Why Dominant Cluster Jets are Different.

Dean M. Sumi and Larry L. Smarr*
Department of Astronomy,
University of Illinois at Urbana-Champaign

ABSTRACT: Recent numerical simulations by Norman et al 1983 have shown that the ability of axisymmetric hydrodynamic jets stabily to propagate through a pressure confining atmosphere depends on two parameters: 1) the ratio of the internal jet density to the external atmosphere's density and 2) the jet's internal Mach number. As the pressure of the external atmosphere changes along the jet's path, these two parameters change accordingly, leading to the possibility that a stable jet can suddenly become unstable. Elliptical galaxies which are stationary with respect to any outside gas medium, can sustain two generic types of atmospheres, 1) an outflowing wind and 2) a radiatively cooling inflow. Isolated elliptical galaxies should have wind atmospheres, whereas dominant galaxies at the center of clusters of galaxies can have cooling inflow atmospheres. We find that jets emerging through wind atmospheres propagate stabily. In contrast, jets emerging through cooling inflow atmospheres rapidly evolve through parameter space, crossing over into the unstable region. The instability manifests itself as a strong planar shock which abruptly brings the jet from a supersonic to a subsonic flow. After this shock we expect a subsonic plume to continue onward. The behavior of jets in these different atmospheres may help explain the three classes of radio morphology found associated with dominant cluster galaxies: close doubles, short jets, and Wide Angle Tail (WAT) radio sources. In particular, our picture explains why these sources are often smaller in size than comparably powered radio sources from isolated elliptical galaxies.

Introduction

On the simplest level, jet morphology is determined by the interaction of the galaxy, the gas in and around the galaxy, and the jet, itself. Observations of the reconfinement shoulder in NGC 315 (Sanders 1983) and dynamic bending in narrow angle tail radio sources (Begelman et al 1979 and Jones et al 1979) demonstrates the initimate relationship between the jet and its surrounding environment. We examine a different aspect of this relationship between jet and environment, namely how Kelvin-Helmholtz instabilities (instabilities at the shear boundary between the jet and its confining medium) can affect a jet as it moves outward through a galaxy's gaseous medium. We will consider only galaxies stationary with respect to any outside gas medium and can, therefore, think of the subsequent gas configuration as an atmosphere around the galaxy. The parameters of the atmosphere will be determined by the potential well of the galaxy, and the energy balance in the atmosphere.

We will restrict ourselves to hydrodynamic jets which are pressure confined by the atmosphere. Within this scope, we look at the stability of jets, discuss the various atmospheres possible in elliptical galaxies, use the various atmospheres to trace a jet's stability through an atmosphere, and finally, look at examples of jets propagating through these atmospheres.

* Alfred P. Sloan Fellow

Jet Instabilities

Jets, by their very nature, are shear flows which are subject to Kelvin-Helmholtz instablilities. The lower order modes are the most observable, i.e. the n=0 mode (The "pinch" mode), and the n=1 mode (The "garden hose" instability or the "helical" mode). Although the helical mode is potentially the fastest growing of the two modes (Hardee 1982), we restrict ourselves to the axisymmetric pinch mode. Many jets (M87, 3C111, NGC 6251) do not appear to be strongly influenced by helical modes over a large fraction of their length, giving us some confidence that pinch modes may be dominant in the nonlinear regime.

Supercomputer simulations of axisymmetric pressure confined jets (Norman et al 1983 (NSW)) indicate that in the nonlinear regime the linear pinch instability saturates into shock fronts. The global structure of these shock fronts are of two basic types depending on the jet's location in a parameter space (see NSW, figure 6) defined by 1) the ratio of the internal jet density and the external confining atmosphere density η; 2) the internal Mach number, M (see figure 1). We will denote this space as (η, M) space. Two runs performed by NSW (our figure 2, and 3 are their figure 10) illustrate the two types of shock structure, one at η = 1, and M = 1.5 (figure 2b) and another at η = 1, and M = 3.0 (figure 3b). The jet in figure 2 has planar shock structure (shocks perpendicular to the jet flow) whereas the jet in figure 3 has biconical shock structure (shocks oblique to the jet flow).

The transition line between these two global structures was mapped out numerically by NSW and was found to correspond to the transition line between different types of pinch instability in the linear regime. From the linear analysis (see literature references in NSW) of idealized slab and cylindrical jet flows, one finds a subdivision of n = 0 pinch mode solutions; the lowest order (m = 0) is known as the ordinary mode (OM) pinch instabilities and the higher order solutions ($m \geq 1$) are known collectively as reflecting mode (RM) pinch instabilities. The relative growth rate of each mode (dependent on η, M, and wavelength) determines the dominance of the mode and, therefore the characteristic mode seen in a particular part of (η, M) space. Cohn (1983) finds a boundary between the OM dominated and RM dominated regime can be given roughly by

$$\eta \cong \left(\frac{M}{2}\right)^{3.3} \qquad (1)$$

where jets with $\eta > (M/2)^{3.3}$ are in the OM dominated regime. NSW noted that planar shock jets fall into the OM dominated regime and biconical shock jets fall into the RM dominated regime of (η, M) space. Though it is not precisely known how these linear modes develop into nonlinear shock structures, we are able to use equation (1) as a guide to the regions in (η, M) space where each shock structure is important. This line is labeled in figure 1 the planar shock / biconical shock (PS/BS) line.

NSW find that the type of shock structure has a strong influence on the jet's ability to propagate supersonically. Planar shocks will strongly decelerate the flow rendering it subsonic. Severe entrainment also occurs as the jet is "necked down" or pinched (see figure 2a). Biconical shocks, however, causes only slight decelerations of the flow and the jet remains supersonic along its entire length. There are only small undulations in the

FIGURE 1

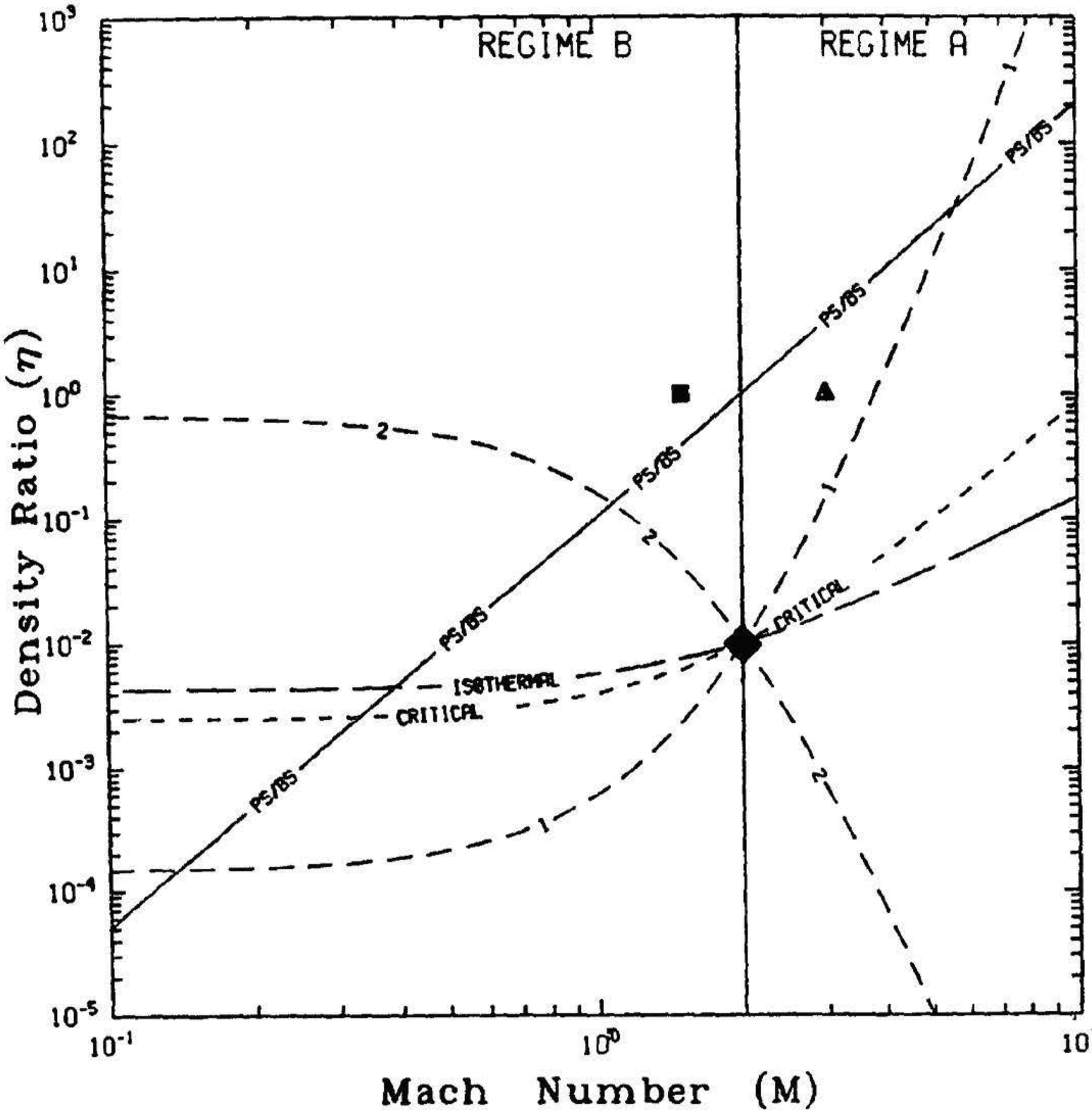
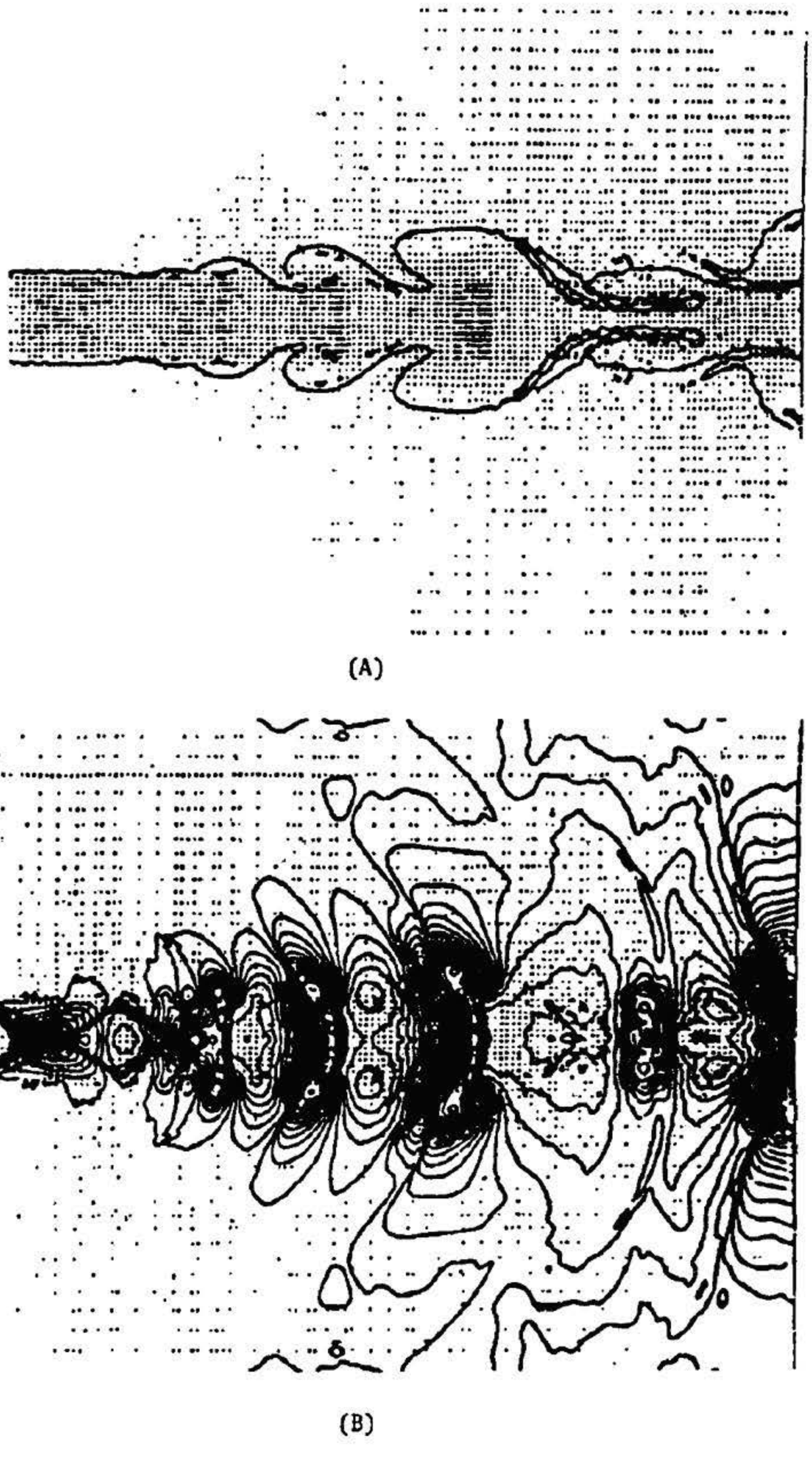


Figure 1. The (η, M) parameter space adapted from NSW figure 6. Plotted are the planar shock / biconical shock (PS/BS) line and jet parameters for the jet in figure 2 (■) and the jet in figure 3 (▲). For η = 0.01 and M = 2 (◆), the A and B regimes are labeled and are separated by regime B, the solid line. The isothermal line designates the boundary line between increasing and decreasing external temperature distribution. The critical line designates the critical jet path (ζ = 3.3) which will intersection with the PS/BS line. Lines 1 and 2 are jets paths passing through (◆) with δ = 2.5 and -2.5, respectively. These illustrate extremes of jet behavior.

FIGURE 2

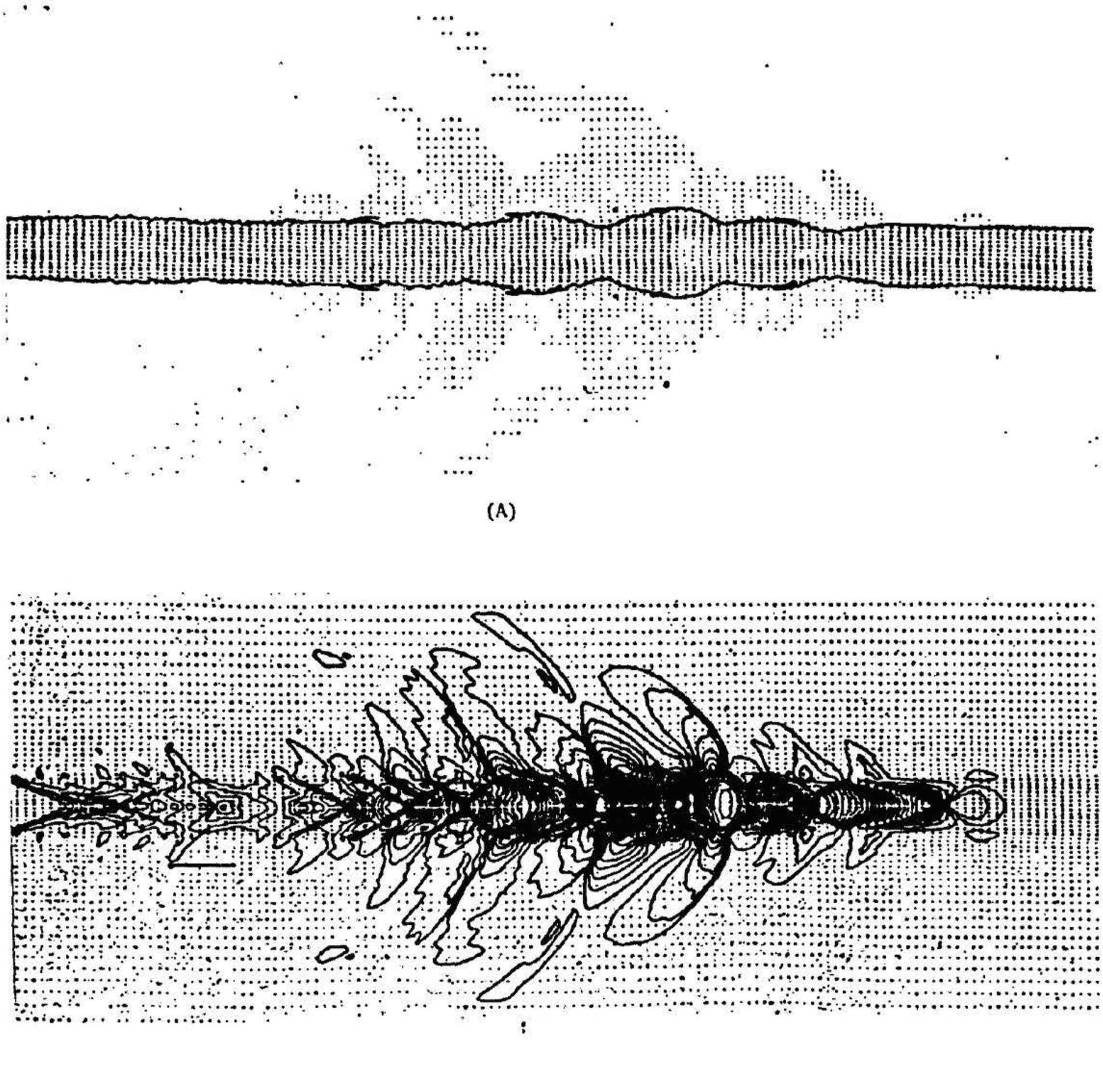


(A)

(B)

Figure 2. NSW simulation of a $\eta = 1.0$, $M = 1.5$ axisymmetric jet in a constant temperature and density medium. A) The jet boundary and velocity vectors. B) The pressure contours. Figure reproduced from NSW figure 10.

FIGURE 3



(A)

(B)

Figure 3. NSW simulation of a η = 1.0, M = 3.0 axisymmetric jet with the same confining medium. A) The jet boundary and velocity vectors. B) The pressure contours. Figure reproduced from NSW figure 10.

jet boundary and consequently no appreciable entrainment (see figure 3b). The (η, M) parameter space thus has regions separated by equation (1) where a jet when perturbed axisymmetrically will continue to propagate supersonically (the biconical shock regime) or will be decelerated down to a subsonic jet and mixed with the outside medium through entrainment (the planar shock regime).

The simulations conducted by NSW were run in a spatially uniform temperature and density confining medium. To assess the stability of pressure confined jets in a real galaxy, we need to be able to determine how the jet will react to the changing external medium and how this will in turn affect the shock structure. In this paper, we sketch out the simpliest approximation to the real world, namely that to lowest order a jet's local (η, M) is determined by the local confining medium's temperature and density through the pressure balance assumption. In general, the confining medium will have varying temperature, density, and pressure thereby changing the local (η, M) of the jet as it emerges from the galaxy. We further assume that the local (η, M) of the jet determines the shock structure, as found in the NSW calculations. Smarr et al 1983 (SNW) point out that the local (η, M) of the jet varies strongly through shocks but on average the values of (η, M) vary slowly along the jet and therefore this assumption is not inconsistent. The next step will be to perform new supercomputer simulations of jets in varying atmospheres to determine whether our "broad brush" picture given herein holds up in detail.

Given these assumptions we can follow a jet's path through (η, M) space as it moves through the confining medium and are able to use its location in this space to determine its ability to continue to propagate supersonically. It should be noted that points along the jet path through (η, M) space indicate the local (η, M) at a particular spatial location along the jet and not the jet as a whole. That is, when we observe a jet we see it at a moment in its propagation. Different points along the jet are at different points in (η, M) space.

Within the scope of our analysis, we can model a jet in terms of an equation of state for the jet given by

$$P_j \propto n_j^{\gamma} \quad , \tag{2}$$

pressure equilibrium

$$n_j T_j = n_{ext} T_{ext}, \tag{3}$$

and energy conservation

$$v_o^2 + \frac{2\gamma k T_o}{(\gamma - 1)\mu} + \phi_o = v_j^2 + \frac{2\gamma k T_j}{(\gamma - 1)\mu} + \phi \quad , \tag{4}$$

where P is pressure, n is the number density, T is temperature, v is velocity, ϕ is the gravitational potential of the host galaxy, k is the Boltzmann constant, γ is the ratio of specific heats, and μ is the mean molecular weight. The subscripts are j for jet, ext for the external medium, o for the initial jet, and * for the initial external medium. We have assumed that we can model a jet using an adiabatic equation of state, equation (2). This obviously will be violated when moving through strong shocks; we must, therefore, assume further that, at least in the biconical shock regime, the shocks are weak.

In terms of the variables of our parameter space one can easily show that

$$\eta \equiv \frac{n_j}{n_{ext}} = \eta_o \left(\frac{n_{ext}}{n_*}\right)^{\left(\frac{1}{\gamma} - 1\right)} \left(\frac{T_{ext}}{T_*}\right)^{\left(\frac{1}{\gamma}\right)} \qquad (5)$$

and

$$M^2 = \left(M_o^2 - \frac{2\mu}{\gamma k T_o}(\phi - \phi_o) + \frac{2}{\gamma - 1}\right)\left(\frac{P_{ext}}{P_*}\right)^{\left(\frac{1}{\gamma} - 1\right)} - \frac{2}{\gamma - 1} . \qquad (6)$$

Both these equations are dependent on only the external parameters of the confining medium.

Confining Atmospheres

We will consider atmospheres which contain an ambient medium plus mass inputs from stellar mass loss and planetary nebulae, energy inputs from supernovae explosions, and energy losses from radiation. We expect two generic types of atmospheres i) an outward flowing 'wind' model where sufficient energy is deposited by supernovae into the atmosphere so that the gas can escape, and ii) an inward flowing cooling model where the central core pressure support is removed by radiative losses causing the atmosphere to collapse (Mathews and Baker 1971). No truly static atmosphere is considered since any static atmosphere will evolve into the wind or cooling inflow regimes.

Cooling inflows can occur in a galaxy when

$$\sigma^2 > \left(\frac{2}{9}\right)\left(\frac{\alpha_{SN}}{\alpha}\right) E_{SN} \qquad (7)$$

(MacDonald and Bailey 1981), where σ is the line-of-sight velocity dispersion of the galaxy, α_{SN} is the specific mass loss rate for supernovae, E_{SN} is energy per unit mass of supernovae ejecta, and α is the total specific mass loss rate. The values for α_{SN}, α, and E_{SN}, are only poorly known, but current estimates (White, and Chevalier 1983) indicate that this dispersion limit is $\sim$ 700 km/sec, which excludes all elliptical galaxies from having cooling inflow atmospheres (The maximum velocity dispersion observed in elliptical galaxies is $\sim$ 400 km/sec, cf. Tonry and Davis 1981).

This limit, however, only pertains to single isolated galaxies. Dominant elliptical galaxies at the kinematic centers of cluster of galaxies are known to have cooling inflows, notably M87 in the Virgo cluster (e.g. Canizares et al 1979) and NGC 1275 in the Perseus cluster (e.g. Fabian and Nulsen 1977). Sumi and Smarr (1984) contend that the small core radii ($\sim$ 50 kpc) of the dark matter in some clusters of galaxies, termed pit clusters (Blandford and Smarr 1982), will naturally cause cooling inflows onto these central galaxies. This concentration of dark matter will tend to increase the effective velocity dispersion of the galaxy to cluster-like dispersions ($\sim$ 1000 km/sec). The galaxy dispersion is unchanged because the dominance of the dark matter occurs outside the optical extent of the galaxy. This higher velocity dispersion, and the relative unimportance of supernovae as energy inputs (Compared with shock heating as gas is stripped from cluster galaxies), allows the atmosphere around central galaxies in clusters of galaxies to satisfy (7), and making possible cooling inflows onto the central galaxy.

With an understanding of where the different atmospheres may be applica-

ble, we now would like to get a feel of the distribution of various important parameters of the two types of atmosphere. In the interest of brevity, we will summarize many years of work by many authors. Various simulations of wind type atmospheres indicate that the density, and pressure are declining as one moves outward from the galaxy. The temperature also declines but only much more slowly and is almost isothermal. In cooling inflow type atmospheres, the temperature strongly increases and the density strongly decreases as one moves outward, near the core of the galaxy. The pressure can also be increasing as one moves outward from the galaxy (a pressure inversion).

Stability of Jets in Galaxy Atmospheres

In this the discussion of stability, we choose simple analytic functions to represent the confining atmosphere. The analysis with more realistic atmospheres will be presented in a later paper. We represent the density, and temperature as power laws:

$$T_{ext} = T_*(\frac{r}{r_*})^{\alpha} \tag{8}$$

and,

$$n_{ext} = n_* (\frac{r}{r_*})^{\beta}. \tag{9}$$

The pressure of this atmosphere is given by

$$P_{ext} = P_*(\frac{r}{r_*})^{\alpha + \beta}. \tag{10}$$

Substituting these equations into (5) and (6), we find that for (5)

$$\eta = \eta_o(\frac{r}{r_*})^{[(1/\gamma - 1)\beta + (1/\gamma)\alpha]} \tag{11}$$

and for (6)

$$M^2 = (M_o^2 + \frac{2}{\gamma - 1} - \frac{2\mu}{\gamma k T_o}(\phi - \phi_o))\ (\frac{r}{r_*})^{[(1/\gamma - 1)(\alpha + \beta)]} - \frac{2}{\gamma - 1}. \tag{12}$$

Solving for r/r_* in (12) and replacing this into (11) we get

$$\eta = \eta_o(\frac{M^2 + \frac{2}{\gamma - 1}}{M_o^2 + \frac{2}{\gamma - 1} - \frac{2\mu}{\gamma k T_o}(\phi - \phi_o)})^{\delta} \tag{13}$$

where

$$\delta \equiv \frac{(1 - \gamma)\beta + \alpha}{(1 - \gamma)(\alpha + \beta)}. \tag{14}$$

To discuss the behavior of the jet we consider two extreme regimes. First, we consider the case where the potential term is negligible compared to the kinetic and thermal terms in (12). Secondly, we will discuss the potential dominated case at the end of this section. This first assumption is equivalent to assuming the jet is unbound gravitationally to its host galaxy and reduces (13) to a parametric representation of the jet in (η, M) space.

Equation (13) is important in that it allows us to find the asymptotic behavior of the jet as either $M \to \infty$ or $M \to 0$. We take the limit as $M \to 0$ of (13) and find that

$$\lim_{M \to 0} \eta = \eta_o \left(\frac{\frac{2}{\gamma - 1}}{M_o^2 + \frac{2}{\gamma - 1}} \right)^{\delta} = \text{constant.} \qquad (15)$$

For a jet of decreasing Mach number, the slope of the jet path in (η, M) space will go to zero.

At the opposite limit, $M \to \infty$

$$\lim_{M \to \infty} \eta = \eta_o (M)^{\zeta} \qquad (16)$$

where $\zeta = 2\delta$. For a jet with increasing Mach number, the coefficient ζ is the asymptotic slope of jet path in (log η , log M), space. We will refer to this as the asymptotic logarithmic slope of the jet path.

To assess the stability of a jet, we use the (η, M) space (figure 1) and determine the jet path in this space using (13). Jet paths which cross into the planar shock regime are presumably thereafter subject to planar shocks and will be degraded into subsonic flows.

For any point in (η, M) space, there is a jet path leading from this point. The character of this path is determined ultimately by the external medium through δ in equation (13). In figure 1, we choose our arbitary point at $\eta = 10^{-2}$ and M = 2.0, this point is designated by (◆). The lines 1 and 2 through (◆) are jet paths from this point with $\delta = 2.5$ and -2.5, respectively. Note that each line has two branches: one toward higher Mach numbers and another toward lower Mach numbers.

From equation (12), we find that the particular branch the jet takes as it propagates outward depends on the α, and β of the confining atmosphere. For $\gamma > 1$ in equation (12), we find that for $\alpha + \beta < 0$(regimes A), the Mach number increases with distance along the jet whereas for $\alpha + \beta > 0$ (regime B), the Mach number decreases. For $\alpha + \beta = 0$ (regime C), the Mach number is constant. In figure 1, the paths 1, and 2 leading from (◆) toward lower Mach numbers are followed by the jet as it propagates outward if the atmosphere is in regime B type; the paths 1, and 2 leading from (◆) toward higher Mach numbers are followed by the jet as it propagates outward if the atmosphere is in regime A. In general, we can separate (η, M) space around any point (η_o, M_o) into 1) $M > M_o$, which encompasses all jet paths propagating through a regime A atmosphere, 2) $M < M_o$, which encompasses all jet paths propagating through a regime B atmosphere and 3) $M = M_o$, the boundary line between regime A and B (regime C). In figure 1, we separate (η, M) space around point (◆) into regime A, and B.

From equation (10), we find that these conditions on α, and β are conditions separating special regimes of the pressure distribution. Regime A is a decreasing pressure distribution, regime B is an increasing distribution (a pressure inversion), and regime C is a constant distribution.

Another important dividing line in the (η, M) diagram separates atmospheres with temperatue distributions with 1) $\alpha > 0$, and 2) $\alpha < 0$. The boundary line where $\alpha = 0$ represents an isothermal atmosphere. Using (13) we can plot this line in figure 1 for point (◆). In regime A, the asymptotic logarithmic slope of this line, ζ, is 2.

Finally, we can delineate the regions where a jet in the biconical shock regime will cross into the planar shock regime. Jet paths into regime B asymptotically go to zero logarithmic slope and will intersect the PS/BS line. For regime A the asymptotic logarithmic slope is given by ζ. The condition for intersection with the PS/BS line is $\zeta = 3.3$ (equation (1)). Thus, there will be an intersection of the jet path with the planar shock regime if:

$$\alpha > - \frac{1.3(1 - \gamma)\beta}{1.3 - 3.3\beta} \qquad (17)$$

Again using (13) we plot the critical PS/BS intersection jet path (the equality in equation (17)) on figure 1 for point (◆).

We now come to our conclusions about jet propagation in the two types of elliptical galaxy atmospheres. As noted in the previous section, isolated ellipticals have wind type atmospheres which are isothermal or have declining temperature distributions and will have declining pressure distributions. Therefore, all jet paths will be in regime A and will move toward higher Mach number. The largest upward logarithmic slope asymptotically can only reach the isothermal line with logarithmic slope equal to 2. A jet with initial conditions below the PS/BS boundary therefore must have a path through (η, M) space which does not intersect this boundary. Consequently such jets can propagate supersonically along its entire length and get out of the galaxy to large distances.

For cooling inflow atmospheres, we can separate the jet's response into either regimes A or B. In regime A, we can use (16) to describe the jet's asymptotic behavior. By its very nature a cooling inflow has $\alpha \geq 0$. Therefore, the smallest asymptotic logarithmic slope of a jet's path is given by the isothermal atmosphere line asymptotic slope of 2. A jet path along this line, as seen in the wind atmosphere case, will not intersect the PS/BS line. However, if a cooling inflow has temperature and density distributions such that condition (17) is satisfied, a jet in this atmosphere will make the transition into the planar shock regime. In regime B, we find that all jet paths will make this transition, since all paths have limiting slopes of zero and move toward lower Mach numbers. We, therefore, have the situation where as long as condition (17) is satisfied by the cooling inflow atmosphere a jet initially in the biconical shock regime will at some point cross into the planar shock regime. The jet then will go subsonic, if perturbed.

The above analysis must be modified to accommodate the potential term, ϕ. This term is especially important for gravitationally bound and nearly bound jets. From (12), we find that as the potential term becomes important the Mach number tends to go to zero for all jets. The density ratio, η, is unaffected by the potential (equation (11)). The jet path in (η, M) space is toward zero Mach number and the asymptotic logarithmic slope also approaches zero. The net result is for all gravitationally bound jets in the biconical shock regime to cross into planar shock regime. Example jet paths for jets which are bound are plotted in figure 4. Jet path 3 would follow the $\alpha = 0$ line if the potential were neglected. Jet path 4 is the same atmosphere parameters as jet path 2 in figure 1 only not neglecting the potential term. For convenience, we have used a linearly increasing potential term. This not meant to represent a physical galaxy potential, but rather to mathematically represent a case between a 1/r (point mass) and a log(r) (extended dark

FIGURE 4

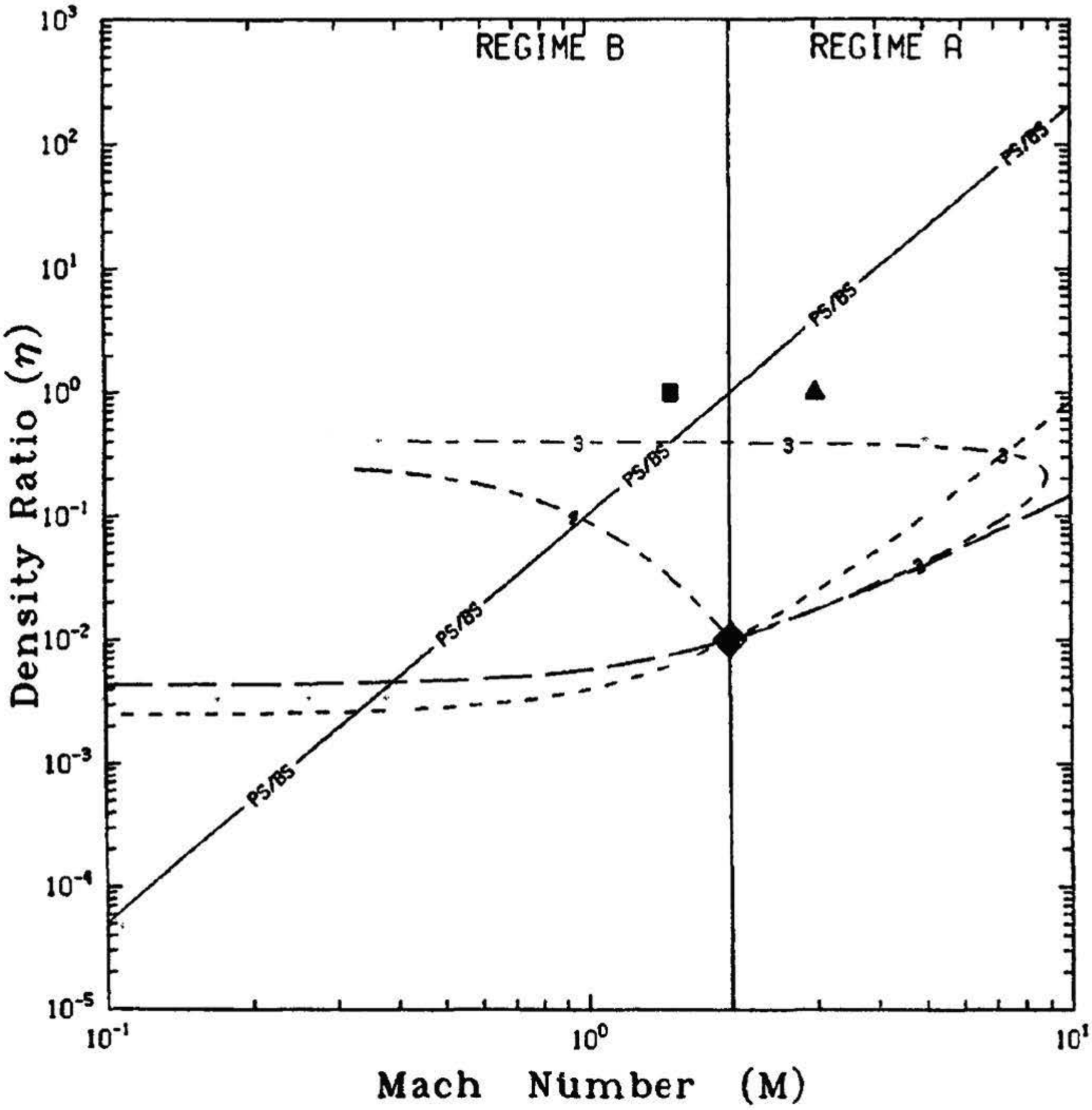


Figure 4. Jet paths for gravitationally bound jets. The potential is chosen to be a linear function of radius. Jet path 3 is initially on the isothermal jet path in figure 1 and jet 4 is initially on the same path as jet path 2 in figure 1. Both jet paths cross into the planar shock regime.

matter) potential.

We find that the type of atmosphere has a profound effect on the ability of a jet to propagate supersonically throughout its entire length. Within certain constraints (17), a cooling inflow type atmosphere can cause a supersonic pressure confined jet to be unstable to becoming subsonic. Wind atmospheres, however, allow a supersonic jet to propagate along its entire length supersonically, as long as the jet is not gravitationally bound to its host galaxy. More realistic calculations of galaxy atmospheres, using observational data, are underway (SS). Full scale numerical simulations with Norman and Winkler are planned later this year.

Discussion

Based on the analysis above, we expect a correlation between jet morphology, the atmosphere type, and, in a special sense, galaxy type. Isolated elliptical galaxies are most likely to have wind atmospheres and should have lengthy supersonic jets. Examples of this type of galaxy/jet might be NGC 315 or NGC 6251 both with long collminated jets and fairly isolated - both are outlying members of Zwicky clusters. NGC 6251 has a jet length of order 200 kpc and a large string of knots. If these knots are shocks induced by pinch instabilities, they only slightly disturb the jet flow, as might oblique shocks (See discussion in NSW and SNW)

Galaxies with known cooling inflows are all dominant galaxies at the kinematical center of their cluster or group. As an example, we speculate that the M87 jet may be showing the biconical shock to planar shock transition (See figure 1 in Biretta et al 1984 (BOH)). Prior to knot A the jet is well collminated and has four knots (D, E, F, I from the nucleus outward). At knot A the jet shocks very strongly. This shock looks like a planar shock in high resolution VLA radio maps (BOH). The post shock flow is much wider than the preshock flow and also has the distorted structure of a subsonic flow. This post shock structure is often called a plume to differentiate it from the preshock jet. In our model knot A represents the disrupting planar shock and the up stream knots represents oblique shocks with the transition after or at knot I. We regard M87's jet morphology as a prototype of "short jets" in dominant cluster members. Other examples include 4C26.42 and 3C84 (NGC 1275).

The basic M87 type morphology (Jet-hotspot-plume) is repeated in many dominant cluster galaxies as noted by Blandford and Smarr (1982). The cD galaxy in Abell cluster 1795 (van Breugel et al 1984) has a radio source, 4C26.42, with inner hotspots at ~ 1 kpc and plume structures in an inversion symmetric configuration. Wide Angle Tail radio sources (WAT) which have been associated with dominant cluster galaxies (Owen and Rudnick 1976) also have the jet-hotspot-plume morphology but on sometimes much larger scales - 4C47.51 has hotspots at ~ 100 kpc. Most of the discussion on WAT sources (e.g. Eilek et al 1984 and references therein) focus on why the subsonic plumes bend at large distances. Our model sheds no new light on this problem.

Finally, as Valentijn and Bijleveld (1983) have pointed out, most (80%) of dominant cluster galaxies with radio jets are unresolved close doubles. As Blandford and Smarr (1982) speculate, these may be examples of the same planar shock phenomena which has been resolved in the "short jets" and the WAT radio sources. We urge attention be given to obtaining high resolution VLA maps of

these sources to see if the basic morphology predicted by our model occurs here.

Summary

We have discussed possible atmospheres a jet might encounter as it emerges from an elliptical galaxy. Wind type atmospheres tend to keep a jet in its initial shock regime. Cooling inflow atmospheres (which may only be possible in galaxies at the center of a cluster of galaxies) will tend to drive a jet toward the planar shock regime and degrading it into a subsonic flow. This type of jet instability may make it possible to understand the observed association between short jet - hotspot - plume sources, in particular WAT radio sources, and dominant central galaxies. More definitive answers will require better observations of elliptical galaxy atmospheres and numerical simulations to verify our simplified model.

Acknowledgements

We wish to thank M. L Norman and K.-H. Winkler for allowing us to reproduce their simulations of jets, and for encouragment and conversations on this project. In addition, we gratefully acknowledge R. D. Blandford and J. F Hawley for clarifying remarks. We also would like to thank F. N. Owen, J. O. Burns, J. A. Eilek and T. Cornwell for interesting conversations on the problems with various radio sources. The National Science Foundation (grants PHY 80 - 01496 and PHY 83 - 08826) and the Alfred P. Sloan Foundation provided partial support for this work. Both of us thank Prof. Dr. R. Kippenhahn for his generous support in allowing us to have an extended visit at the Max Planck Institut fuer Physik und Astrophysik, Institut fuer Astrophysik, where much of the preliminary work on this project was done.

References

Begelman, M. C., Rees, M. J., and Blandford, R. D. (1979) Nature, 279, 770.
Biretta, J. A., Owen, F. N., Hardee, P. E. (1983) Astrophys. J., 274, L27.
Blandford, R. D., and Smarr, L. L. (1982) University of Illinois Astronomy Department Preprint # IAP 82-39.
Canizares, C. R., Clark, G. W., Markert, T. H., Berg, C. , Smedira, M., Bardas, D., Schnopper, H., and Kalata, K. (1979) Astrophys. J., 234, L33.
Cohn, H. (1983) Astrophys. J., 269, 500.
Eilek, J. A., Burns, J. O., O'Dea, C. P. O., and Owen, F. N., (1984) Astrophys. J., 278, 37.
Fabian, A. C., and Nulsen, P. E. J. (1977) Monthly Notices R. Astr. Soc., 180, 479.
Hardee, P. E., (1982) Astrophys. J., 257, 509.
Jones, T. W., and Owen, F. N. (1979) Astrophys. J., 234, 818.
MacDonald, J., and Bailey, M. E. (1981) Monthly Notices R. Astr. Soc., 180, 995.
Mathews, W. G., and Baker, J. C. (1971) Astrophys. J., 170, 241.
Norman, M. L., Smarr, L. L., and Winkler, K.-H. A. (1984) Max Planck Institut fuer Physik und Astrophysik Preprint MPA 115.
Owen, F. N., and Rudnick, L. (1976) Astrophys. J., 205, L1.
Sanders, R. H. (1983) Astrophys. J., 266, 73.
Smarr, L. L., Norman, M. L., and Winkler, K.-H. A. (1984) Physica D. - Proceeding of the Conference on Fronts, Interfaces, and Patterns, Los

Alamos. In press.
Sumi, D. M., and Smarr, L. L. (1984) in preparation.
Tonry, J. L., and Davis, M. (1981) Astrophys. J.,246, 666.
Valentijn, E. A., and Bijleveld, W. (1983) Astron. and Astrophys., 125, 223.
van Breugel, W., Heckman, T., Miley, G. (1984) Astrophys. J., 276, 79.
White, R. E. III, and Chevalier, R. A. (1983) Astrophys. J., 275, 69.