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INERTIAL CONFINEMENT OF ASTROPHYSICAL JETS

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ABSTRACT

Observations of the X-ray jet of SS 433 and of newly formed stars suggest collimation at scales too small for the pressure of an ambient medium to have played a role, since cooling of the necessarily dense confining matter would be rapid on a dynamical timescale. Inertial confinement by material on the compact scale is investigated here using two-dimensional hydrodynamic simulations. The results indicate that even modest cooling can spoil collimation for density ratios that would yield good collimation in the noncooling limit. Collimation of a cooling flow can be obtained if the jet material is sufficiently underdense compared to the ambient confining medium, but the range of parameter space for which the scheme works may be restricted.
Subject headings: hydrodynamics — ISM: jets and outflows — stars: individual (SS 433) — X-rays: stars

Old models for jet collimation invoke the pressure of an ambient medium (Sheuer 1974; Blandford & Rees 1974; Canto et al. 1981; Eichler 1982) that may be taken to be static. In the past decade or so, however, observations of the X-ray jet of SS 433 and of newly formed stars suggest collimation at the scale of the jet's origin, that is, at scales too small for the pressure of an ambient medium to have played a role. In general, it is unlikely that the accretion disks surrounding nascent stars could provide pressure support adequate for collimation, because the cooling would be too severe to allow for any sort of corona in hydrostatic equilibrium.

An alternative, investigated here via two-dimensional axisymmetric numerical hydrodynamic simulations, is the possibility that a cold ambient medium can collimate a galactic jet by inertial effects. This has been suggested already by Icke and coworkers (1991 and references within) and also explored numerically by Frank & Balick (1993), who do not include cooling and argue that it should not affect the results too much. However, if the collimation specifically takes place on compact scales, the question remains as to whether the jet would not decollimate as it leaves the confining medium. If there is no cooling, then it could be argued that the confinement is not permanent (or that permanent collimation is at best modest), since the retained thermal energy could go into reexpansion. The issue of the permanence of the collimation of an adiabatic jet has not, to our knowledge, been addressed adequately by numerical simulations, perhaps because of the inherent time limitations. A gradual tapering of the confining medium could in principle shape the jet via a gun barrel or nozzle effect along the lines originally suggested by Sheuer (1974) and Blandford & Rees (1974), but then the problem of global hydrodynamic instabilities arises. (Magnetic confinement schemes, otherwise an attractive and popular alternative, suffer similar problems of global stability [Eichler 1993].) Such instabilities could be prevented by assuming the jet cavity shape to be maintained by ram pressure as opposed to thermal pressure (Eichler 1982, 1985), but the collimation of a noncooling jet would surely involve shock heating, and the jet, after passing through one or two Mach disks, say, would degenerate into turbulence. This problem, in turn, could possibly be circumvented if the shocked jet material rapidly cools, but then this cooling could reduce the putative jet to dense blobs, which would be much harder to collimate. Even in a code restricted to axisymmetry, the density enhancement would hinder the collimation. This is the dilemma we investigate here. Can inertial collimation, which can work only if the ambient density is appreciable compared to that of the jet material, enjoy the stability enhancement offered by cooling without paying the penalty that might result from too large a density enhancement?

In our simulations, we explore the interrelated issues of cooling and density contrast. We vary the density contrast and include cooling in both the ambient medium and jet material. This isolates the effect of inertia in the ambient medium by ensuring that its pressure be insignificant.

Although we treat the ambient medium as being initially motionless here, it is meant to represent the effects of an inflow or outflow of an accretion disk that presumably surrounds the outflow that becomes, via collimation, the jet. The outer outflow could have originated from disk material flung out by magnetocentrifugal ejection (Blandford & Payne 1982; Königl & Wardle 1993) or it could be the funnel-like inflow that feeds the accretion disk. Evidence that there is a two-component outflow—generally with the inner component the hotter, more tenous one—has been discussed by several authors in a variety of contexts. Königl (1982), in the context of newly forming stellar systems, conjectures that the inner jet of ionized material was collimated by the outflow that goes into driving molecular clouds outward. Two-component outflows have also been discussed by Shu and coworkers (1988) in the context of nascent stars, and by Eichler (1993). These authors invoke other motivations, both observational and theoretical, for the assumption of two components to the flow. Blandford (1993) has made a similar conjecture in the context of AGNs, that is, that the jet emerges in the form of Poynting flux from a black hole, and is perhaps collimated by outflow from the accretion disk. Levinson & Eichler (1993) have argued that baryonic outflow from a neutron star merger is obligatory, and that cosmological gamma-ray bursts, if they originate in neutron star mergers, survive quenching by this outflow because they

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are produced by an inner jet of material that is produced on black hole–threading field lines. These various motivations have been discussed in spite of the added assumption of an additional component to the outflow.

By way of comparison to previous work, we note that even a noncooling ambient medium contributes an inertial component to the confinement, since the ever accumulating cocoon must push the ambient material out of its way and therefore be overpressured relative to the latter. This is seen in simulations of high Mach number jets (e.g., Loken et al. 1992; Peter & Eichler 1993). But the accumulation of cocoon material and its space retention capabilities depend strongly on its thermal lifetime, so that neglect of cooling in simulations may overestimate its hydrodynamical role.

The two-dimensional axisymmetric hydrodynamic code used to simulate the jet dynamics is based on the piecewise parabolic method of Collela & Woodward (1984). The code is similar to the one used to model astrophysical jets in previous studies (PE; Blondin, Fryxell, & Königl 1990, hereafter BFK). 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 $\rho_{\rm jet}$ is injected at the origin $z = 0$. The jet has a radius $r_{\rm jet}$ and 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 $r < r_{\rm jet}$, outflow boundary conditions for $z = 0$ and $r > r_{\rm jet}$, a reflecting boundary condition at $r = 0$, and enforcement of zero gradients at the downstream boundaries $z = z_{\rm max}$ and $r = r_{\rm max}$. The equations which are solved are

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

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

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

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 $\bar{m}$ 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).

A time snapshot of a simulation for a filled-in jet propagating into a pressure-matched ambient medium with an opening angle of 20° is presented in Figure 1. The opening angle of 20° has no special physical significance for a jet emanating from a compact object, but was used for comparison to an earlier study (PE) on the X-ray jet of SS 433. The simulations had a computation region with an axial length of 300 cells and a radial width of 150 cells, with a resolution of up to 10 cells per jet radius. Because the jet widens somewhat after the opening, the numerical resolution across the jet is better downstream.

The time snapshot in Figure 1*a* is in the form of a density contour plot (r vs. z), and the normalized time at which the snapshot was taken was $t = 40 r_{\rm jet}/v$. A Mach number $M_A =$ of

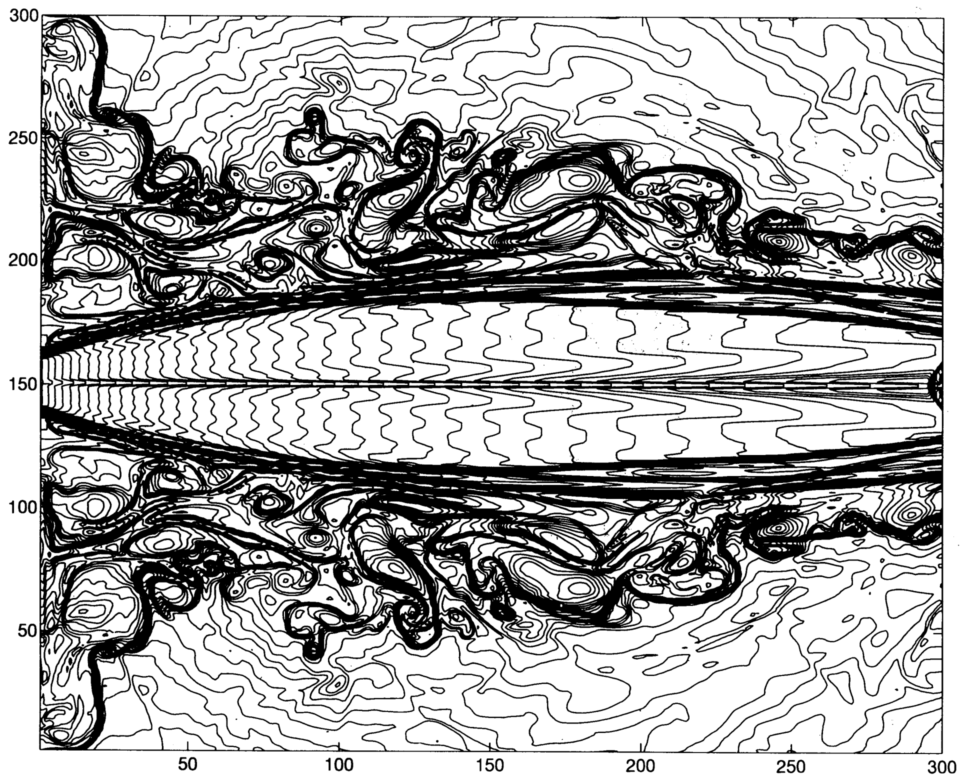

FIG. 1*a*

FIG. 1.—Simulation snapshots (r vs. z) of density contours for a filled-in adiabatic conical jet with $M_A = 20$, and opening angle 20° at a normalized time $t = 40\, r_{\rm jet}/v$. The jet propagates through a pressure-matched ambient medium, and there are 10 cells per jet radius. The units are the number of grid cells from the origin ($r = 0, z = 0$). The $r = 0$ symmetry axis is halfway up the ordinate axis (cell number 150). Shown are (*a*) jet with $\eta = 1$, (*b*) jet with $\eta = 0.1$.

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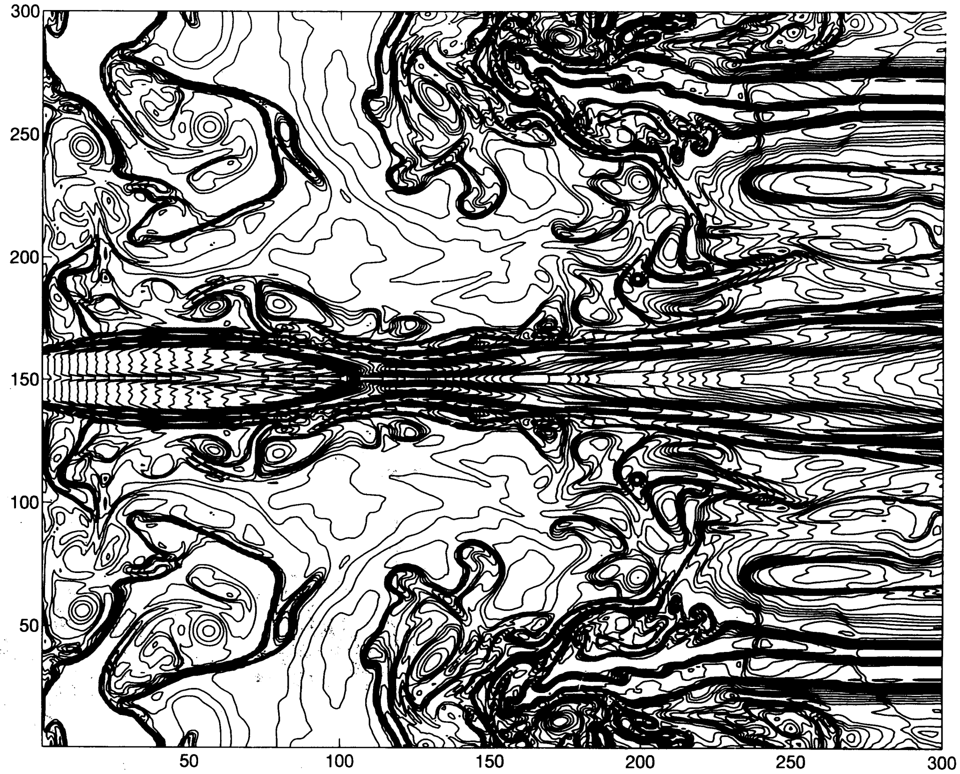

FIG. 1b

20 was assumed, and a density contrast η (jet to ambient medium density ratio, ρ_{jet}/ρ_a) was unity. Note that the channel shape in Figure 1a is described by the analytic expression derived in Peter & Eichler (1993, hereafter PE):

$$y = \begin{cases} 2[E(k) - E(\beta, k)] - [K(k) - F(\beta, k)] & 0 < y(x) < y(x_{max}) \\ 2[E(k) + E(\beta, k)] - [K(k) + F(\beta, k)] & y(x_{max}) < y < y_c , \end{cases} \quad (2)$$

where the angle χ is the complement of the opening angle, x is the cross-sectional channel radius, and the y-axis is the axial axis of symmetry along which the jet propagates. The functions $F(\beta, k)$ and $E(\beta, k)$ are the elliptic integrals of the first and second kind, respectively, and $K(k)$ and $E(k)$ are the complete integrals of the first and second kind. The quantities β and k are defined as

$$\beta = \sin^{-1}\left(\frac{1 - \sin \chi}{1 - \sin \chi_0}\right)^{1/2}, \quad k = \left(\frac{1 - \sin \chi_0}{2}\right)^{1/2}. \quad (3)$$

A plot of the channel shape $y = y(x)$ for an opening angle of $\theta_0 = 20°$ is shown in Figure 2 from the solution in equation (2).

The scale length for pressure collimation is $L = (\mathcal{P}/\pi v P)^{1/2}$, where P is the pressure of the ambient medium, v is the jet velocity, and $\mathcal{P}$ is the (fixed) power in the jet. For small opening angles, PE showed that the pressure of an ambient medium can collimate a jet at a scale length of πL. The collimation length in the simulations (e.g., Fig. 1a) was somewhat less than the predicted theoretical value. One reason for this is overpressure in the cocoon. Inertial confinement, like cocoon overpressure, also results in increased jet collimation. This is seen for a jet with density contrast $\eta = 0.1$ pictured in Figure 1b, which should be compared with the same jet for $\eta = 1.0$ in Figure 1a.

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, for example, 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. 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).

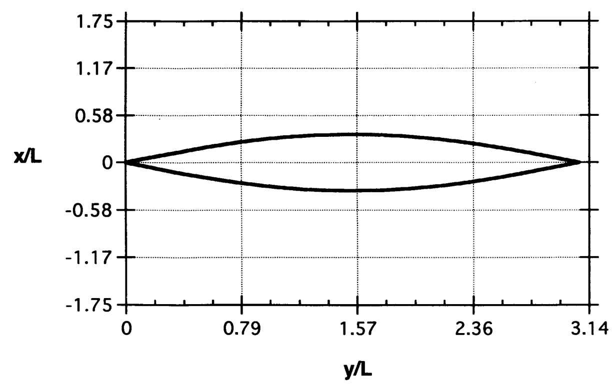

FIG. 2.—Theoretical shape of a jet collimating by means of ambient pressure from Peter & Eichler (1993). The curve is x vs. y and is a plot of eq. (2) for an opening angle of 20°.

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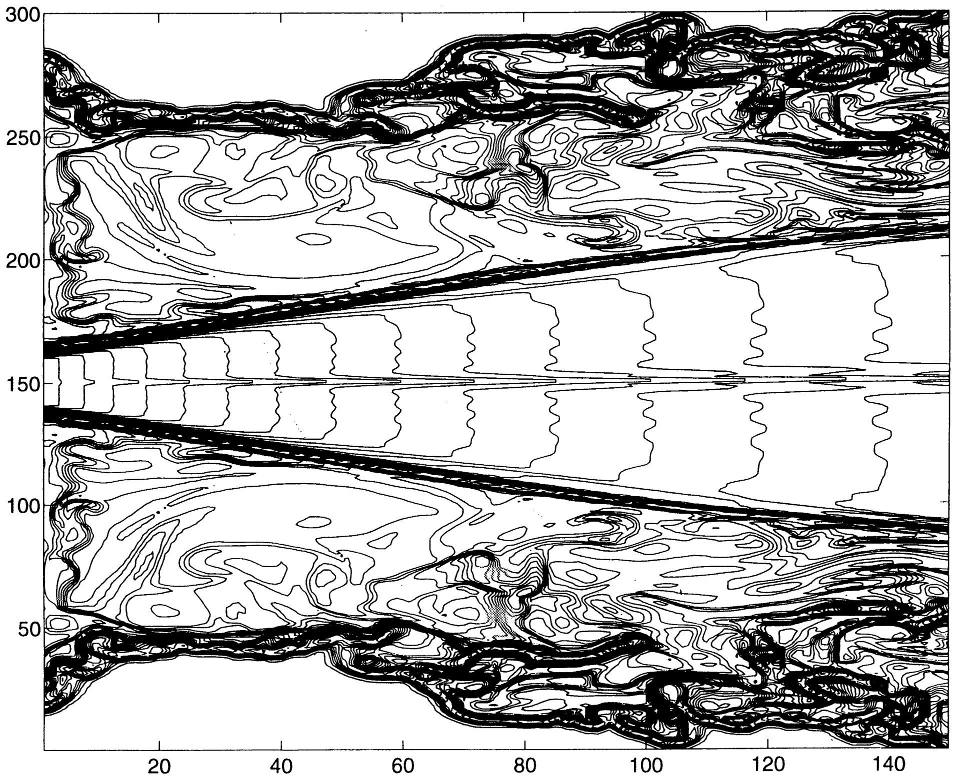

FIG. 3a

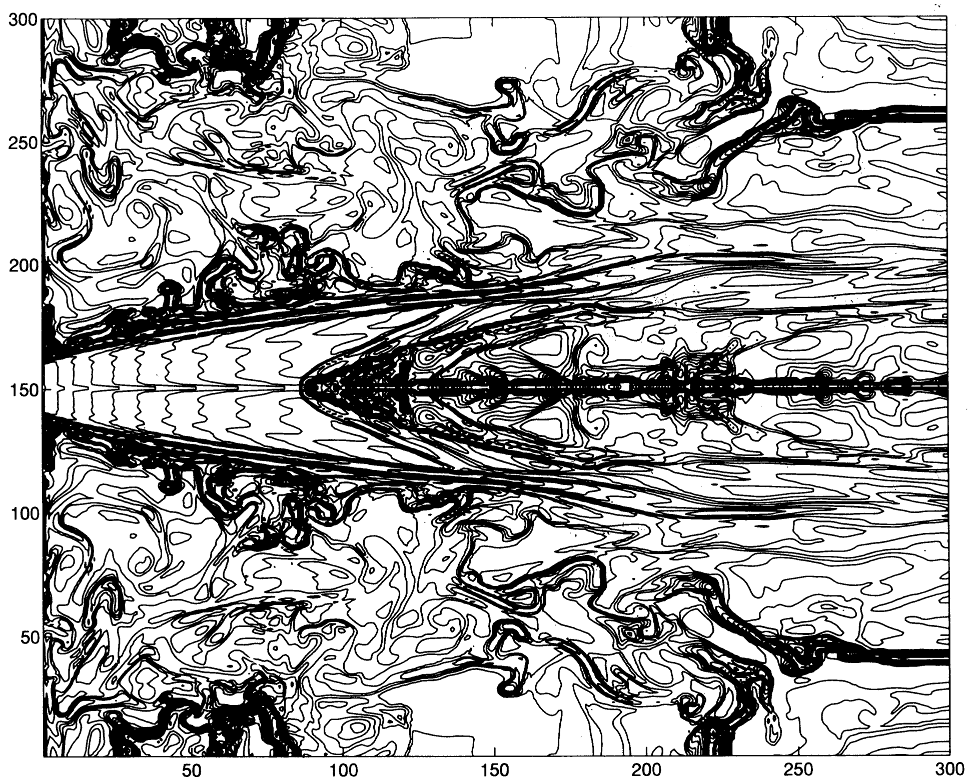

FIG. 3b

FIG. 3.—Density contours for filled-in cooling jets with $M_A = 20$, and opening angle 20° at a normalized time $t = 40\ r_{\rm jet}/v$. The figures have $\chi = 0.6$ and a jet "floor" temperature equal to 0.01 of the initial jet temperature. The geometry is equivalent to that of Fig. 1. (*a*) Cooling jet with $\eta = 1$, and (*b*) cooling jet with $\eta = 0.04$.

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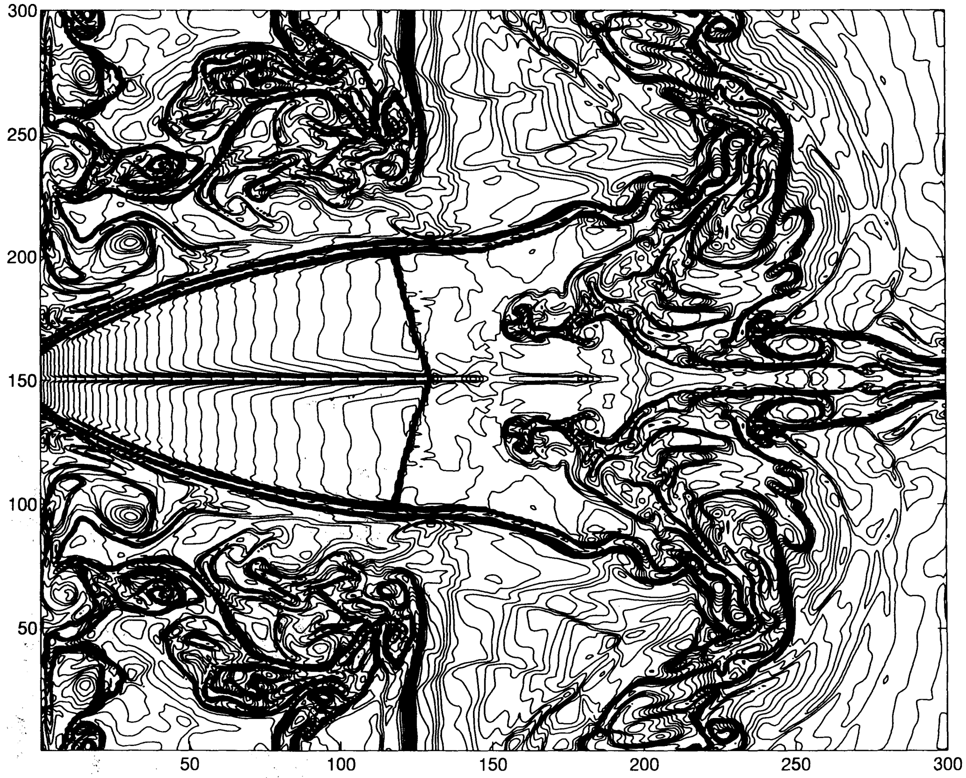

FIG. 4*a*

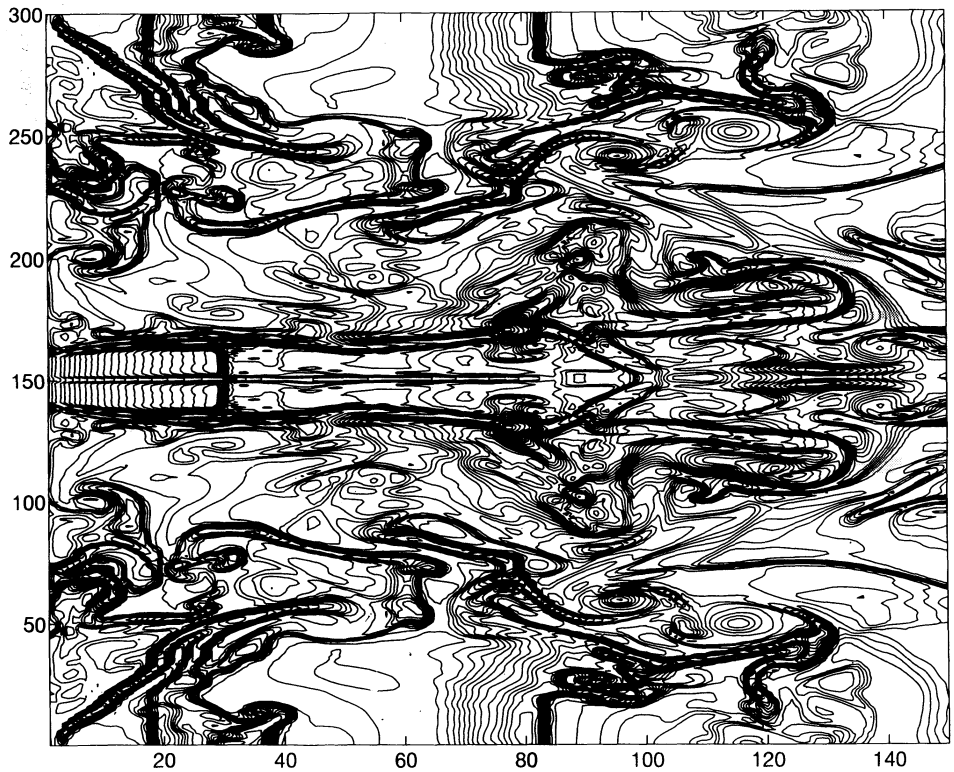

FIG. 4*b*

FIG. 4.—Density contours for a filled-in, $M_A = 20$ jet with an opening angle of 40° at a normalized time of $t = 40\,r_{\rm jet}/v$. (*a*) Adiabatic jet, $\eta = 1$; (*b*) adiabatic jet, $\eta = 0.1$.

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

$$d_{\rm cool} \approx \frac{9 v_s^3 \bar{m}}{64 n_0 \Lambda(T_s)}, \quad (4)$$

where n_0 is the preshock number density of nuclei, $\bar{m}$ 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 $\chi \lesssim 1$.

Given the same density contrast, cooling jets do not collimate as well as noncooling jets (BFK). This is because the cooling ambient medium cannot provide the usual pressure support. An example of this is shown in Figure 3 for a jet with an opening angle of 20° and a linear cooling function with χ taken to be 0.6. The two snapshots are taken at the same time $t = 40\ r_{\rm jet}/v$. Note that the lack of pressure support in a cooling jet is not fatal to collimation. In Figure 3 we show density contour plots of radiatively cooling simulations at a time $t = 40 r_{\rm jet}/v$ to demonstrate the characteristics of the collimation. The simulation in Figure 3*b* is equivalent to that of Figure 3*a* except that the density contrast is 0.04 instead of unity. The jet in the former case is seen to collimate in the denser ambient medium, and the collimation of the jet is comparable to the (pressure-supported) adiabatic case shown in Figure 1*a* (for which $\eta = 1.0$). Even though there is little *pressure* support to collimate the jet in Figure 3*b*, this jet collimates because the ambient medium is *denser* than the jet itself. We call this *inertial* collimation.

In Figure 3 the "floor" temperature of the cooling jet was taken to be 0.01 of the initial jet temperature. Note how the jet in Figure 3*b* appears to "hollow out" and an intricate shock pattern in the interior of the "wings" is evident. Simulations were also run for a floor temperature of 10^{-6} of the initial jet temperature, to allow the jet to cool to a much lower temperature. The results are similar to those of Figure 3 except that the scale length over which collimation occurs is usually larger (the collimation is somewhat poorer).

As reported by Stone & Norman (1993), there exist some morphological differences between jets for which time-independent and time-dependent cooling functions are used. These differences are apparently attributable to differences in the respective cooling rates between the two formalisms. Nevertheless, the structure and evolution of the jets appear to be quite similar. (In fact, the cooling rate in the time-independent formalism was even indicated to be larger than the rate in the time-dependent case. This suggests that the time-independent cooling function used here should actually be overly pessimistic regarding jet collimation). In any case, the purpose of the present study was to demonstrate the proof of principle of inertial confinement and not to map out detailed regions of parameter space for which inertial confinement would occur. The cooling rate used in our simulations was treated as a free parameter. Even for high cooling rates, (e.g., $\chi = d_{\rm cool}/r_{\rm jet} = 0.04$), there were always low enough values of the density contrast for which the jet was able to be collimated (subject to numerical resolution problems for some simulations with high cooling rates, for which no results are claimed).

Inertial effects, when acting in conjunction with the pressure of an ambient medium, can have dramatic results on jets with large opening angles for which the ambient pressure alone is not able to cause collimation. In Figure 4*a* we show a density contour snapshot of a jet with an opening angle of 40° and a density contrast $\eta = 1.0$. In Figure 4*b* the same jet is shown propagating into a medium 10 times denser; the increased collimation due to inertial effects is evident. We conclude that hydrodynamic jets can be inertially collimated by a medium, even if both the medium and the jet suffer radiative cooling. Such a mechanism may be responsible for the collimation seen in astrophysical jets. A more realistic simulation would include the motion of the exterior medium, which is presumed to be flowing into or out of the accretion disk (or that part of it) that surrounds the source of the jet material. However, we believe that the simulation results presented here establish the viability of inertial collimation as a physical principle when the material to be collimated is sufficiently tenuous relative to the ambient collimator.

The runs displaying collimation demonstrate global stability only to axisymmetric perturbations. However, inertial collimation works because the outer region of the flow is denser than the inner, collimated region. We thus expect interchange stability at the boundary where the inner, light fluid is collimated by the denser exterior fluid.

We further conjecture that a flow can maintain collimation of its inner parts if it both cools rapidly and originates from a source with a doughnut-like topology. There would always be a tendency of the inner region to fill the "hole," and hence to be directed inward. The rapid cooling of shocked material would limit the inner region's ability to rebound off the axis of symmetry. This conjecture, however, has not been demonstrated here and is envisioned as a subject of future work.

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REFERENCES

Blandford, R. 1993, in Proc. 2d Compton Symp., ed. T. Gehrels & M. Friedlander (New York: AIP), 578
Blandford, R., & Payne, D. G. 1982, MNRAS, 199, 883
Blandford, R. D., & Rees, M. J. 1974, MNRAS, 169, 395
Blondin, J. M., Fryxell, B. A., & Königl, A. 1990, ApJ, 360, 370 (BFK)
Canto, J., Rodriguez, L. F., Barral, J. F., & Carrel, P. 1981, ApJ, 224, 102
Collela, P., & Woodward, P. R. 1984, J. Comp. Phys., 54, 174
Eichler, D. 1982, ApJ, 263, 571
———. 1983, ApJ, 272, 48
———. 1985, in Unstable Current Systems and Plasma Instabilities in Astrophysics, ed. M. R. Kundu & G. D. Holman (Dordrecht: Reidel), 425
———. 1993, ApJ, 419, 111
Frank, A., & Balick, B. 1993, 404, L25
Icke, V., Mellema, G., Balick, B., Eulderink, F., & Frank, A. 1991, Nature, 355, 524
Kafatos, M. 1973, ApJ, 182, 433
Königl, A. 1982, ApJ, 261, 115
Königl, A., & Wardle, M. 1993, ApJ, 410, 218
Levinson, A., & Eichler, D. 1993, ApJ, 418, 386
Loken, C., Burns, J., Clarke, D., & Norman, M. L. 1992, ApJ, 392, 54
Peter, W., & Eichler, D. 1993, ApJ, 417, 170 (PE)
Sheuer, P. A. G. 1974, MNRAS, 166, 513
Shu, F. H., Lizano, S., Ruden, S. P., & Najita, J. 1988, ApJ, 328, L19
Stone, J. M., & Norman, M. L. 1993, ApJ, 413, 198

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