Interpretation of Extragalactic Jets

Michael L. Norman

Los Alamos National Laboratory
P.O.Box 1663, Los Alamos, N.M. 87544
and
Institute for Astrophysics
Department of Physics and Astronomy
University of New Mexico, Albuquerque, N.M. 87131

1. Opening Comments

The subject of this paper is the interpretation of extragalactic radio jets. In this paper I will focus on what we have learned about the nature of extragalactic jets on the basis of model calculations. By model I mean any set of calculations, whether analytic, semi-analytic or numerical, which, when carried through from their respective assumptions to their internally self-consistent conclusions, help place constraints on the physical parameters and processes in the jets and their associated radio lobes. In this field, a visual inspection of a modern high-resolution radio interferometric observation (see review by PERLEY in these proceedings) often leads to statements like "that looks just like such and such in Landau and Lifschitz; I betcha that's what's going on!" This I call a speculation, or, at best, a hypothesis. I am addressing here the step beyond hypothesis, namely modeling, which is necessary to confront not only the object in question, but more importantly, the hypothesis itself. In the end, we will remember only the hypotheses.

The models I will be discussing all adopt the basic hypothesis that extragalactic jets are outflows of matter which can be described within the framework of fluid dynamics, and that the outflows are essentially continuous. This *fluid beam hypothesis*, which we owe to BLANDFORD and REES [1] and SCHEUER [2], is presently over a decade old, but we are only just now acquiring the observational and calculational capabilities to begin seriously testing the validity of this hypothesis.

What is important for the purpose of this conference is that extragalactic jets are radiating fluid flows. Unfortunately, the bulk of the radiation we detect from these objects is continuum radio-wave radiation via the synchrotron process, which tells us relatively little about the physical state of this fluid-like plasma (i.e., its density, temperature, velocity and magnetic field strength). Consequently, we are quite uncertain about the physical regime of radio jets and hence their governing equations of motion.

To give an example of just how uncertain we are, consider the following list of properties of jets (dubbed a Chinese menu by John Dreher), which are currently being debated in the astronomical literature. One is challenged to select from either column A or column B whether extragalactic jets are:

A		**B**
free	or	confined
subsonic	or	supersonic
laminar	or	turbulent
hydrodynamical	or	magnetohydrodynamical
nonrelativistic	or	relativistic
continuous	or	intermittant
radiation hydrodynamical	or	electrodynamical ???

I haven't even mentioned real plasma physics, which most people don't even like to think about. It is only through constructing models with different combinations of items from column A and column B and matching to observation that we can decide between competing hypotheses. Each of the items listed above is almost certainly important for some jet somewhere along its way out from the galactic nucleus. What we would like to know is how these ingredients combine to form the different classes of objects with the distinct morphologies which Dr. Perley has described in his review.

https://doi.org/10.1017/S0252921100086206 Published online by Cambridge University Press

I shall restrict my discussion to the interpretation of large-scale (i.e., kiloparsec-scale) extragalactic jets, leaving out the parsec-scale jets observable with VLBI techniques, for two reasons. First, due to the large number of large-scale jets now observed (≈200), one has reasonably well-defined "average" properties within morphological classes, and quantified trends between morphological classes, which suggest that we are sampling different regions of a physical parameter space defined by the jet and its environment. Second, the NRAO Very Large Array (VLA) is mapping the large-scale extragalactic radio sources with such an unprecedented degree of detail, that decisive model comparisons are now feasable. I believe these objects can be and *should* be modeled and understood at a comparable level of detail, and not just at the level of a cartoon. As even more powerful arrays of radio interferometers with even longer baselines reveal the structures of the smaller scale jets, we will in principle be able to understand them too by applying the same modeling techniques developed for the large-scale jets.

The central problem is thus to infer the physical parameters of the jets from observed distributions of total and polarized intensity and angle of polarization as a function of frequency. An exciting prospect is that in doing so, we may learn a great deal about the environments of radio galaxies, and thereby the evolution of clusters of galaxies, as already mentioned by Dr. Blandford in his review. Also, a determination of the jet's parameters will be useful in constraining the properties and mechanism of the central engine producing it. I would like to point out that this process is not unique to astrophysics: geologists measure the properties of the plumes and jets of gas-rich volcanoes, and the square-acreage of flattened trees to infer the state of volcano interiors [3].

2. Jets in Low Luminosity Sources

Some of the earliest discovered and, from a modeler's viewpoint, observationally best characterized extragalactic jets are those found in nearby weak [$P_{1.4}$ (=total power at 1.4 Ghz) $\leq 10^{24.5}$ W/Hz] radio galaxies (the so-called Fanaroff-Riley Class I radio sources [49]). Jets occur in some 65-80% of such radio sources and are predominantly two-sided [4]. Observationally, these jets have a turbulent appearance resembling a thermal plume in the earth's atmosphere, however they are characterized by a variable spreading rate $d\Phi_{FWHM}/d\Theta$ [$\Phi_{FWHM}(\Theta)$ is the jet's full-width at half-maximum intensity a distance Θ along the jet from the radio core], unlike their terrestrial look-alikes, which exhibit a remarkably constant opening angle. A second distinguishing feature of such jets is that their projected large-scale magnetic field orientation as determined from radio polarization studies is perpendicular to the jet axis, in contrast to the parallel field orientation found in jets from high power radio sources (Sec. 3).

Finally, and most difficult to explain, is the jets' so-called subadiabatic intensity evolution. Briefly, one can show [5] that in an expanding *laminar* jet which conserves magnetic flux (assumed perpendicular) and in the absence of relativistic particle reacceleration, $I_\nu \propto R_j^{-3.5} v_j^{-3.1}$, where I_ν is the jet's central brightness, and R_j and v_j are the jet's local radius and speed. Assuming $\Phi_{FWHM} \propto R_j$, then a laminar hypersonic jet at its limit speed (i.e., v_j= constant) will have $I_\nu \propto \Phi^{-3.5}$. The actual variations of I_ν with Φ are considerably slower than this over long regions of many jets, with a typical dependence being $I_\nu \propto \Phi^{-n}$ with n=1.2 to 1.6 [5].

Early models to explain this slow intensity decline keyed off the turbulent appearance of these jets and invoked turbulent particle acceleration [6-8] to partly counteract the radial expansion losses of the synchrotron-emitting electrons. A host of uncertainties with these models hampers their application to real radio jets, however, such as the nature of the turbulence (e.g., fluid dynamical, hydromagnetic, plasma), how it is excited and sustained, and how it feeds into the relativistic particles. And although some theories successfully predict the observed spectral index of the radio emission [8], none have successfully accounted in detail for the intensity evolution $I_\nu(\Phi)$.

In 1982, FANTI et al. [9] noted that a turbulent jet entraining matter *decelerates*, and that the resulting longitudinal compression of the radiating plasma would partly offset the radial expansion losses, thus reducing the rate of decline of intensity with distance. From the relation above, we find that a "typical" dimming law of $I_\nu \propto \Phi^{-1.4}$ will result from $v_j \propto R_j^{-0.68}$ without resort to particle reacceleration.

Measured deceleration rates of momentum-driven turbulent jets in the laboratory asymptotically approach $v_j \propto R_j^{-1}$ [10] for a constant spreading rate, whereas a bouyant plume in the earth's atmosphere tends to a $R_j^{-1/3}$ dependence [11]. It is plausible, therefore, that a combination of entrainment-related deceleration and bouyant acceleration in a pressure-stratified galactic atmosphere could result in the required deceleration law.

An attractive feature of decelerating jet models is that perpendicular magnetic field orientations are a natural consequence. Furthermore, since the rates of spreading and deceleration are in principle related in a turbulent jet, a self-consistent theory should be able to predict *both* $\Phi_{FWHM}(\Theta)$ and $I_v(\Theta)$ and hence $I_v(\Phi_{FWHM})$ for direct comparison with observation.

Unfortunately, no theory of turbulence, self-consistent or otherwise, exists for the case of supersonic jets in non-constant backgrounds. However, recently BICKNELL has constructed a semi-empirical model of turbulent jets [12,13] in which the velocity variation is inferred from the observed spreading rate, which successfully predicts the observed $I_v(\Phi)$ in two well-observed low luminosity radio sources (3C 31 [12] and NGC 315 [14]). In addition, his model provides a simple explanation for the latter's striking collimation behavior [15]. Although requiring a numerical solution in the general case, the basic idea of Bicknell's approach is contained in his "hot jet" model, in which he assumes that 1) the jet pressure is dominated by relativistic particles; i.e., $P_j \propto n_{rel}^{4/3}$, 2) the number of relativistic particles n_{rel} is conserved; i.e., $n_{rel} v_j R_j^2$= constant, and 3) the jet is pressure-confined by the galactic atmosphere; i.e., $P_j = P_{atm}$. Combining these relations yields $v_j \propto R_j^{-2} P_{atm}^{-3/4}$. By relating R_j to Φ_{FWHM} and assuming a form for P_{atm}, one has the velocity variation one needs for computing $I_v(\Phi)$ via the equation above.

A detailed application of this technique to the main jet in NCG 315 is displayed in Fig. 1, taken from [14]. Figure 1a shows the spline fit (solid line) to the observed Φ_{FWHM} (Θ) (crosses), while Fig. 1b shows several different model fits (labeled A,B and C) to $I_v(\Phi)$ differing only slightly in assumed jet and atmospheric parameters. Figures 1c and 1d plot the corresponding runs of velocity and Mach number, which allow the following explanation for the so-called "recollimation shoulder" seen in Fig. 1a. According to BICKNELL [14], "Initially, the jet is turbulent [thus spreading and decelerating rapidly] but becomes non-turbulent due to the effect of increasing Mach number and a favourable pressure gradient causing the jet to collimate. As the pressure flattens out to the background pressure the jet becomes turbulent again and starts to re-expand." As can be seen, the periods of rapid deceleration coincide with the flattening of the $I_v(\Phi)$ profile. The uniformly poor fits of the model at $0<\log\Phi<0.5$ occurs in the "gap" region before the jet "turns on", which is likely a region of quasi-laminar free expansion, and thus not addressed by the model.

There are several aspects of this model which I find reassuring and which indicate to me that it is largely correct. First, the model reproduces the experimentally-determined correlation of decreasing level of turbulence (as measured by spreading rates) with increasing Mach number and increasing density ratio [58]. Second, the predicted dimensionless jet parameters are reasonable on physical and astronomical grounds. Figure 1c shows the jet Mach number hovering around 2 - a transonic jet is the likely result of a balance between turbulent deceleration and buoyant acceleration. The model predicts an initial density ratio $\eta=\rho_j/\rho_{ext}$ of ≈ 0.01, which is consistent with buoyancy and which leads to acceptable mass fluxes once the velocity is estimated. In addition, Bicknell's model for NGC 315 predicts that the jet looses buoyancy due to cumulative entrainment along the jet precisely where it is observed to stop and bend back in the direction of its parent galaxy. Finally, a consideration of the energy budget [14] yields jet velocities in the range 3500-5000 km s^{-1}, which is similar to the jet speeds O'DEA finds from an analysis of narrow-angle-tail radio jets ([16] and Sec. 4). The importance of this finding is discussed in Sec. 6.

3. Jets in High Luminosity Radio Sources

High luminosity extragalactic radio sources [$P_{1.4} \geq 10^{25}$ W/Hz] are associated with distant elliptical galaxies and quasars, and typically posess the characteristic double-lobed radio morphology exhibited, for example, by Cygnus A (cf. Fig. 1 in PERLEY, these proceedings). These are the so-called Fanaroff-Riley Class II radio sources[49]. The fluid beam hypothesis was motivated by a need to explain the structure and energetics of such objects, and also to explain the origin of compact regions of intense radio emission located near the outer edges of the lobes known as hot spots. The basic picture was supplied by BLANDFORD and REES [1], and holds that hotspots are points of impact and thermalization of high velocity streams of plasma - jets - with a denser intergalactic gas, and that the radio lobes are continuously supplied with plasma freshly energized at this "working surface". The hotspots are so-called because their relativistic particle pressures, as derived from synchrotron theory arguments, are often much greater than the possible thermal pressure of the surrounding medium. For a jet of Mach number M, ram pressure balance at the working surface yields a hot spot pressure of

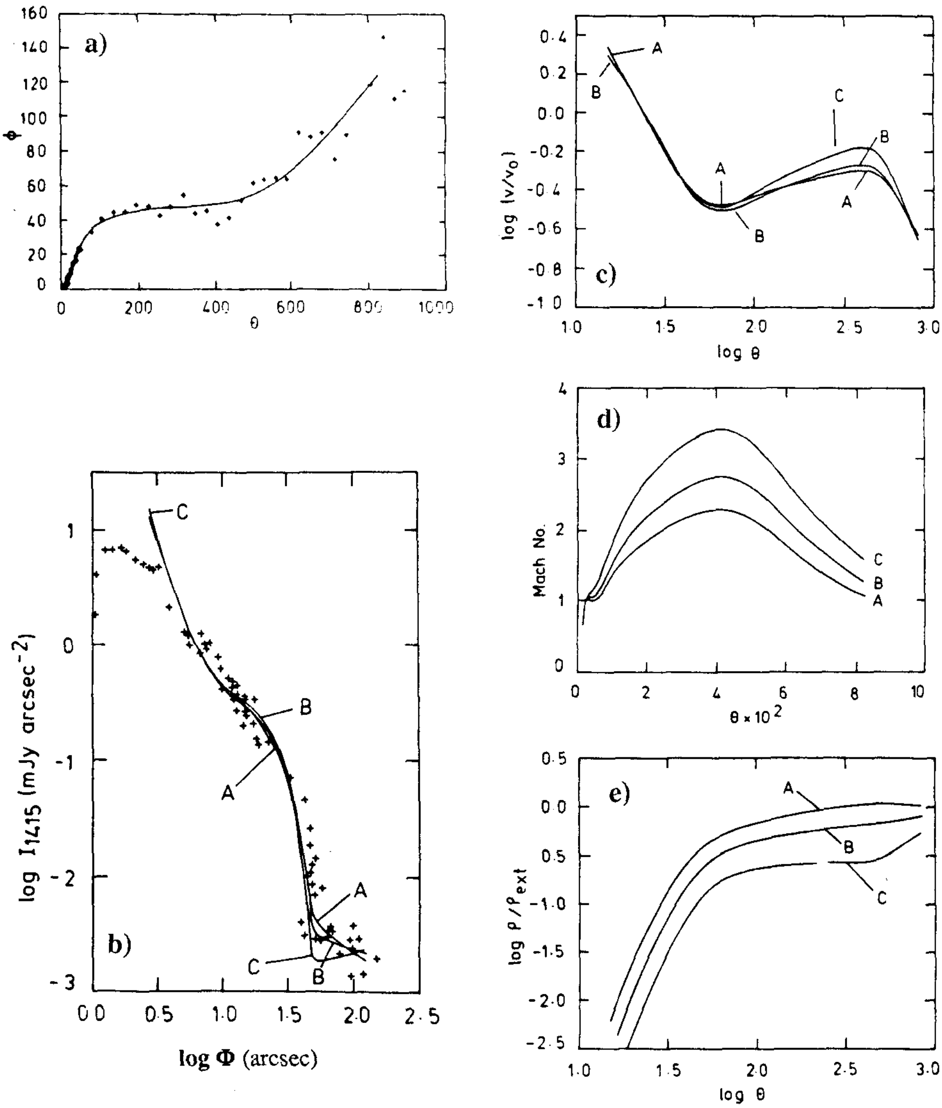

Fig. 1 Bicknell's semi-empirical model of a turbulent, entraining, transonic jet as applied to NGC 315, from [14]. **a)** Spline fit (solid line) to the observed Φ_{FWHM} (Θ) (crosses); **b)** Model fits to the intensity profile $I_\nu(\Phi)$; **c)** dependence of jet velocity with distance; **d)** dependence of jet Mach number with distance **e)** dependence of jet density ratio with distance

order M^2 higher than the static background pressure. The observations therefore imply that the jets powering these sources are highly supersonic. Only recently have the jets themselves been observed, and only then in a fraction of all luminous sources [4]. Estimates of jet speeds in classical double radio sources range from 0.1c to near the speed of light [48].

Numerical hydrodynamical simulations have been invaluable in elucidating the complex fluid dynamics of the working surface. The self-consistent structure of a high Mach number, low density (relative to the background density) jet was first revealed by NORMAN et al. [17], and has been confirmed by subsequent investigations [18-20]. Figure 2 shows the results of a 2-D axisymmetric computation using 50,000 zones to resolve a Mach 6 jet of 0.1 times the ambient density. The simulations reveal an intricate terminal shock structure which is highly nonstationary, but otherwise confirming the Blandford and Rees picture. New features discovered in the simulations are the common occurrence of oblique shockwaves internal to the supersonic beam and a complex vortical structure of the cocoon/lobe which is fed by a strong backflow from the working surface. 3-D simulations by ARNOLD and ARNETT [21] have demonstrated an azimuthal zonal structure to these vortex cells, which ultimately may help explain the filamentary structure discovered in the lobes of Cygnus A [22].

A detailed comparison of high-resolution observations of radio hot spots and numerical hydrodynamical models constitutes an important test of a key tenet of the fluid beam hypothesis - namely, that macroscopically the radiating plasma behaves like a collisional gas and flows into the radio lobe in a manner that can be described by fluid dynamics. An alternative hypothesis investigated by MYERS and SPANGLER [23] is that the freshly accelerated relativistic electrons freely stream from the hot spot to the lobe at the speed of light. They show that this hypothesis is inconsistent with observations of spectral index variations in five luminous 3C radio galaxies, and conclude that bulk transport of the radiating plasma at speeds of $\approx 10^4$ km s^{-1} can satisfactorily account for the observed synchrotron aging. In addition, SMITH et al. [24] have constructed surface brightness distributions of numerically simulated hotspots, and were able to reproduce several quite common features of observed hot spots: sharp leading edges, twin wings and tails extending back toward the nucleus, and complex subcomponent geometries such as two bright peaks transverse to the source axis. Figure 3 shows an example of a simulated hotspot map containing all these features, and is displayed using the contouring, shading and smoothing algorithms of the AIPS image processing system. Work is in progress by colleagues and myself to incorporate a variety of emission models relating the fluid variables to local synchrotron emissivity, and the results will be processed with AIPS "side by side" with observations so that a more complete and objective comparison can be made.

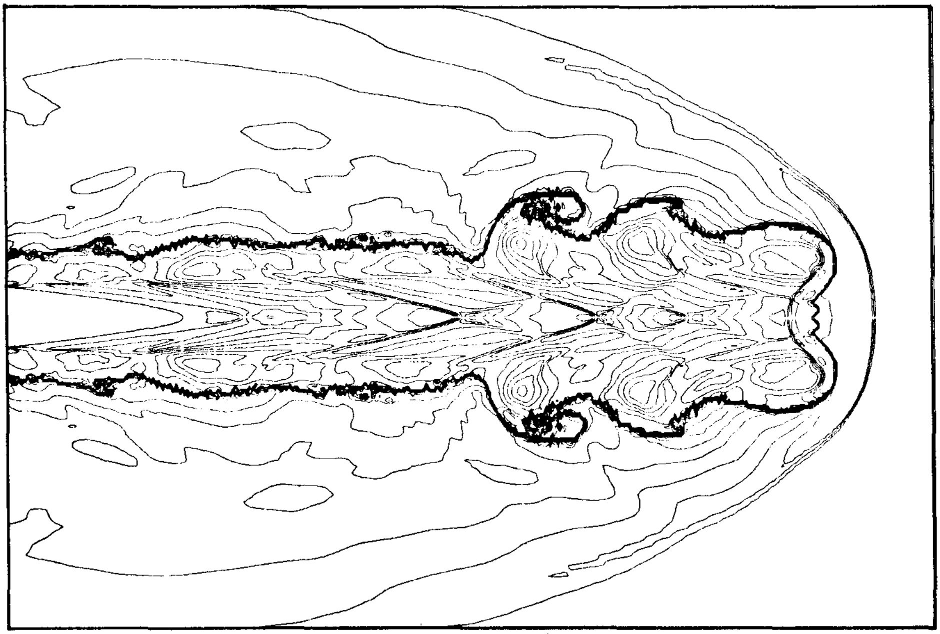

Fig. 2 Hydrodynamical simulation of an axisymmetric, pressure-matched, supersonic (M=6) jet of lower than ambient density (η=0.1), from [17]. A computational mesh of 640 axial by 75 radial zones is used; 20 zones span the beam radius at the inlet at left.

https://doi.org/10.1017/S0252921100086206 Published online by Cambridge University Press

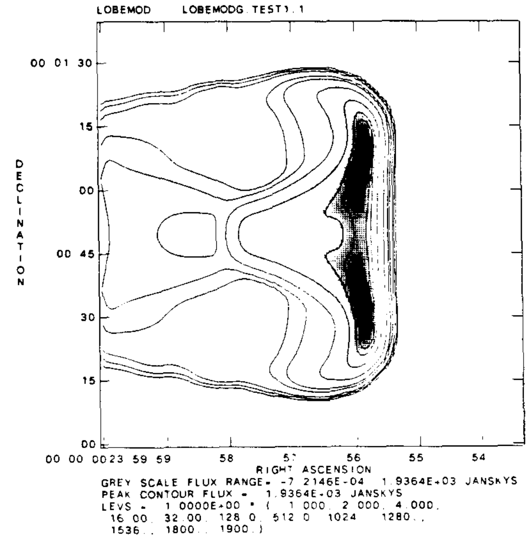

Fig. 3 Radio surface brightness distribution of a hotspot seen edge-on, as determined from hydrodynamic simulations. Synchrotron emissivity is assumed to be proportional to the gas pressure squared within the jet working surface (Fig. 2). The map is smoothed and displayed using AIPS shading and contouring algorithms.

Numerical simulations are also beginning to grapple with the issue of jet stability, which may be related to the low detection rate (<10%)[4] of jets in luminous radio galaxies. As we have seen in the models of Bicknell described in the last section, the slow decline of radio brightness with distance in FR I jets may be a strong indication of entrainment-related deceleration in low Mach number outflows. It is known from laboratory studies that the spreading rate of planar shear layers, which is governed by entrainment, decreases suddenly beyond Mach 2 [59]. In addition, NORMAN, WINKLER and SMARR [25] have shown that the rate of entrainment drops dramatically in supersonic jets upon crossing into the so-called reflection mode regime [26-28] of the Kelvin-Helmholtz pinch instability. To be in this regime the jet's speed must exceed the *sum* of the internal and external sound speeds. This corresponds to a flow Mach number of two for equal sound speed internal and external gases. Therefore the possibility strongly suggests itself that the high Mach numbers jets powering luminous radio lobes are essentially *laminar and accelerating* or of roughly constant velocity. The radiating electrons in such a jet would experience considerable expansion losses on the journey out to the lobes, resulting in a jet of low surface brightness (compared to the lobe) requiring high dynamic range to detect.

In cases where jets have been detected in powerful classical double radio sources, they tend to be clumpy [29]. Significantly, simulations show that reflection-mode pinch instabilities, which have significant growth rates at high Mach numbers, saturate in the nonlinear regime by forming an array of oblique internal shock waves which induce localized "knots" of enhanced emission [25,26,30].

4. Bent jets: narrow-angle tail radio sources

An important class of extragalactic jets are those with large-scale bends associated with head-tail radio sources (cf. Fig. 3 in PERLEY, these proceedings). Tailed radio sources fall into two morphological subclasses depending upon whether the angle subtended by the dual radio jets or trails is less than or greater than 90 degrees, and are referred to as narrow-angle tail (NAT) and wide-angle tail (WAT) radio sources, respectively. The basic interpretation, provided by MILEY et al. [31], holds that tailed radio sources are caused by the active galaxy's motion through a dense intracluster medium (ICM), the galaxy's velocity producing an effective ram pressure sufficient to distort the radio structure. Ram pressure bending models have been applied to both NAT and WAT radio sources with mixed results - the models adequately explain the former but not the latter. This is attributed to the fact that whereas the parent galaxies of NAT radio sources are "average" cluster ellipticals with a typical velocity dispersion of ≈1000 km/sec, WAT radio sources are associated with the dominant galaxy in the cluster, which occupies a central and nearly stationary position with respect to the ICM. Models for WAT radio sources are discussed in sec. 5. Here I shall review ram pressure bending models as applied to NAT radio galaxies, drawing from the work of O'DEA [16].

The basic relation in models of ram pressure bending is $\rho_{ICM}V_g^2/h = \rho_j V_j^2/R$, expressing a balance between ram pressure and centrifugal forces in a curved channel. Here ρ_{ICM} is the ICM mass density, V_g is the galaxy velocity relative to the ICM, and ρ_j and V_j are the jet density and velocity, respectively. R is the radius of curvature of the bent jet and h is a model-dependent scale height over which the pressure difference $\rho_{ICM}V_g^2$ is assumed to operate. Two variants of this model have been developed by JONES and OWEN [32] (hereafter JO) and BEGELMAN, REES and BLANDFORD [33] (hereafter BRB), which differ in their choice of h. JO note that an elliptical galaxy can retain a portion of its interstellar medium (ISM) despite ram pressure stripping, citing numerical calculations of LEA and DEYOUNG [34], and accordingly take h to be the ISM radius which they determine. BRB picture an unshielded jet (i.e., no ISM), and accordingly take h to be the radius of the jet - typically more than an order of magnitude smaller than JO's value.

The utility of the ram pressure balance equation is to provide an estimate of the jet speed - a poorly known quantity - since all other quantities can, in principle, be determined by observations. Unfortunately, as discussed by PERLEY (these proceedings), radio depolarization measurements can only provide an upper limit on ρ_j, and hence only a lower limit on V_j. A way around this is to supplement the momentum constraint with an energy balance equation relating the jet kinetic energy flux to the radio luminosity. One is then able to solve simultaneously for the two unknowns ρ_j and V_j. BRB assume that the entire source radio luminosity is derived from jet kinetic energy. Because smaller jet velocities follow from larger scale heights, JO must assume that the radio trails are energized by wake turbulence behind the ISM. The new uncertainty introduced by this procedure, however, is the conversion efficiency between kinetic and radiated energy. O'DEA notes [16], however, that if one can set an upper limit on the jet velocity through relativistic beaming arguments, one can derive a lower limit on the conversion efficiency, which is typically 1% or greater.

Table 1 summarizes the inferred physical parameters in 19 NAT radio sources investigated by O'DEA [16] for the two ram pressure bending models. For an assumed energy conversion efficiency of 1%, the JO model predicts jet velocities in the range - 10^3 - 10^4 km s^{-1}, whereas the BRB model predicts velocities which are systematically higher by a factor of about 10. This follows directly from a difference in assumed pressure scale height h between the two models. BRB also predicts higher jet Mach numbers (2-4) than JO (≈1). Otherwise, both models give similar estimates for the jet density, which is quite low compared to previous estimates based on depolarization measurements which are now in doubt [35]. These densities are generally lower than X-ray determined ICM densities, implying that NAT jets are buoyant.

Table 1 Properties of jets in narrow-angle tail radio sources (from O'DEA [16])

	JO	BRB
V_j (km/s)	10^3 - 10^4	10^4 - 10^5
M_j	~1	2 - 4
n_j (cm^{-3})	10^{-6} - 10^{-4}	
n_j/n_{ICM}	10^{-3} - 1	
$\dot{m}$ ($M_\odot$/yr)	10^{-3} - 10^{-1}	

5. Bent jets: wide-angle tail radio sources

Wide-angle tail (WAT) radio sources are of intermediate luminosity [$P_{1.4} \approx 10^{24.5}$ W/Hz] between the weak, edge-darkened radio sources discussed in Sec. 2, and the powerful, edge-brightened radio sources discussed in Sec. 3. Furthermore, they occur predominantly in the central dominant galaxies of clusters of galaxies, unlike the narrow-angle tail radio sources discussed in Sec. 4, which are associated with "average" cluster members. Originally, it was thought that the smaller bending angles found in WAT radio sources merely reflected higher jet speeds and lower galaxy-ICM relative speeds than found in NAT radio sources, but that ram pressure bending models nevertheless applied. Recent studies [36-38] have shown ram pressure bending to be insufficient in general, as it now appears the associated galaxies (typically supermassive cD galaxies) are virtually at rest with respect to the ICM at the optical and x-ray centers of rich clusters. Alternate jet bending mechanisms were considered by EILEK et al. [37] for the well-studied source 3C 465, ranging from buoyancy and collisions with dense, cool clouds to magnetic deflection of a current carrying jet. No satisfactory mechanism was found.

High resolution and high dynamic range VLA maps of WAT radio sources reveal a morphology which is also at odds with what one expects from ram pressure bending; instead of smooth bends one finds straight jets which suddenly flare and bend at a hot spot followed by a relaxed plume-like tail (e.g. 1919+479 [38]). In addition, although typically only one jet is detected, hot spots and tails are found on both sides of the central galaxy starting at roughly the same distance from the galactic center. This distance varies from source to source, ranging from 10-100 kpc. The sudden "phase transition" in radio morphology may indicate a localized change in the atmosphere through which the jet is propagating, perhaps at the boundary between the ISM and the ICM which plausibly may exist on similar length scales [39].

Dr. J.O. BURNS and myself have been investigating the effects of nonconstant atmospheres on jet propagation with WAT radio sources in mind. In view of the fact that subsonic plumes are easier to deflect than supersonic jets, we have been particularly interested in jet disruption mechanisms in the sort of atmospheres that may conceivably surround massive central elliptical galaxies. The following numerical simulations are meant to be illustrative of such disruption mechanisms. Although highly idealized, I will indicate how the various situations might arise in real radio galaxies. All calculations were performed at the Los Alamos National Laboratory on a Cray X-MP supercomputer using the techniques described by NORMAN and WINKLER [40]. More detailed accounts are in preparation.

SMITH [41] proposed that jets may be disrupted at the edge of gaseous halos in galaxies due to a sudden decrease in ambient pressure. In this model, it is supposed that the jet overexpands and forms a Mach disk shockwave upon subsequent reconfinement, in exact analogy to laboratory underexpanded supersonic jets [42]. Downstream of the Mach disk, the jet is subsonic and turbulent, and mixes readily with the ambient gas. In a radio galaxy, this part of the jet would correspond to the radio tail. Figure 4 shows a hydrodynamical simulation of "pressure disruption" of an axisymmetric supersonic jet.

Jet gas enters continuously at left with an internal Mach number of 1.5 with one-tenth of the ambient density and in local pressure balance. The atmosphere is isothermal and has an axial density dependence given by

$$\rho(Z) = \rho_0[(1-f)\exp(-Z^2/h^2) + f]$$

where Z is the axial distance in units of the initial jet radius, h is the scale height of the atmosphere, and f is the floor factor, less than unity. In this calculation $f=0.01$ and $h=1$, thus the atmospheric pressure rapidly drops by a factor of 100 over a distance of one jet radius.

We find that Mach disk formation and hence jet disruption is sensitive to h but quite insensitive to f, provided $f<<1$. In this example, the jet disrupts. In an identical calculation with $h=10$, the jet does not disrupt; instead, oblique internal shock waves accompany the radial expansion and reconfinement of the jet. Such shock waves have the property that the axial velocity remains supersonic.

Aside from the lack of a bend, which cannot be addressed in this axisymmetric simulation, the flowfield in Fig. 4 is isomorphic with the east arm of the WAT radio source 3C465 (cf. Fig. 3 in Ref. [37]). The jet's radio brightness distribution indicates an equipartition pressure drop of more than a factor of two hundred where the jet is observed to flare. Although the existing x-ray data on this cluster do not preclude an ambient pressure drop of this magnitude, it is unclear how such a pressure discontinuity could arise and be maintained. Hydrostatic equilibrium would require an equally sudden change in gravitational potential, which is unlikely.

https://doi.org/10.1017/S0252921100086206 Published online by Cambridge University Press

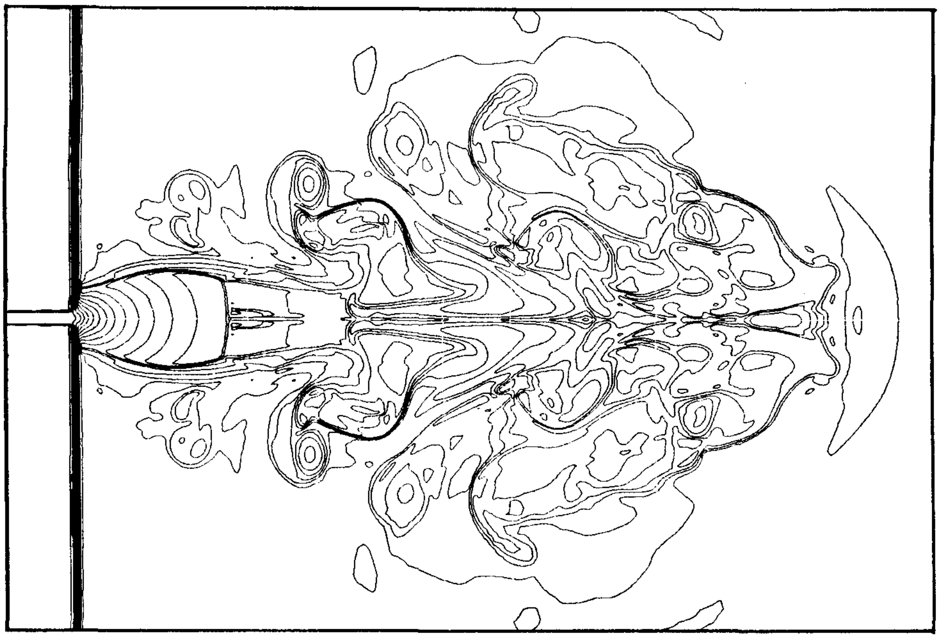

Fig. 4 Disruption of a supersonic (M=1.5) jet caused by a rapid decrease in ambient pressure. Overexpansion and reconfinement creates a Mach disk shockwave (highlighted) within the jet beyond which the flow is subsonic. This mechanism may be responsible for producing the plume-like tails in radio galaxies. A computation mesh of 500 axial zones by 150 radial zones is used; 5 zones span the initial beam radius.

Another possibility is to associate the pressure discontinuity with an outward facing shock in a cooling core inflow. Cooling core inflows are thought to exist around many central dominant galaxies in rich clusters, and may actually have formed these galaxies [43]. Shock formation would require nonspherical supersonic inflow. Spherical supersonic inflow has been studied by WHITE and CHEVALIER [44], and SUMI [45]. These authors find a direct dependence between sonic radius and the core radius of the gravitating matter (luminous and dark). To produce a sonic radius on the tens of kiloparsec length scales would require a core radius at least an order of magnitude larger, i.e., a cluster core radius, not a galactic core radius. Work is in progress to investigate this possibility.

A second mechanism for jet disruption [45] is to utilize the temperature inversion produced by a supersonic cooling core inflow, which can amount to four orders of magnitude or more. The criterion for jet stability to disruptive Kelvin-Helmholtz modes is that the jet speed exceed the sum of the internal and external sound speeds [28]. One can easily imagine an initially stable jet by this criterion becoming unstable at a temperature inversion, where the external sound speed may increase by a factor of one hundred or more.

Figure 5 shows a hydrodynamical simulation of "temperature disruption" of an axisymmetric jet in a constant pressure background. Initially, the temperature of the undisturbed atmosphere smoothly increases by a factor of ten over a distance of ten initial jet radii. The background density accordingly decreases by a factor of ten in this region, which can be seen one quarter of the way from the left hand boundary in Fig. 5. The jet parameters were chosen so that to the right of the transition, $V_{jet} < C_{jet} + C_{ext}$. The result is the onset and growth of the fundamental mode of the the Kelvin-Helmholtz pinch instability, which rapidly leads to jet deceleration via mass entrainment.

https://doi.org/10.1017/S0252921100086206 Published online by Cambridge University Press

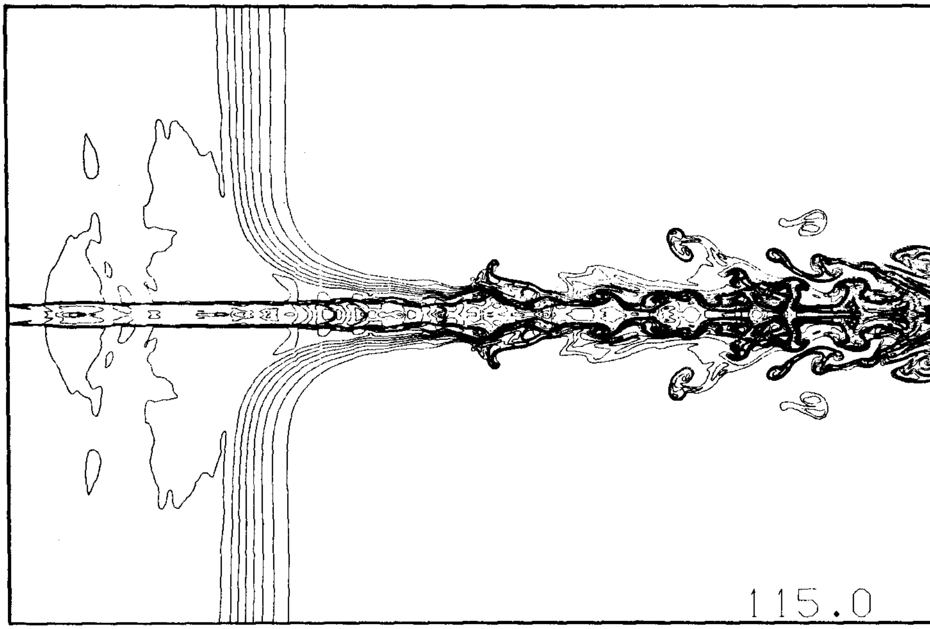

Fig. 5 Disruption of an axisymmetric supersonic (M=5) jet caused by a rapid increase in ambient temperature. The supersonic criterion $V_{jet} > C_{jet} + C_{ext}$ is satisfied to the left of the temperature transition (seen as parallel contours in the left half of the frame), but not to the right. As a consequence, the jet boundary becomes unstable to the fundamental mode of the Kelvin-Helmholtz instability, leading to mass entrainment and deceleration. A computational mesh of 1000 axial zones by 200 radial zones is used; 20 zones span the initial beam radius.

The effects of nonaxisymmetric kink instabilities can be guaged by the 2-dimensional cartesian "slab jet" simulation shown in Fig. 6. The background medium is as before. A 1% transverse perturbation is applied to the jet at the inlet, and varies sinusoidally in time at the resonant frequency of the slab [46]. The perturbation grows rapidly in the hot tenuous medium to the right of the transition, producing a broadening stream of jet material. In three dimensions, one could expect some superposition of these two modes of instability.

SUMI and SMARR [60] have argued that temperature disruption is responsible for confining radio sources within the nucleus of central cluster galaxies with massive cooling inflows (e.g., PKS 0745-191 [47]). In such cases, the mass accretion rate is high (100-1000M_0/yr), and sudden cooling of the inflowing gas occurs on 0.1 to 1 kpc length scales. Further studies are needed to determine whether lower accretion rates and larger core radii can lead to significant temperature jumps further out, say on tens of kiloparsec length scales, as would be required for temperature disruption of jets in WAT radio sources.

6. Concluding Comments

Are we making progress in understanding the physics of extragalactic radio jets; are we able to begin deciding between the various choices in the Chinese menu (Sec. 1) for a particular class of source? Can we begin unifying on a physical basis the different morphological classes of radio sources? I believe the answer is yes.

Take for example the low luminosity (FR I) radio sources discussed in Sec. 2 and the narrow-angle tail (NAT) radio sources discussed in Sec. 4. Aside from the large-scale bends in the latter, BURNS concluded [50] on the basis of a comparison of jet occurrence, size, spectra, magnetic

https://doi.org/10.1017/S0252921100086206 Published online by Cambridge University Press

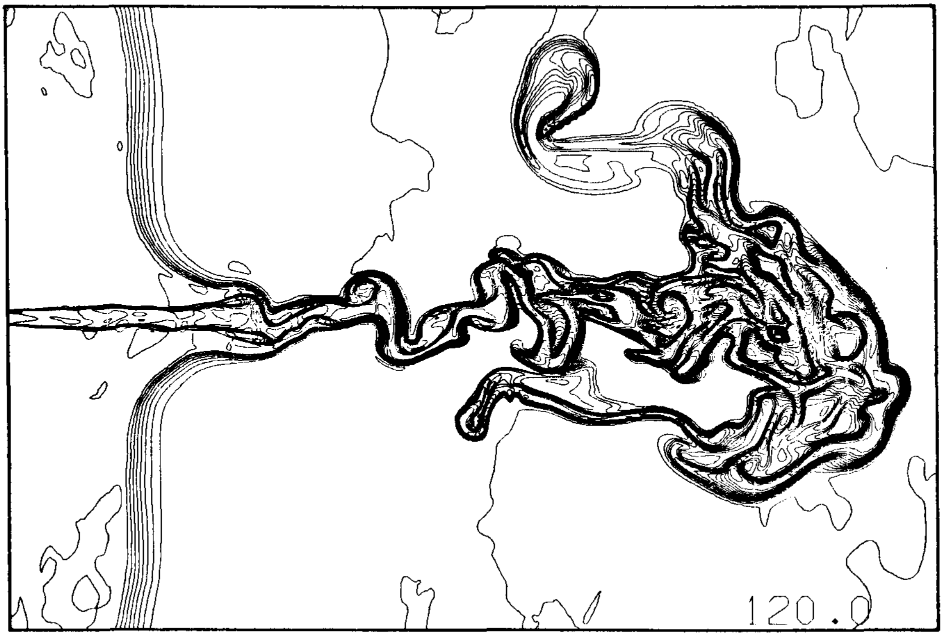

Fig. 6 Disruption of a slab-symmetric supersonic (M=5) jet caused by a rapid increase in ambient temperature. A 1% transverse perturbation is applied at the inlet (at left) with a sinusoidal time dependence at the resonant frequency of the slab [46]. The perturbation grows rapidly into large-scale kinks in the hot tenuous medium to the right of the temperature transition. A computational mesh of 750 longitudinal by 300 transverse zones is used; 20 zones span the initial slab width.

field structure, sidedness and morphology, that the characteristics of the jets in these two morphological classes are "not significantly different". If this is so, then the model calculations should predict similar physical parameters. In fact, they do; both Bicknell's decelerating jet model (Sec. 2) and the ram-pressure bending models analyzed by O'Dea (Sec. 4) predict jet velocities of order 10^3-10^4 km/s and lower-than-ambient jet densities. This is in sharp contrast with ballistic jet models (e.g., [51]), which predict jet velocities an order of magnitude lower and implicitly assume higher-than-ambient jet densities. Given the greatly different assumptions that go into the hydrodynamical models, their agreement is very encouraging and, I believe, significant. The model results indicate that FR I and NAT radio sources are produced by pressure-confined, mildly supersonic jets in which turbulence, mass entrainment and bouyancy are important processes, and whose precise spreading and bending patterns are governed by the local distribution of thermal and ram pressure. Refinements of Bicknell's model should allow us to infer the pressure stratification around quasi-stationary galaxies.

As previously mentioned, DREHER [48] infers jet speeds of 10^4 to $\approx 3 \times 10^5$ km/s (i.e., light speed) in powerful classical radio doubles (FR II sources). This is consistent with the velocity range cited for the lower power jets above in the following rough sense. Since jet power $\alpha\ V_j^3$, an order of magnitude in velocity corresponds to three orders of magnitude in power. Now, the ratio of total luminosity between the most powerful radio sources with observed jets ($P_{1.4} \approx 10^{28}$ W/Hz) and the FR I - FR II transition luminosity ($P_{1.4} \approx 10^{25}$ W/Hz) is approximately 10^3 [4]. The luminosity ratio between the FR I - FR II transition and the weakest radio sources with observed jets ($P_{1.4} \approx 10^{22}$ W/Hz) is also approximately 10^3 [4]. Assuming relativistic jets power the highest luminosity sources, the jet velocities corresponding to these powers would be 3×10^5, 3×10^4 and 3×10^3 km/s, respectively. These numbers coincide remarkably closely with the inferred velocity ranges in the two classes of sources. Taking this result at face value, then if internal densities and pressures are similar in high power jets and low power jets, the former may have internal Mach numbers in the range of 10-50.

https://doi.org/10.1017/S0252921100086206 Published online by Cambridge University Press

Laboratory experiments have scarcely addressed the structure of hypersonic jets of lower than ambient density; Mach numbers of ten or greater have, to my knowledge, never been obtained. We must thus rely on numerical simulation for insight into this physical regime. We may find that hypersonic flows hold some surprises in store for us, for example, concerning stability. Simulations [25,46] have already shown us how shock waves dominate the stability properties of 2-dimensional jets of moderate Mach number. The range of possible shock configurations is considerably larger in three dimension.

The qualitative agreement between observed and simulated hotspots from hydrodynamic models of working surfaces [19,24], coupled with the synchrotron aging models of MYERS and SPANGLER [23], give us some confidence that the fluid hypothesis is valid for classical double radio sources. Detailed, quantitative modeling of hotspots should tell us whether magnetohydrodynamic effects are operative, and possibly give us some information about plasma processes and particle acceleration mechanisms.

A study of wide-angle tail radio sources is forcing us to pay more attention to the environment in and around dominant central galaxies in clusters of galaxies. Hydrodynamic models provide some candidate scenarios for WAT source formation (Sec. 5), and hence environmental parameters, but better observations of cluster gas distribution are needed by the next generation of x-ray satellites in order to discriminate between models.

Finally, there are the quasar jets, which are problematical on two counts: 1) all are one-sided yet occur in dual-lobed systems, however statistics argue against Doppler-boosting to account for their appearance [52]; 2) many jets appear overpressured with respect to their environment [53], which has lead to speculation on alternate confinement mechanisms, including magnetic confinement [54,55]. Models of magnetically-dominated jets are in their infancy. Some [56,57] are based on analogies to force-free magnetic equilibria created in the laboratory, which may or may not be relevant to a system with a large kinetic energy contribution to the total energy. D. CLARKE and myself have begun building a magnetohydrodynamics simulation code in order to gain some insight into the properties of magnetically-dominated jets and to identify observable magnetic "signatures". It is premature to describe this work here.

Acknowledgements

I would like to thank Jack Burns for his continued interest and assistance in radio source modeling, and Dimitri Mihalas for his patience.

References

1. R.D. Blandford & M.J. Rees: Mon. Not. R. astr. Soc., **169**, 395 (1974)
2. P.A.G. Scheuer: Mon. Not. R. astr. Soc., **166**, 513 (1974)
3. S.W. Kieffer & B. Sturtevant: J. Geophys. Res. B, **89**, 8253 (1984)
4. A.H. Bridle & R.A. Perley: Ann. Rev. Astron. Astrophys., **22**, 319 (1984)
5. A.H. Bridle: in *Physics of Energy Transport in Extragalactic Radio Sources*, NRAO Workshop No. 9, eds. A.H. Bridle & J.A. Eilek, 1 (1985)
6. J.A. Eilek: Astrophys. J., **230**, 373 (1979)
7. G.V. Bicknell & D.B. Melrose: Astrophys. J., **262**, 511 (1982)
8. J.A. Eilek & R.N. Henriksen: Astrophys. J., **277**, 820 (1984)
9. R. Fanti, C. Lari, P. Parma, A.H. Bridle, R.D. Ekers, E.H. Fomalont: Astron. Astrophys., **110** (1982)
10. G.N. Abramovich: *Theory of Turbulent Jets* , MIT Press, Cambridge (1963)
11. C.J. Chen & W. Rodi: *Vertical Turbulent Buoyant Jets*, Pergamon Press, Oxford (1980)
12. G.V. Bicknell: Astrophys. J., **286**, 68 (1984)
13. G.V. Bicknell: Astrophys. J. in press (1986)
14. G.V. Bicknell: in *Jets from Stars and Galaxies*, eds. R.N. Henriksen & T.W. Jones, Canadian Journal of Physics, in press (1986)
15. A.H. Bridle, E.B. Fomalont, R.N. Henriksen: in preparation
16. O'Dea, Astrophys. J.: in press (1986)
17. M.L. Norman, L.L. Smarr, K.-H. Winkler, M.D. Smith: Astron. Astrophys., **113**, 285 (1982)
18. M.J. Wilson & P.A.G. Scheuer: Mon. Not. R. astr. Soc., **205**, 449 (1983)

19. A.G. Williams & S.F. Gull: Nature, **310**, 33 (1984)
20. M. Yokosawa, S. Ikeuchi & S. Sakashita: Pub. Astron. Soc. Japan, **34**, 461 (1982)
21. C.N. Arnold & W.D. Arnett: Astrophys. J. Lett., in press (1986)
22. R.A. Perley, J.W. Dreher, J. Cowan, Astrophys. J. Lett., **285**, L35 (1984)
23. S.T. Myers & S.R. Spangler: Astrophys. J., **291**, 52 (1985)
24. M.D. Smith, M.L. Norman, K.-H.A. Winkler, L. Smarr: Mon. Not. R. astr. Soc., **214**, 67 (1985)
25. M.L. Norman, K.-H.A. Winkler, L. Smarr: in *Physics of Energy Transport in Extragalactic Radio Sources*, NRAO Workshop No. 9, eds. A.H. Bridle & J.A. Eilek, 150 (1985)
26. M.L. Norman & K.-H.A. Winkler: Los Alamos Science, **12**, 38 (1985)
27. H. Cohn: Astrophys. J., **269**, 500 (1983)
28. D.G. Payne & H. Cohn: Astrophys. J., **291**, 655 (1985)
29. J.O. Burns, J.P. Basart, D.S. DeYoung, D.C. Ghiglia: Astrophys. J., **283**, 515 (1984)
30. M.L. Norman, L.L. Smarr, K.-H.A. Winkler: in *Numerical Astrophysics*, eds. J. Centrella, J. LeBlanc & R. Bowers, Jones and Bartlett, Portola Valley, CA (1985)
31. G.K. Miley, G.C. Perola, P.C. Van der Kruit, H. Van der Laan: Nature, **237**, 269 (1972)
32. T.W. Jones & F.N. Owen: Astrophys. J., **234**, 818 (1979)
33. M.C. Begelman, M.J. Rees, & R.D. Blandford: Nature, **279**, 770 (1979)
34. S.M. Lea & D.S. DeYoung: Astrophys. J., **210**, 647 (1976)
35. R.A. Laing: in *Physics of Energy Transport in Extragalactic Radio Sources*, NRAO Workshop No. 9, eds. A.H. Bridle & J.A. Eilek, 90 (1985)
36. J.O. Burns: Mon. Not. R. astr. Soc., **195**, 523 (1981)
37. J.A. Eilek, J.O. Burns, C.P. O'Dea, F.N. Owen: Astrophys. J., **278**, 37 (1984)
38. J.O. Burns, C.P. O'Dea, S.A. Gregory, T.J. Balonek: Astrophys. J., in press (1986)
39. C. Norman & J. Silk: Astrophys. J. Lett., **233**, L1 (1979)
40. M.L. Norman & K.-H.A. Winkler: in *Astrophysical Radiation Hydrodynamics*, eds. K.-H.A. Winkler & M.L. Norman, D. Reidel, Dordrecht (1986)
41. M.D. Smith: Astrophys. J., **259**, 522 (1982)
42. T.C. Adamson & J.A. Nicholls: J. Aerospace Sci., **26**, 16 (1959)
43. C.L. Sarazin: in *Dark Matter in the Universe*, IAU Symposium 117, eds. J. Kormendy & G. Knapp, D. Reidel, Dordrecht, in press (1986)
44. R.E. White & R.A. Chevalier: Astrophys. J., **280**, 561 (1984)
45. D.M. Sumi: Ph.D. Dissertation, University of Illinois (1986)
46. P.R. Woodward: in *Astrophysical Radiation Hydrodynamics*, eds. K.-H.A.Winkler & M.L. Norman, D. Reidel, Dordrecht (1986)
47. A.C. Fabian, K.A. Arnaud, P.E.J. Nulsen, M.G. Watson, G.C. Stewart, I. McHardy, A. Smith, B. Cooke, M. Elvis, R.F. Mushotsky: Mon. Not. R. astr. Soc., **216**, 923 (1985)
48. J.W. Dreher: in *Physics of Energy Transport in Extragalactic Radio Sources*, NRAO Workshop No. 9, eds. A.H. Bridle & J.A. Eilek, 109 (1985)
49. B.L. Fanaroff & J.M. Riley: Mon. Not. R. astr. Soc., **167**, 31P (1974)
50. J.O. Burns: in *Astrophysical Jets*, eds. A Ferrari & A.G. Pacholczyk, D. Reidel, Dordrecht, 67 (1983)
51. A.C. Gower & J.B. Hutchings: Astrophys. J. Lett., **25**, L63 (1982)
52. J.F.C. Wardle & R.I. Potash: in *Physics of Energy Transport in Extragalactic Radio Sources*, NRAO Workshop No. 9, eds. A.H. Bridle & J.A. Eilek, 30 (1985)
53. R.I. Potash & J.F.C. Wardle: Astron. J., **75**, 707 (1979)
54. G.V. Bicknell & R.N. Henriksen: Astrophys. Lett., **21**, 29 (1980)
55. G. Benford: in *Astrophysical Jets*, eds. A Ferrari & A.G. Pacholczyk, D. Reidel, Dordrecht, 271 (1983)
56. A. Kõnigl & A.C. Choudhuri: Astrophys. J., **289**, 173 (1985)
57. A. Kõnigl & A.C. Choudhuri: Astrophys. J., **289**, 188 (1985)
58. J.C. Lau: J. Fluid Mech., **105**, 193 (1981)
59. P. Bradshaw: in *1980-81 AFOSR-HTTM Stanford Conference on Complex Turbulent Flows*, eds. S.J. Kline, B.J. Cantwell & G.H. Lilley, Stanford University, 364 (1981)
60. D.M. Sumi & L.L. Smarr: in *Physics of Energy Transport in Extragalactic Radio Sources*, NRAO Workshop No. 9, eds. A.H. Bridle & J.A. Eilek, 170 (1985)