INSTABILITIES IN ASTROPHYSICAL JETS: DISEASE AND CURE

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I. Introduction

A striking feature of extragalactic radio jets is that they are so narrow. Theories of collimation should account for opening angles of order 1^o or less (as opposed to those of laboratory jets which become turbulent and typically open up to more than 10^o). This makes instabilities particularly troublesome for theories of collimation in which they are present. While instabilities might not entirely destroy the general bipolar nature of the flow, they decollimate it by definition.

There have been many papers concerning instabilities in jets and they are reviewed by Norman and Ferrari at this conference. The hydrodynamic (Kelvin-Helmholtz type) instabilities are basically "centrifugal", that is, if a small bend in the flow develops, the centrifugal force of the flow as it shoots around the bend pushes it out further. For subsonic flow, the work done by the centrifugal force exceeds the energy in the acoustic deformation of the fluid that is associated with it, and the remaining energy goes into the growth of the instability.

Helical magnetic fields have been invoked to contain jet material by magnetic tension. However, as Parker (1977) has pointed out, balancing the pressure in the field with its tension requires just the right pitch, but in a steady-state, field-dominated configuration in a column of varying cross section, the pitch necessarily varies along the axis of the column. Too much pitch ($B_\psi/B_z \gtrsim 2$) causes the coiled magnetic field to be under compression, in which case it is unstable to buckling.

The general criterion for the various instabilities is that internal stress, thermal or magnetic, supports the disruption of the flow. Following an argument (section II) that instabilities are a serious problem for jet models that invoke dynamically significant internal stresses, a model is presented in section III for the

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hydrodynamic collimation of jets having no significant internal stresses.

II. Are the Instabilities Critical?

It is often suggested that instabilities do occur in astrophysical jets but that they are not critical. Some of these suggestions and their difficulties are reviewed here.

Blandford and Rees (1974) suggested that the turbulence at the edge of the jet is constantly cleansed by the convective action of the moving jet material. But this does not address global instabilities (i.e. those having a scale as large as the jet itself). Several authors (e.g. Hardee 1979, Cohn 1983) have suggested that the instabilities help the knots form that are sometimes observed. But a Kelvin-Helmholtz type instability that has grown to large amplitude destroys the collimation of the flow and there is no obvious reason why the jet, knotty or not, should maintain its collimated form.

Axisymmetric 3-D numerical simulations (Norman et al 1981) demonstrate a fluid nozzle operating, without being disrupted by axisymmetric perturbations, over a limited range of jet power that corresponds to "fat" jets, where the jet thickness is comparable to the ambient scale height. However, this simultaneously implies poor collimation near the nozzle even for a stable jet. Moreover, 2-D simulations (Woodward, in preparation) suggest that kink-mode instabilities are even more dangerous than axisymmetric ones; thus, a true 3-D jet would have an operating range that is more narrow than that given by the axisymmetric simulations and possibly vanishing.

It is sometimes conjectured that a sharp density contrast between the jet material and the stationary ambient medium can solve the stability problems, because the growth rate decreases with decreasing jet density ρ_j. However, the velocity at which ripples at the contact surface propagate in the direction of the jet is proportional to ρ_j whereas the imaginary part of the frequency varies only as $\rho_j^{1/2}$; thus, decreasing the jet density only serves to increase the number of e-folding times over which a perturbation remains within a given scale height.

The basic difficulty underlying all these suggestions can perhaps be stated in a general way by noting that collimation, like instabilities, is just the bending of flow lines. In the former case, the flow lines are bent systematically towards the axis, whereas in, say, a kink instability, they are all bent in the same direction. There is no obvious reason, given that the instabilities do exist, why flow lines should be bent preferentially towards the axis. While the instabilities may be "weak" in some sense for some parameter regimes (Blandford and Pringle 1976), neither is there any obvious reason why the flow should resemble the symmetric pattern

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that the theorists perturb around. The contention of the author is that the stability problems for jet confinement (when there is internal pressure equilibrium) are serious and motivate alternative models specifically designed to avoid them.

III. Jets Without Internal Stress

An alternative confinement scheme for radio jets that is purely hydrodynamic has been proposed by myself (Eichler 1982, 1983) for radio jets. Canto and co-workers independently proposed a scheme that is basically the same at the general level in the context of bipolar outflows from young star systems in the galaxy (Canto et al 1981) which recently have been associated with the problem of radio jets. The key assumption of the model is that there is no significant internal pressure or magnetic stress; the ejected material is assumed to be a supersonic, high Alfven Mach number wind by the time it expands to the collimation scale. Acoustic and magnetic signals cannot propagate through the jet over the dynamical timescale as would be necessary to support global instabilities. The collimation occurs close to the wall of the channel opened up by the outflow. Shocks would occur near the channel wall and, in order to maintain a high Mach number, the internal energy of the post-shock material would have to be dissipated somehow. Possible dissipation mechanisms include cyclotron emission or other photon radiation, escape of high energy particles or their collisional by-products, or heat conduction into the channel wall, depending on the field strength, optical depth, and other parameters of the flow. Many of these possibilities obviously would predict that much of the beam power escapes as some sort of radiation from the scale of collimation.

The axisymmetry in this model is enforced by the axisymmetry or rapid rotation of the central object emitting the supersonic wind; the interior of the jet is mechanically decoupled from the confining cloud so it can neither be destabilized nor symmetrized by it. There are possibly very small scale instabilities within the sheath of shocked material at the channel wall, but they do not seem nearly as dangerous as the global instabilities that have been eliminated by the assumptions of the model.

The analysis of the channel wall shape and the extent of collimation, which neglects the jet's internal pressure and equates its inertial forces with the ambient pressure, is in a sense the reverse of Blandford and Rees (1974), who keep the internal pressure and neglect its inertial forces. It can be shown that for a pressure profile proportional to r^{-4} and an axisymmetric wind, the channel shape is a perfect cylinder, so for $P \propto r^{-\alpha}$; $\alpha < 4$, the ambient pressure focuses the jet to a point on the axis.

The equation that described the channel shape can be shown to be (Eichler 1982)

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$$P_a = v\frac{d\dot{M}}{d\Omega}\left(r\frac{d\theta}{dr}\right)^2/r^2\left[1+\left(r\frac{d\theta}{dr}\right)^2\right] +$$
$$\left(r\cos\theta\ R_c\right)^{-1}\int_0^{\theta} v\cos\psi(\theta')\frac{d\dot{M}}{d\Omega}\cos\theta'\,d\theta' \qquad (1)$$

Here P_a is the ambient pressure, v is the velocity, the channel shape is expressed as a function $\theta(r)$ in polar coordinates ($\theta \equiv 0$ at the equator), ψ is the angle of impact with the channel wall, R_c is the radius of curvature of a meridianal cross-section of the channel, and $d\dot{M}/d\Omega$ is the ejected mass flux per unit solid angle. The first term on the right hand side is the ram pressure of the material hitting the channel wall and the second is the centrifugal pressure of the material as it shoots around the channel wall subequent to its impact.

The cylindrical channel shape

$$\cos\theta = \frac{1}{r} \qquad (2)$$

for which $R_c^{-1} = 0$, is a solution when $P_a = 1/r^4$, and v and $dM/d\Omega$ are spherically symmetric (unit for all Ω). Thus an ambient pressure that decreases more slowly than r^{-4} focuses the flow inward.

Given dissipation of the transverse motion by shocks at the focal point, the final collimation is arbitrarily good. That is, the "small number" in the theory that can be associated with the very small opening angles of many radio jets is the fraction of internal energy that is retained by the post shock material.

This confinement scheme does not require a carefully tailored pressure profile to draw the jet material into a slender form over many pressure scale heights as do the schemes invoking internal pressure equilibrium within the jet (leaving aside stability questions). Given effective dissipation, good collimation results from any pressure profile that falls off less rapidly than r^{-4} along the channel wall as long as the confining cloud is oblate enough to allow the fluid to escape along the axis.

A second analytic solution to (1), which illustrates the recollimation of a precessing beam by a uniform ambient medium, can be obtained by taking P_a to be constant, and $d\dot{M}/d\Omega$ to be proportional to $\delta(\theta-\theta_o)$, corresponding to a precession cone of angle θ_o. For $\theta > \theta_o$, the ram pressure term in (1) vanishes and the centrifugal term simplifies to a term proportional to R_c^{-1}. Writing R_c^{-1} in cylindrical coordinates z (height) and x (radius) - $R_c^{-1} = d/ds \arctan(\frac{dz}{dx})$, where $ds = (dz^2 + dx^2)^{1/2}$, yields the generalized solution

$$z' = \frac{\left(\frac{x^2}{2} + \sin\theta_o\right)}{\left[1 - \left(\frac{x^2}{2} + \sin\theta_o\right)^2\right]^{1/2}} \qquad (3)$$

This is readily integrated numerically, and one derives a focal length z_f of about $3(L/\pi v P_a)^{1/2}$, where L is the jet power, at which point the jet converges back into the axis. This value for the focal length is consistent wiht observations of laboratory jets, where the focal lengths (which are expected to be slightly shorter because the jets are filled in, so that the average opening angle is only $\sim 2/3\ \theta_o$) are between 2 and 3 times $(L/\pi v P_a)^{1/2}$. The calculation is relevant to jets that appear to have been focused while supersonic, such as the one in the supernova remnant W50 (SS433) and possibly some extragalactic jets, where observational limits can be set on L, P_a, and z_f.

In conclusion, cold, pressureless jets seem to be easier to collimate than those that are in pressure equilibrium wiht their surroundings. They can in fact be focused, and are qualitatively more stable during collimation. Because shocks form, the shocks must be dissipative in order to keep the jets could over many focal lengths. But perhasp this assumption is worth making if it yields a satisfactory theory of jet collimation.

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DISCUSSION

Henriksen: I have several comments: i) Jets are not limb brightened in general. ii) Compressible turbulence can be recollimated by the external pressure. iii) Turbulent jets that are compressible may have a non-uniform viscosity and a core-halo structure. iv) Eddy scale dissipation is $R/(dR/dz) \sim z$. Locally in our models (Henriksen, Bridle, Chan) dissipation power is about what is required for synchrotron brightness. v) Turbulence is regenerated by entrainment (HBC).

Eichler: I agree that jets are not, in general, limb brightened on large scales. On scales smaller than 1 pc, where the intitial collimation may take place, no one knows.

The main problem that I see with turbulent jets is that, as you seem to agree, the turbulence at some point z along the jet dissipates over a scale of about z. Over a very large increase in scale size, it seems

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likely that most of the energy in the jet, including the flow energy, would be dissipated, and the jet would peter out. This is what happens in laboratory turbulent jets, including those that start out supersonic. The challange to proponents of truly turbulent extragalactic jets where there are global instabilities, much entrainment of surrounding material etc. - is to explain what difference about them from laboratory jets enables them to survive the development of turbulence.

Incidentally, I agree that some turbulence is present in these jets, I merely argue that global instabilities are not present.

Benford: The hidden assumption here is cylindrical symmetry, imposed by spinning the cloud, or a precessing jet. Doesn't it seem equally simple to use the instrinsic cylindrical symmetry of a current, which imposes a confinging B_θ and can also ameliorate sidewise instabilities if there is a parallel magnetic field as well?

Eichler: The assumption of a cylindrically symmetric wind is there, and mentioned explicitly. On the other hand, I know of no demonstration in the literature that currents in a dynamically active $\vec{B}$ field are "intrinsically" symmetric; the kink instability seems to be a counter example. The challenge that should be met by proponents of magnetic confinement is to show that B_ϕ/B_z can be large enough to collimate the flow but not large enough to destabilize it in or near the zone of collimation. There is much skepticism that this can be achieved, even with careful planning.

Gilden: If the stability of the walls requires that the source not be dynamically coupled, how is force balance achieved? Is there not a shock propagated into the cloud and then overall expansion?

Eichler: No, the cloud is assumed to be in hydrostatic equilibrium or some other steady state. The only shocks are in the jet.

Norman: For a collimated jet propagating in an atmosphere with a density profile $\rho \propto r^{-2}$, $\alpha > 2$, the jet will break free in a few scale heights. Essentially, the transverse velocity exceeds the sound speed. Firstly, why doesn't this happen here? Secondly, what is the physical basis for your models critical exponent of $\alpha = 4$?

Eichler: Your first sentence is true only according to a particular, popular set of assumptions; ruining the assumptions doesn't necessarily ruin the jet. I agree that if $\alpha < 2$, the transverse velocity will generally exceed the sound speed and shocks will form. This does happen here. But if the post-shock fluid dissipates its energy somehow, as I hypothesize, the jet does not break free. The "critical exponent", as you call it, is just the value of α below which the thin sheath of shocked material is bent back towards the axis. It is d + 1, where d is the dimensionality of the flow, since, for a supersonic wind striking a cylindrical shell, $\rho\, v^2 \sin^2 x$ goes as $r^{-(d+1)}$; i.e. $\rho \propto r^{-d+1}$, $v =$ const, and $\sin x \propto r^{-1}$.

Coppi: Do you have any comment about the accretion funnel model that was proposed some time ago?

Eichler: I presume that the accreting material, in this model, acts as the confirning material. So it seems to be a special case of hydrodynamic confinement, applied to a region very close to the central compact object in active galactic nuclei. I have no quarrel with the location, and am not very familiar with some of the other details.

Bridle: The jet in NGC 6251 definitely shows alternating regimes of rapid and slow expansion, on scales of tens of kiloparsecs. The 3° opening angle that has been referred to here is only an average behavior. The detailed collimation behavior shown by the VLA observations (Perley et al, to appear in Ap.J. Supplements) clearly shows there some recollimation goes on over scales comparable with that of the associated galactic atmosphere, rather than being set once and for all on the parsec scale of the VLBI jet.

Eichler: I agree (see Eichler, D., Ap.J., Sept. 1983); the jet in W50 is another example. But I still feel that a jet as striking as the one in NGC 6251 could not have suffered global instabilities at any point along its length.

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