VISCOUS DISSIPATION IN JETS

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ABSTRACT The slow decline of surface brightness along many large-scale jets indicates that their internal pressures are determined largely by dissipation. If dissipation arises from a viscous interaction between a jet and its environment, then the observed degree of collimation enables one to constrain the nature of the viscous stress. Simple phenomenological models of the stress account for the frequently observed "gaps" and provide a means of slowing down jets without their becoming decollimated.

The variation of radio surface brightness along multikiloparsec-scale jets is often flatter than one would expect from a simple magnetohydrodynamic model (Bridle, this volume). Corresponding values of the minimum pressure are generally comparable with or larger than estimates or upper limits for the ambient pressure; hence it is likely that relativistic electrons and magnetic fields are near equipartition, and contribute a substantial fraction of the total pressure. If one treats the equipartition pressure as proportional to the total pressure and the radio contours as indicative of the flow pattern, then one concludes that the flow is "subadiabatic", i.e., the gas within the jet becomes hotter as it expands (Begelman *et al.* 1982). The likeliest source of energy for this heating is the kinetic energy of the jet. This energy may be tapped by viscous stresses which carry some of the jet's momentum into the surrounding medium. Unfortunately, as with accretion disks we have little understanding of the viscosity mechanism, except to recognize that the dominant processes probably involve fluid turbulence or magnetic fields rather than "molecular" interactions. Nevertheless, there are some qualitative constraints which the dissipation mechanism must satisfy in order to be compatible with observations.

Consider a pressure-confined fluid jet, subject to a viscous stress S and heat flux H. Schematically, the steady-state equations of motion and thermodynamics are

$$\rho v \cdot \nabla v = -\nabla p - \nabla \cdot S \qquad (1)$$

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$$\frac{1}{\gamma-1}\, pv\cdot\nabla\ln(p/\rho^{\gamma}) = -\nabla\cdot H - \frac{\partial v}{\partial x}S \qquad (2)$$

where γ is the adiabatic index and $\partial v/\partial x$ represents the shear. H probably scales $\sim Sv$; the absence of limb-brightening may be evidence for the internal redistribution of heat, corresponding to a Prandtl number of order unity. Under this assumption, the requirement that dissipative heating be effective over several pressure scale heights h yet not destroy the jet implies that S must have the scaling

$$S \sim \frac{d}{h}\, p \qquad (3)$$

where d is the half-thickness of the jet. If S becomes much larger than this, then p/ρ^{γ} will exponentiate and the jet will heat and decollimate dramatically. Is S is much smaller, then the heating will be too weak to alter the adiabatic relation between p and ρ. Substituting (3) into (1) and setting $\nabla\cdot S \sim S/d$ we find that the pressure and stress terms are comparable, hence the stress has an important effect on the thrust of the jet only if the jet is marginally sonic or subsonic.

A physically suggestive way to express the scaling relation (3) is to write S in the form

$$S \sim \alpha p \qquad (4)$$

where α is a dimensionless quantity which need not be constant. Given a specific form for α, one can determine whether the jet approaches a dissipative configuration

$$\frac{d}{h} \sim \alpha \qquad (5)$$

and whether this configuration will be maintained over large distances. For simplicity, suppose that α is a constant $\ll 1$. This model is simply the "α-model" of accretion disk theory (Shakura and Sunyaev 1973). If a jet starts out from the nucleus of a galaxy with an opening angle $\lesssim 1$ radian, the effects of dissipation will not be important until the jet has been collimated to an opening angle of order 2α. In this initial zone, adiabatic losses outweigh the heating due to viscous dissipation, and if the latter is responsible for most of the particle acceleration then we should not expect to observe much radio emission from this region. We might therefore associate these regions with the "gaps" of several kiloparsecs often seen in weaker sources.

Once dissipation becomes important, the exponential sensitivity of p/ρ^{γ} to S in equation (2) forces the jet to track relation (3). For constant α and a power-law run of p, the jet evolves with a constant opening angle $\sim 2\alpha$. At first, the jet remains supersonic. Thrust and velocity are only weakly affected by the dissipation, but the Mach number M decreases with distance r, $\propto r^{-1}p^{-1/2}$, due to a steady increase in the internal sound speed. When $M \lesssim 1$, the thrust is affected by both the stress and the pressure gradient, but in opposite senses. Further evolution depends on the details of the dissipation process, particularly on the rate

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of entrainment. The Mach number may continue to decrease, or may hover near unity if the pressure forces come into balance with the viscous forces. In either case, the jet will continue to track condition (3). If the jet does not lose much heat to the ambient medium, the energy flux, $\propto pvd^2$, is approximately conserved, hence the velocity decreases $\propto p^{-1}r^{-2}$. Variations in Mach number and mass discharge are then related through the scalings $\dot{M} \propto M^2/v^2 \propto M^2p^2r^4$. Note that if M is constant or decreasing, there must be substantial entrainment along the jet.

Thus, a subsonic, dissipative jet can decrease its velocity and increase its mass discharge by orders of magnitude, without being decollimated. It can do so because the external pressure gradient continually transforms heat back into kinetic energy through adiabatic expansion along the jet. The principal requirements are that the stress be always smaller than the pressure, and have a feedback property which enables the jet to stably track condition (3). Other stress prescriptions besides the α-model possess this property. For example, models with $S/p \propto M^a$ will track condition (3) if a is not too negative. The precise stability criterion depends on the run of p as well as initial conditions and the equation of state in the absence of dissipation. Qualitatively, the requirement is that the importance of stress relative to pressure should increase with increasing Mach number.

Despite the absence of sound theoretical grounding, simple phenomenological stress prescriptions may help to unify several observational features of jets. First, a jet evolving dissipatively in a power-law pressure distribution should have an opening angle $\sim 2\alpha$, independent of the power-law index. If the viscosity arises from turbulence and/or tangled magnetic fields, then α should differ little from source to source (Eardley and Lightman 1975, Lynden-Bell and Pringle 1974) and may help to explain the rough consistency in jet opening angles. Second, the model provides a means for smoothly decelerating and adding mass to jets without disrupting or decollimating them. This feature may aid in understanding the correlation between jet visibility and the power of the associated nuclear and extended sources (Bridle, this volume). Third, the rather sharp onset of strong dissipation predicted by phenomenological stress models can provide a natural interpretation of the observed "gaps".

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