THEORY OF JET DISSIPATION

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Abstract

An understanding of the physical processes by which collimated astrophysical flows lose their initial momentum and transfer mass and energy to their environment ("jet dissipation") is perhaps the only means by which we will be able to determine the actual mass and energy fluxes contained in these outflows. This review focuses on the physics of jet dissipation and in particular on those mechanisms that appear to be universal and/or more or less inevitable in mediating jet dissipation. Both hydrodynamic and magneto-hydrodynamic processes will be discussed, including the results of non-linear time dependent calculations. The use of extant or future observational data to discriminate among dissipation processes is included.

1 Introduction and motivation

The word "dissipation" carries with it connotations of decay, loss of energy, and eventual death. And so it is when the word is applied to astrophysical jets, where dissipative processes are taken to be those that cause a loss of energy and/or momentum from such jets, reduce their ordered nature, decelerate them, and cause their eventual dissolution. Dissipative processes can be either local or global in nature; i.e., the dissipation can occur in a very localized place such as a shock front or at the site of a jet-cloud collision, or it can operate throughout the jet length or volume. Dissipation can be self-inflicted due to the evolution of internal processes within the jet or it can arise from conditions in the external environment. Finally, dissipation in jets can be "inevitable" or it can be induced, e.g., by presumed processes occurring deep in the region where the jet originates. All these possibilities will be discussed here with varying degrees of completeness. Although most of the discussion will be applicable to all astrophysical jets, the emphasis here will be on the large scale extragalactic jets (e.g., De Young 2002).

In terms of observable quantities, dissipative processes in extragalactic jets are intimately related to radio source morphologies, extragalactic emission lines, the "alignment effect" in high redshift radio sources, X-ray knots and hotspots, and possibly the metallicity of the early intergalactic medium (IGM) and intracluster medium (ICM).

2 Global processes - interaction with the environment

One of the few actually true statements in contemporary astronomy is that astrophysical jets do not propagate *in vacuo*. The presence of an interstellar medium guarantees this verity, and the likelihood of circumgalactic and intracluster gas around all astrophysical jets adds additional weight to the conclusion. From this follows a basic conclusion, namely that interaction of jets with this ambient material *must* occur at some level. This is true even if specially contrived magnetic field geometries or other insulating mechanisms are assumed to be in place, as will be discussed in more detail below.

Jet interaction with the ambient environment is, as will be seen, the most important form of dissipation in jets. As argued above, it falls into the "inevitable" category, and it is global in that this interaction occurs along the entire length of the jet to varying degrees and is present when ever the jet is moving relative to the ambient medium. This interaction mediates the transfer of mass, momentum and energy between the jet and the environment, and an understanding of its details may be the only reliable way to determine jet content, jet bulk flow speeds, and perhaps jet magnetic fields. Thus this interaction may provide the most well defined constraints on models for the "nuclear engine" deep within active galactic nuclei.

2.1 Dissipation via surface instabilities

Surface instabilities are the gateway mechanism that leads to jet dissipation through interaction with the environment. As they grow into their non-linear phase they produce a turbulent mixing layer that has profound effects upon both the evolution of the jet and the surrounding medium. This layer entrains ambient medium into the jet and also mixes jet material into the surrounding gas. If the jet has passed through a metal rich ISM and has incorporated some of that material into its interior, later mixing processes in the ICM or IGM can provide enrichment of the metallicity of that medium. The mixing layer transfers momentum and energy from the jet to its surroundings, and this will lead to deceleration of the jet and its eventual decay into a meandering subsonic plume. Further details about the onset and growth of this mixing layer are considered in the following sections.

2.1.1 Hydrodynamic dissipation - the Kelvin-Helmholtz instability

The onset of a surface instability at the interface between two inviscid fluids in relative motion is very well known, but the fundamental physical mechanism at work, including the non-linear growth, is basic to the formation of mixing layers under a very wide variety of conditions, including relativistic motion and the presence of magnetic fields. A small sinusoidal perturbation in the direction of relative motion will grow, as can be seen from Bernoulli's Theorem. In the linear regime all wavelengths are unstable in the absence of restoring forces, and the shortest wavelengths are the most unstable. The growth rate in the linear regime is just

$$\Gamma = k\Delta U(\rho_1\rho_2)^{1/2}/(\rho_1+\rho_2). \qquad (1)$$

A classic and extremely clear explanation of this instability is found in Chandrasekhar (1961).

In the quasi-linear regime the waves caused by the perturbation "break" and then roll up into the well known "cat's eye" configuration, as shown in Fig. 1. This orderly behavior is more complex in three dimensional flows, but at early times in the development of the instability this picture is fundamentally correct. The fully non-linear development of the Kelvin-Helmholtz (K-H) instability and the development of a mixing layer is shown in Fig. 2. Several important features are seen in this figure. The remnants of the original roll-up and cat's eye formation can be seen, but within

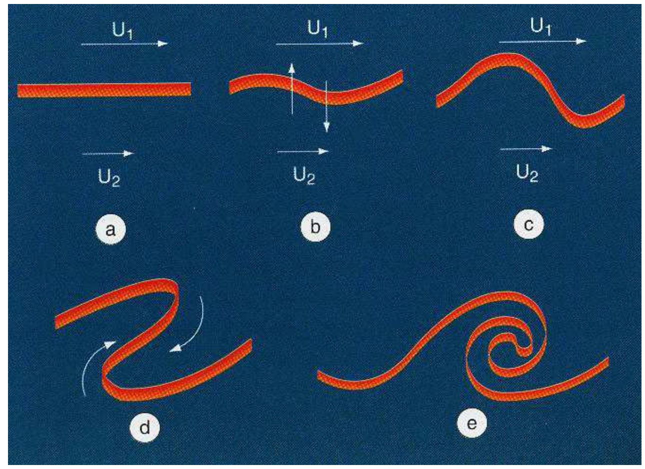

Figure 1: Cartoon depiction of the development of the Kelvin-Helmholtz instability.

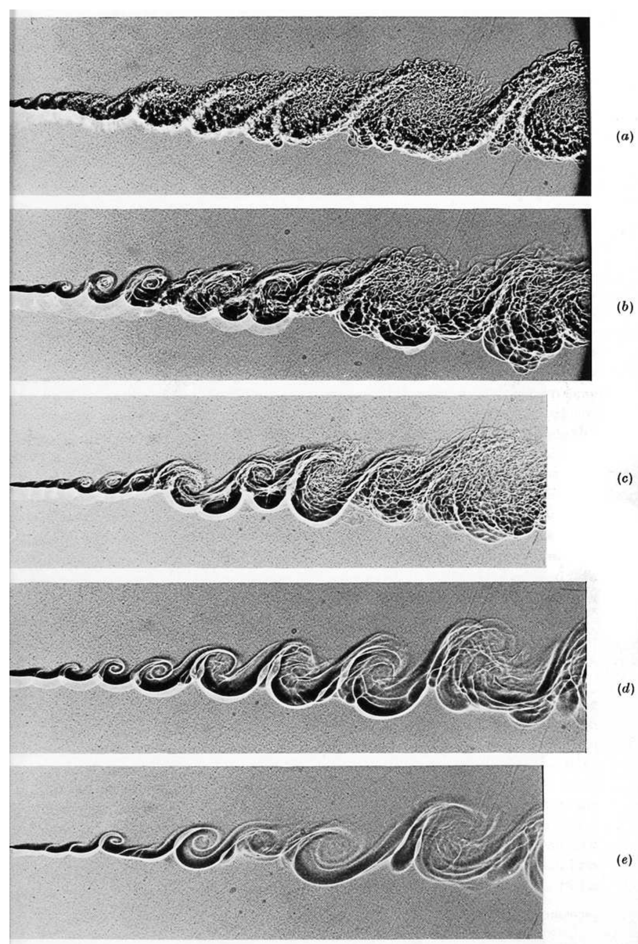

Figure 2: Examples of fully developed mixing layers. The Reynolds number of the flow increases from bottom to top.

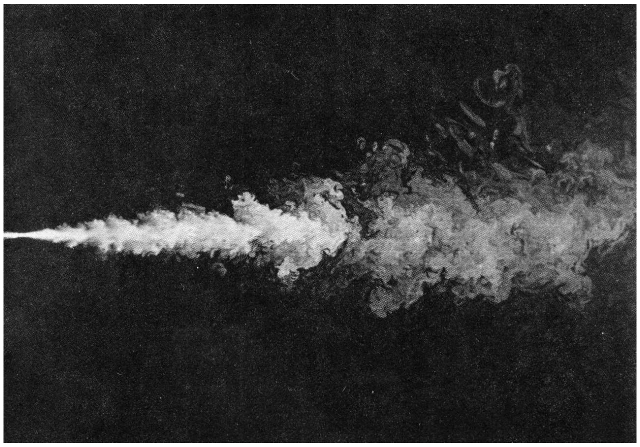

Figure 3: Example of a fully turbulent jet.

the large vortices produced is a wealth of fine structure which leads to mixing on many scales. These multilevel structures contain within them the elements of turbulent flow with energy cascades from large to small scales. Both experiment and numerical simulations show that the entrainment process in this mixing layer proceeds from a large scale "gulping" of material into the mixing layer followed by a fine scale mixing within the large vortices - ingestion and digestion. Finally, it is clear that the thickness of the mixing layer increases with time in a comoving coordinate or with distance along the interface, and in a surprisingly linear manner. The spreading rate of the mixing layer is given by

$$\tan\phi = C(\rho_L/\rho_H)^{\alpha}(v_{rel})^{-\beta}, \tag{2}$$

where ϕ is the opening angle of the mixing layer and ρ_L is the density of the less dense medium while ρ_H is the density of the more dense medium. Obviously equal densities in the jet and surrounding are also possible. In general α is of order 1/2 and β is of order 1. The thickening of the layer can continue until the mixing layer permeates the entire jet, from periphery to the center, resulting in a completely turbulent jet. An example of this is shown in Fig. 3.

The development of mixing layers occurs in supersonic flow as well (where supersonic is defined as the jet speed exceeding the sound speed in the ambient medium). An example of supersonic mixing layer development is shown in Fig. 4, and Eq. 2 above is also a good approximation in the supersonic regime. Clearly the mixing layer develops more slowly in these high speed flows, since $\tan\phi \propto M_j^{-1}$, but the mixing and its attendant consequences still must occur. (Here M_j is the Mach number of the jet flow relative to the ambient medium.)

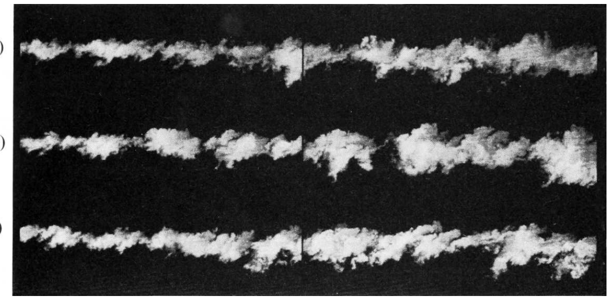

Figure 4: Example of the development of a mixing layer in supersonic shear flows. The three layers shown are the mixing layer at slightly different times.

For even higher jet speeds that reach relativistic values, the experimental data are obviously very sparse. However, high quality numerical simulations in three dimensions can be used to gain some insight into jet dissipation in relativistic flows (e.g., Aloy et al. 2000). These simulations show little evidence of "backflow", which is a notion that gained widespread popularity when it appeared in 2-dimensional axisymmetric simulations. (three dimensional non-relativistic simulations also show little indication of "backflow" as well, which is a cautionary note about the misleading results that enforced symmetry can produce.) In addition, these relativistic simulations also show the development of shear and mixing layers along their surface, and this is accompanied by jet deceleration, just as in the non-relativistic case.

2.1.2 Dissipation in magneto-hydrodynamic jets

The introduction of magnetic fields causes some very important changes in fluid flows. Magnetic fields remove isotropy and add an effective (anisotropic) viscosity. This "viscosity" arises from terms in the magnetic energy tensor that correspond to the equivalent of a "tension" along the field lines which can act to stabilize the interface between the jet and its surroundings. For perturbations of wavenumber $\mathbf{k}$ and relative fluid velocities $\mathbf{U_R}$, the K-H growth rate becomes

$$\Gamma = 0.5|\mathbf{k}\cdot\mathbf{U_R}|[1-(2v_A\mathbf{k}\cdot\mathbf{B})^2/(\mathbf{k}\cdot\mathbf{U_R})^2]^{1/2}, \tag{3}$$

where v_A is the Alfven speed. This means the flow is stable if the Alfven Mach number satisfies the following inequality:

$$M_A = U_R/v_A \leq 2 \quad (4)$$

for k, B, and U_R all parallel.

Equation 4 above basically says the flow is stabilized when the magnetic energy density is comparable to the kinetic energy density of the flow, which is intuitively obvious. However, some basic issues and uncertainties immediately arise. What are the field strengths in jets? What are the field geometries, locally and globally? What is the origin of magnetic fields in jets? Only indirect estimates are available for the first two questions, and the third question remains entirely unanswered. The fact that jets propagate at all and do not decollimate from excessive internal pressure implies that on average the kinetic energy density is greater than the magnetic energy density, though this may not be at all the case in localized regions. These arguments can be used to supply limits on field strengths, and they suggest that the magnetic fields may not be strong enough to suppress the K-H instabilities except on very small scales.

In addition, the very naive one-dimensional treatment that sets field, velocities and wave vectors all parallel is misleading. To obtain a more accurate view, two and three dimensional treatment of the magnetohydrodynamic (MHD) case must be done, and these treatments must pursue the instability into the non-linear regime, just as has been done for the purely hydrodynamic case. Such calculations have recently been carried out by T. Jones and his co-workers (e.g., Ryu et al. 2000). These calculations show that in two dimensions a mixing layer is again formed, but that areas of enhanced local field develop due to field line stretching. In addition, the simple "cat's eye" geometry forms but is then subsequently destroyed during the later states of the non-linear growth of the instability. In the case of three dimensions, the added degrees of freedom result in an even more complex evolution. The instability rapidly produces a fully turbulent layer, again similar to that seen in the purely hydrodynamic case, and this is accompanied again by regions of high magnetic field. In addition, turbulent amplification of the field occurs, and enhanced dissipation is seen to arise from the effects of magnetic recombination within the turbulent region. In the words of the authors of these calculations, the instability remains "essentially hydrodynamic". An example of the evolution of the magnetic field and the vorticity from such a calculation is shown in Fig. 5.

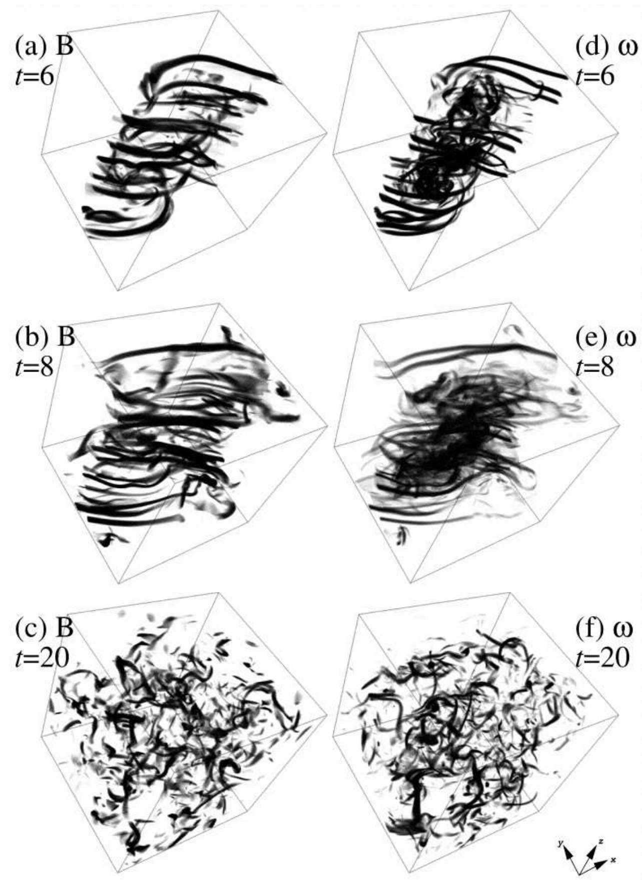

Figure 5: Non-linear development of the K-H instability in MHD flows shown at three different times. On the left is the magnetic field structure and on the right is the vorticity. Note how the flow becomes fully turbulent at later times. (From Ryu et al. 2000.)

3 Implications of global dissipation

The previous section has shown that global dissipation caused by mixing layers formed from surface instabilities occurs under a very large range of conditions: subsonic flow, supersonic flow, relativistic flow, and MHD flows. The non-linear phase of the mixing layer growth leads to turbulence, possibly throughout the jet, to mass entrainment, and to possible turbulent amplification of any magnetic fields in the jet. Such fields could arise from entrainment as well as from fields originally present in the jet. Entrainment rates for extragalactic jets have been calculated with varying degrees of sophistication and suggest entrainment rates of a few solar masses per year. Mass entrainment can

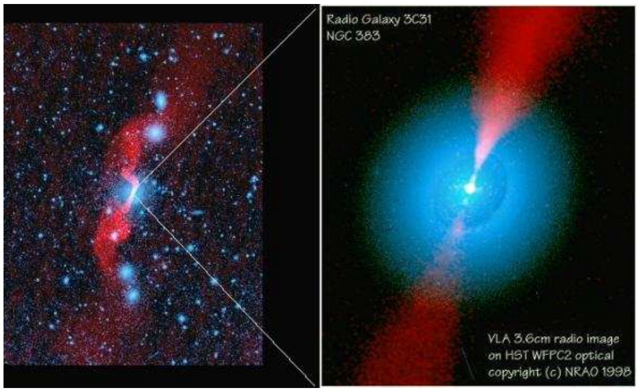

Figure 6: FRI radio source 3C31.

result in significant jet deceleration; once the deceleration begins, the entrainment rates rise as the jet slows, and this can reduce originally relativistic or supersonic flows to subsonic plumes.

Subsonic plumes have very different morphologies than do supersonic jets, and this difference is very similar to the difference in morphology between the FRI and FRII radio sources. Thus the investigations of jet dissipation and mixing layer development have led naturally to the suggestion that this process can account for the difference between the FRI and FRII objects (e.g., De Young 2002 and references therein). A compelling example of an FRI source as a subsonic plume is shown in Fig. 6. Such saturated and thoroughly mixed jets can, via mass entrainment, transport astrated material from the interstellar medium of their parent galaxy to extragalactic scales. This process could contribute to the production of emission lines seen in the ICM and at large extragalactic distances. The cooling due to these metals could also enhance jet induced star formation and produce the observed extragalactic blue continuum and the "alignment effect" seen at large redshifts. Finally, this transport outward of enriched material will result in the injection of metals into the ICM and IGM, and thus for high redshift sources it could contribute to the contamination of the IGM at very early epochs.

4 Local dissipative processes: internal shocks

Although the global dissipative processes discussed above are those that contribute most to the evolution of astrophysical jets, there are local dissipation processes that can be important in the overall energy budget of jets and than can also have a significant influence on the surrounding medium.

Figure 7: Example of internal shocks in a collimated supersonic jet due to a sudden drop in external pressure. The fact that the SR-71 is airborne shows that the internal shocks have little effect on the propagation and energy flux of the jet.

The first of these are internal shocks in the jet. The production of such shocks requires special circumstances that cause conditions in or around the jet to change. One way to accomplish this is to change the conditions at the jet origin; such changes may be responsible for the knots and moving features commonly seen on very small (parsec) scales in jets observed with very long Baseline Interferometry techniques. Another source of internal shocks can arise from sudden changes in the medium external to the jet. Ambient pressure changes or ambient density changes are natural candidates for causing internal shocks, and these can lead to jet expansion, jet bending, and even jet disruption. An example of internal shocks due to a pressure mismatch is shown in Fig. 7.

Internal shocks cause partial thermalization of the flow behind the shock front. They can also be sites of particle acceleration (see the review by J. Kirk in these proceedings), and the compression behind the front can also result in magnetic field enhancement for that component of the field parallel to the shock front:

$$B_1 \approx B_0(\gamma + 1)/(\gamma - 1).$$

These shocks cause radiative losses either through thermal radiation from the hotter gas behind the

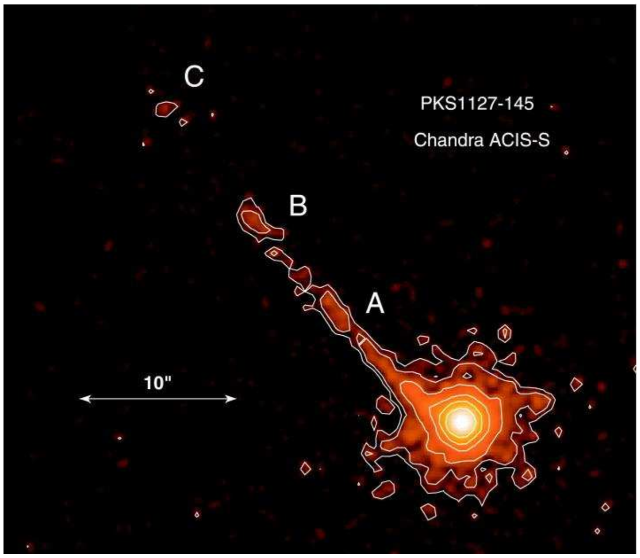

Figure 8: Example of X-ray knots in an astrophysical jet that may indicate the presence of internal shocks.

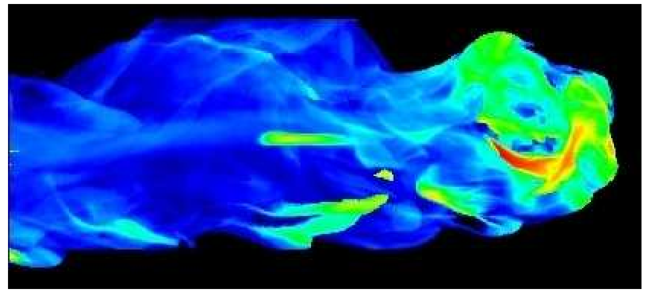

Figure 9: Complex shock structure at the termination of an MHD jet. (From Tregillis et al. 2001.)

shock or through enhanced synchrotron radiating resulting from both the increased particle energy density and magnetic field strength behind the shock from ($P_{synch} \propto B^2 E^2$). These internal shocks are mostly oblique (see Fig. 7), mostly cause slight redirection of the flow and are not disruptive (see Fig. 7 again). Hence the constitute internal "weather" that converts a small fraction of the kinetic energy flux of the jet flow into changes in temperature, magnetic field strength, and particle energy. Thus in terms of jet dissipation these shocks are not particularly significant. However, their radiative signature at radio, optical and X-ray wavelengths can provide useful diagnostics (e.g., Fig. 8). In particular, this emission may provide constraints on the elusive jet speeds if it can be *conclusively* shown that the X-ray signature arises either from synchrotron self-Compton processes or from inverse Compton scattering of the cosmic microwave background by the relativistic electrons in the jet.

5 Local dissipative processes: termination shocks

The endpoint of a collimated supersonically propagating jet is a shock interaction with the ambient medium. Early axisymmetric treatments of this interaction showed a tidy picture of a leading bow shock, followed by a contact discontinuity, then followed by a standing shock or Mach disk internal to the jet. Such idealized treatments of supersonic flow are almost always misleading, and this one was not an exception. More realistic three dimensional time dependent calculations show that the terminal shock region for such jets is a very complex and evolving interaction, with many shocks coexisting and with features that come and go as the jet propagates. This is the case for both purely hydrodynamic jets and for MHD jets, and an example of the complex shock structure at the termination of an MHD jet is shown in Fig. 9.

The key point is that termination shock regions deposit most of the jet energy into a relatively small volume. This energy is in the form of large scale flows, turbulence, magnetic energy. relativistic particles, and heat. It is this rich broth that provides the sustenance for the large scale radio lobes seen in the FRII sources. If equipartition magnetic fields exist in these lobes they cannot have been simply advected outward with the jet (e.g., De Young 1980), and the termination region provides both the seed magnetic fields and the turbulent kinetic energy needed to drive turbulent regeneration of the field strength. The long standing debate over the need for particle re-acceleration within the lobes is also relevant to the termination shocks, since these systems may well be the site of significant particle reacceleration, and the turbulence "downstream" from the terminal shocks can also contribute to stochastic re-acceleration of particles.

Acknowledgments

Thanks to Kristy Dyer and Lorant Sjouwerman for organizing an excellent meeting.

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