not.

We conclude that an ejected outflow can maintain collimation of its inner parts if it both cools rapidly and originates from a source with a ringlike topology. There is a tendency of the inner region to fill the "hole," and hence to be directed inward. The rapid cooling of shocked material limits the inner region's ability to rebound off the axis of symmetry.

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