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THE RECONFINEMENT OF JETS

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ABSTRACT

The jets in several extragalactic radio sources appear to open with a more or less constant angle out to some critical distance from the nucleus, and then broaden much less rapidly or even become more narrow. This "reconfinement shoulder" seems to be a fairly typical property of jets observed with sufficiently high resolution to map the structure transverse to the jet axis. This may be due to the fact that the internal pressure in a free jet decreases very rapidly with distance from the nucleus, and therefore the jet would be expected to come into pressure equilibrium with an ambient medium. But the flow in free jets must be highly supersonic; thus, the process of reconfinement is certain to be accompanied by shocks. In the present paper, the structure of inviscid steady state jets in the presence of a realistic ambient medium is calculated by means of the method of characteristics. It is shown that reconfinement is accompanied by conical shocks which heat the jet causing it to reexpand as free jet. The typical jet shape can be reproduced by this process. If particle acceleration results from internal shocks, multiple "attempts" at reconfinement could produce symmetric knots in a two-sided jet symmetrically placed with respect to the ambient medium.

Subject headings: galaxies: structure — hydrodynamics — particle acceleration — shock waves

I. INTRODUCTION: CONFINED AND FREE JETS

It is now generally accepted that the radio emitting lobes of extragalactic radio sources are more or less continuously supplied with energy by jets of plasma from the nucleus of the parent object (Blandford and Rees 1974). The high degree of collimation observed in radio continuum jets (Readhead, Cohen, and Blandford 1978) or implied by compact "hot spots" in the lobes of extended sources (Hargrave and Ryle 1974) requires that the jet be either hydrostatically confined by an external medium (Blandford and Rees 1974), self-pinched by its magnetic field (Benford 1979; Chan and Henriksen 1980; Bridle, Chan, and Henriksen 1981), or free and highly supersonic. In the present discussion, I will only consider nonrelativistic and nonmagnetized jets, i.e., hydrostatically confined or ballistic free jets.

Hydrostatic confinement simply means that the gas pressure inside the jet balanced by the pressure of a surrounding ambient medium;

$$p_j = p \,. \tag{1}$$

Therefore the transverse shape of the jet $r(z)$ (jet radius as a function of distance along the jet) is determined entirely by the pressure gradient in the external medium. From the equation of continuity and the Bernoulli equation (Courant and Friedrichs 1948) one may show that in the highly supersonic region

$$\frac{r}{r_*} = \left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/4} \left(\frac{p_*}{p}\right)^{1/(2\gamma)} , \tag{2}$$

where r_* and p_* are the jet radius and ambient pressure at the sonic point and γ is the ratio of specific heats. It may also be shown from the Bernoulli equation that the Mach number will increase along the jet as

$$M = \left(\frac{\gamma + 1}{\gamma - 1}\right)^{1/2} \left(\frac{p_*}{p}\right)^{(\gamma - 1)/2\gamma} . \tag{3}$$

All jets in radio sources must in some sense be initially confined because of high collimation. But it is also true that a confined jet can break free if the pressure gradient in the external medium is sufficiently steep. A rough condition for jet breakout may be stated thus: if in a frame of reference moving with the jet stream velocity, the walls of the jet are falling away faster than the sound speed, the jet will break free in a rarefaction front. Mathematically this condition may be expressed

$$M > (\tan \theta_0)^{-1} , \tag{4}$$

where M is the jet flow Mach number and θ_0 is the jet opening angle ($\tan \theta_0 = dr/dz$). Combined with equations (2) and (3) above, this condition becomes

$$-\frac{d \ln p}{dz} > 2\gamma \left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/4} \left(\frac{p}{p_*}\right)^{1/2} r_*^{-1} . \tag{5}$$

From this relationship it is possible to show that if the pressure distribution in the ambient medium is exponential or gaussian, breakout will always occur a few scale heights above the sonic point. Moreover, if the pressure distribution is a power law, $p \sim z^{-\alpha}$, breakout will occur for $\alpha > 2$.

Recent VLBI results strongly suggest that initial collimation of jets in radio sources occurs on a very

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small scale (Readhead and Pearson 1982); indeed, there are theoretical reasons to believe that collimation must occur on the scale of the central energy source (Rees 1982). But as we see above, for a reasonable ambient pressure gradient in the nuclear region, the jet will break out and become a free, supersonic ballistic jet. It is certainly unlikely that the jet is continuously in pressure confinement from the nuclear region all the way out to the intergalactic medium.

The observational signature of a free jet is a constant opening angle; roughly

$$\theta_0 \sim \frac{1}{M_0}, \tag{6}$$

where M_0 is the Mach number at breakout. But in fact, no radio jet observed at the VLA with sufficient resolution to resolve the jet in the transverse direction has a constant opening angle (Bridle 1982*b*). Indeed, there seems to be a rather characteristic jet shape, $r(z)$, as exemplified by the radio jets NGC 315 and NGC 6251 (Bridle 1982*a*). The jets do not seem to be free along their entire length; there is a constant opening angle of 10°–20° in the inner 10–20 kpc, but at greater distances from the nucleus there is a "reconfinement shoulder," a considerable distance interval along the jet over which the jet does not get wider at all and may even become more collimated. This reconfinement region is approximately 70 kpc $< z <$ 100 kpc for NGC 315.

Such reconfinement is not entirely unexpected on theoretical grounds, because in a free supersonic jet, the pressure decreases very rapidly along the jet, i.e.,

$$\frac{p_j}{p_b} \approx \left(\frac{z}{z_b}\right)^{-2\gamma} \approx \left(\frac{z}{z_b}\right)^{-2.67} \quad (\gamma = \tfrac{4}{3}), \tag{7}$$

where p_b is the jet pressure at the point of breakout, z_b. An extended gaseous halo around a radio galaxy (as in M87) or an intracluster medium would probably have a less steep pressure gradient. X-ray observations of galactic halos or cluster media imply $p \propto z^{-1.5}$ for an isothermal medium (Fabricant, Lecar, and Gorenstein 1980; White and Silk 1980). Therefore, at some critical distance from the parent galaxy, the internal pressure of a free jet will fall below the pressure of an external medium; i.e., the jet will in some sense become reconfined. Since the Mach number of a free jet increases with distance from the source, i.e.,

$$\frac{M}{M_0} \approx \left(\frac{z}{z_b}\right)^{\gamma-1} \approx \left(\frac{z}{z_b}\right)^{1/3} \quad (\gamma = \tfrac{4}{3}), \tag{8}$$

the free jet, at the point of pressure equilibrium with the external medium, will be highly supersonic; therefore, the process of reconfinement is likely to be accompanied by internal shocks.

The purpose of the present paper is to present the results of axisymmetric hydrodynamical calculations which may be relevant to this process of reconfinement. The problem is approached by the method of characteristics (Courant and Friedrichs 1948). It is assumed that the jet is purely hydrodynamical (no magnetic field), adiabatic, inviscid, and steady state; thus, any possibly devastating effects of radiation losses, boundary irregularities induced by shear, turbulence, and time variable flow in the jet are completely ignored. Even given these simplifying assumptions, it is shown that hydrodynamic reconfinement can account for some generally observed aspects of the structure of jets.

II. THE PROBLEM OF RECONFINEMENT

The behavior of supersonic jets in the presence of an external medium is a long and well studied subject. Prandtl (1907) showed that a supersonic jet which exits into a chamber containing a medium with a pressure slightly lower than the jet pressure ($p_a < p_j$) exhibits periodic variations of width until destroyed by the turbulent boundary layer. The wavelength of these variations is roughly

$$\lambda_P \sim Mr, \tag{9}$$

where M is the Mach number and r is the radius of the jet. This, obviously, is just the distance along the jet axis over which a sound wave propagates from the boundary to the axis. A situation which is actually more relevant to the reconfinement of radio jets is that of a diverging jet which exits into a chamber containing a medium at a much lower pressure as in molecular beam machines (see Bier and Hagena 1963). In this case a conical shock develops near the boundary of the jet, propagates in toward the axis and is reflected back to the boundary, either in a Mach reflection (at a Mach shock disk) or in an approximately conical reflection. The resulting jet structure cannot be strictly periodic because of increase of entropy in the shocks.

Reconfinement of an extragalactic jet would certainly involve the development of such internal shocks. In the NGC 315 jet, reconfinement begins to occur at about 20 kpc from the nucleus where the jet radius is about 4 kpc (i.e., the observed opening angle of the jet decreases beyond this point). Since the original opening angle of the jet is in the order of 13° (Willis *et al.* 1981), the Mach number must be at least 4 (eq. [6]). Therefore, the Prandtl wavelength is $\lambda_P \sim 20$ kpc. This is the distance along the jet over which the jet can respond laterally to pressure changes at the boundary. If the jet had originally broken free at $z \sim 5$ kpc and the jet pressure becomes comparable to the ambient pressure at $z \sim 20$ kpc, then, from equation (3), after another 20 kpc (the Prandtl wavelength) the ambient pressure will exceed the jet pressure by more than a factor of 5. Therefore, on a time scale which is short compared to the lateral response time of the jet, the jet is struck by a very large pressure jump, and shocks must develop. If the ambient pressure were constant, we might expect the jet structure to be quasi-periodic, but the ambient pressure most likely decreases outward along the jet as well. Therefore, the problem is to determine the steady state structure of the jet in a medium with a realistic pressure gradient.

Mathematically the problem may be formulated as follows: Given that u and v are the velocities in the z

and r direction, respectively, and C_S is the sound speed, the steady state equation of motion is

$$\frac{\partial u}{\partial z}\left(1-\frac{u^2}{C_S{}^2}\right)-\frac{uv}{C_S{}^2}\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial z}\right)+\frac{\partial v}{\partial r}\left(1-\frac{v^2}{C_S{}^2}\right)+\frac{v}{r}=0\,, \quad (10)$$

and the equation of irrotational flow is

$$\frac{\partial v}{\partial z}-\frac{\partial u}{\partial r}=0\,. \quad (11)$$

In equation (10) the mass continuity equation has been applied to eliminate the gas density (Courant and Friedrichs 1948). The method of characteristics essentially consists of transforming the above two equations into a curvilinear coordinate system consisting of characteristic or Mach curves. This results in four first-order differential equations for the dependent (u, v) and independent (r, z) variables:

$$\frac{dr}{dz}=\tan\left(\theta \pm \mu\right)\,, \quad (12)$$

$$\frac{dw}{dz}\mp w\tan\mu\frac{d\theta}{dz}-w\frac{\sin\theta\sin\mu\tan\mu}{\cos\left(\theta\pm\mu\right)}=0\,, \quad (13)$$

where w is the fluid speed

$$w=\left(u^2+v^2\right)^{1/2}\,; \quad (14)$$

θ is the direction of the flow; μ is the Mach angle,

$$\mu=\arcsin\left(\frac{1}{M}\right)\,. \quad (15)$$

The Mach number may be determined from the flow velocity by the Bernoulli equation, i.e.,

$$\frac{1}{M^2}=\frac{\gamma-1}{2}\left(\frac{w_m{}^2}{w^2}-1\right)\,, \quad (16)$$

where w_m is the maximum possible flow speed for a given stagnation pressure p_0 and density ρ_0,

$$w_m{}^2=\frac{2\gamma}{\gamma-1}\frac{p_0}{\rho_0}\,. \quad (17)$$

The practical advantage of this technique is that the form of the characteristic equations (eqs. [12] and [13]) is quite simple. Two partial differential equations (eqs. [10] and [11]) are transformed into four ordinary differential equations (eqs. [12] and [13]) involving a derivative by only one independent variable (z). These equations may be easily integrated numerically by the method of successive approximations: differencing equations (12) and (13), one may determine the unknown flow parameters at a point P_3 connected by characteristic lines to points P_1 and P_2 where the flow parameters are known (Carafoli 1956). By repeating this procedure a characteristic grid or network is constructed as shown in Figure 1. A complication is that shocks do occur in this problem; therefore, the postshock characteristic

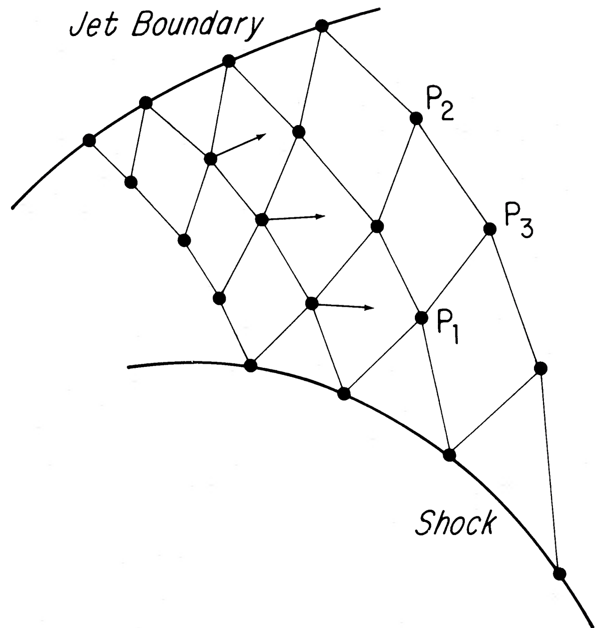

FIG. 1.—A schematic diagram of the characteristic network behind the shock from the boundary to the axis. Given known fluid parameters at points P_1 and P_2, the fluid parameters at points P_3 connected by characteristic lines to P_1 and P_2 may be determined by differencing the characteristic equations. This figure is schematic and only indicates the form of the grid. In the actual calculations, 30 points define a Mach curve between the boundary and the shock.

network must be matched to the jump conditions across the oblique shocks. These jump conditions are:

$$\frac{p_2}{p_1}=\frac{2\gamma}{\gamma+1}M_1{}^2\sin^2\phi-\frac{\gamma-1}{\gamma+1} \quad (18)$$

and

$$\cot\chi=\tan\phi\left[\frac{(\gamma+1)M_1{}^2}{2(M_1{}^2\sin^2\phi-1)}-1\right]\,, \quad (19)$$

where M_1 is the preshock Mach number; ϕ is the angle of the shock with the preshock flow; p_1 and p_2 are preshock and postshock pressures; and χ is deviation of the flow direction at the shock (Courant and Friedrichs 1948). The pressure at any point is also determined from the Bernoulli equation, i.e.,

$$\frac{p}{p_0{}'}=\left[1-\left(\frac{\gamma-1}{2}\right)M^2\right]^{-\gamma/(\gamma-1)}\,, \quad (20)$$

where $p_0{}'$ is a reduced stagnation pressure due to increased entropy across shocks—i.e.,

$$\frac{p_0}{p_0{}'}=\left[\left(\frac{2\gamma}{\gamma-1}\right)M_1{}^2\sin^2-\frac{\gamma-1}{\gamma+1}\right]^{1/(\gamma-1)}\times\left[\left(\frac{\gamma-1}{\gamma+1}\right)\frac{M_1{}^2\sin^2+2}{M_1{}^2\sin^2}\right]^{\gamma/(\gamma-1)} \quad (21)$$

(Carafoli 1956).

This points out a flaw with the method of characteristics as applied to this problem. Since the conical shocks may be curved in the meridional plane then p_0' and the specific entropy will vary from streamline to streamline; that is to say, the postshock flow is not strictly irrotational, or, in other words, equation (11) is not precisely true in the postshock regions. I will return to this point after considering the results of specific calculations.

The primary advantage of the steady state method-of-characteristics calculation as applied to this particular problem is that the jet structure may be determined over regions where the internal and ambient pressure vary by orders of magnitude. It is not clear that sophisticated time-dependent calculations (e.g., Norman *et al.* 1982) can be easily applied in such a situation, although such calculations are vital to an understanding of the detailed structure of a jet in the presence of an ambient medium with comparable pressure.

It should be stressed that the conditions of this calculation (such as steady state flow and a dynamically unimportant magnetic field) are probably not fully satisfied in real sources. Indeed, there are objects such as 4C 32.69 (Potash and Wardle 1980) which do not seem to possess an ambient medium of sufficiently high pressure to confine the jet—which suggests that magnetic self-pinching may be important, at least in some cases. Nontheless, we see below that this simple steady state hydrodynamical model can account for the characteristic lateral expansion profile in the well-resolved sources.

III. RESULTS OF CALCULATION

It is assumed that the jet is initially free and highly supersonic with a constant opening angle (eq. [6]). It is further assumed that the jet exists in the presence of an extended ambient medium which I take to be an isothermal gas in hydrostatic equilibrium in a spherically symmetric Hubble law potential. That is to say, the total mass density distribution giving rise to the potential is of the form

$$\frac{\rho_t}{\rho_{t_0}} = \left(1 + \frac{R^2}{R_c^2}\right)^{-3/2} , \tag{22}$$

where

$$R^2 = r^2 + z^2 , \tag{23}$$

and R_c is the core radius. If the total mass and potential energy of the system are not to diverge, the above density distribution must be truncated at some maximum radius R_m. The gravitational potential resulting from such a density distribution is given by

$$\Phi - \Phi_0 = \frac{-1.7a_0^2 R_m}{R_c}\left\{\frac{R_c}{z}\ln\left[\frac{z}{R_c} + \left(\frac{z^2}{R_c^2} + 1\right)^{1/2}\right] - 1\right\} \tag{24}$$

as a function of z, the distance along the jet. Here a_0 is the virial velocity of the Hubble law sphere:

$$a_0^2 = 2.67\frac{GM}{R_m} . \tag{25}$$

(the numerical constants in eqs. [24] and [25] depend upon the ratio R_m/R_c which in this case is taken to be 50). The density distribution of the isothermal ambient medium with thermal velocity a is

$$\frac{\rho_g}{\rho_{g_0}} = \exp\left(\frac{\Phi - \Phi_0}{a^2}\right) , \tag{26}$$

where ρ_{g_0} is the central gas density, and the pressure is

$$p_a = \tfrac{2}{3}\rho_g a^2 . \tag{27}$$

It is assumed that $a = a_0$; i.e., the thermal velocity dispersion of the gas is equal to the virial velocity. This gives a density distribution of hot gas which is consistent with the X-ray intensity profiles of clusters and galactic gaseous halos (White and Silk 1980; Fabricant, Lecar, and Gorenstein 1980). In particular, the pressure gradient is not too steep; $p \propto z^{-1.4}$ outside of the core.

The problem as formulated involves only three dimensionless free parameters: z_0/R_c, the point at which the jet breaks free in terms of the core radius; $(p_j/p_a)_0$, the initial jet pressure in terms of the ambient pressure at $z_0(>1$ for the free jet); θ_0, the initial opening angle of the free jet. The initial Mach number is $M_0 \approx \theta_0^{-1}$ (eq. [6]). The ratio of specific heats in the jet, γ, is 4/3 in these calculations; which is to say, the pressure of relativistic particles is assumed to dominate. Specifying ρ_{g_0}, R_c (or z_0) and a_0 determines the physical scale of the problem.

Integration of the characteristic equations (eqs. [12] and [13]) is started at the point in the boundary where the free jet pressure has fallen to the pressure of the ambient medium (z_e). At larger z boundary pressure is set equal to the pressure of the ambient medium with the boundary Mach number and flow speed thus determined by the Bernoulli equation (eqs. [20] and [16]). The direction of the boundary flow (θ) then follows from differencing the characteristic equation. At some point ($z > z_e$) characteristic curves from the boundary will cross because the boundary curves inward (see Courant and Friedrichs 1948, p. 390). This defines the initial position of the shock which runs from the boundary to the axis (the incident shock). A characteristic network is constructed behind the incident shock as in the schematic Figure 1, with each characteristic curve defined by 30 points (this is the numerical resolution of the calculation). Shock reflection occurs where the incident shock intersects the axis, and the parameters of the reflected shock near the reflection point are given by the usual conditions for regular oblique shock reflection (Courant and Friedrichs 1948). There is a second characteristic network which describes flow conditions behind the reflected shock. Thus we see that there are three separate domains for the flow;

Region I is the free jet flow upstream of the incident shock where the fluid parameters are only a function of z and given by equations (7) and (8); region II is between the two shocks and is described by a characteristic network between the boundary and the shocks as in Figure 1; region III is the flow behind the reflected shock and is described by a characteristic network between the axis and the reflected shock. These three separate regions are indicated in Figure 2.

Determination of the jet structure out to the point where the reflected shock reaches the jet boundary required about 10 seconds of computing time on an IBM 4341; therefore, a wide domain of the parameter space could be explored. The only model discussed here, however, is that which gives transverse jet profile similar to that observed for NGC 315.

The free parameters in this case are:

$$z_0/R_c = 0.075 ,$$

$$(p_0/p_a)_0 = 66 ,$$

and

$$\theta_0 = 0.24\ (13.5°) .$$

The initial Mach number is $\theta_0^{-1} = 4.3$. The solution for the boundary and the shock positions in the meridional plane as well as two streamlines are shown in Figure 2. It should be noted that the radial scale in this figure is expanded by more than a factor of 10 over the z scale; the jet is actually very long and thin. In physical units $R_c = 35$ kpc and $z_0 = 2.625$ kpc.

In Figure 3, the pressure of the ambient medium and the pressure inside the jet (along streamline A) are shown as functions of distance along the jet. It is seen that the free jet pressure falls very rapidly as a function of z, and at $z = 13.2$ kpc, the internal jet pressure becomes equal to the pressure of the external medium. At this point the flow is highly supersonic with $M = 8$. The pressure along streamline A continues to drop (according to eq. [7]), because fluid elements along streamline A are not affected by the higher boundary pressure until they cross the incident shock at about $z = 40$ kpc. At this point $M_1 = 10$, and the pressure jump at the shock is a factor of 3.3. That is to say, even though the shock makes a small angle with the flow ($\sim 8°$), the shock is still quite strong because of the highly supersonic flow.

From Figure 2 it is seen that the flow behind the incident shock is generally radially inward, and by $z = 50$ kpc the transverse expansion of the jet boundary is stopped; at larger z the jet becomes thinner. Shock reflection occurs at $z = 76$ kpc, and by $z = 122$ kpc the reflected shock has reached the jet boundary. Even before the streamline A crosses the reflected shock, the pressure along streamline A exceeds the pressure of the ambient medium (Fig. 3); therefore, reexpansion must occur. At the point where the reflected shock reaches the boundary, the postshock boundary pressure exceeds the ambient pressure by more than a factor of 3. Thus, the jet will reexpand as a free jet, although by $z = 152$ kpc, the jet boundary pressure has once more fallen below the ambient pressure, and the process of reconfinement begins again.

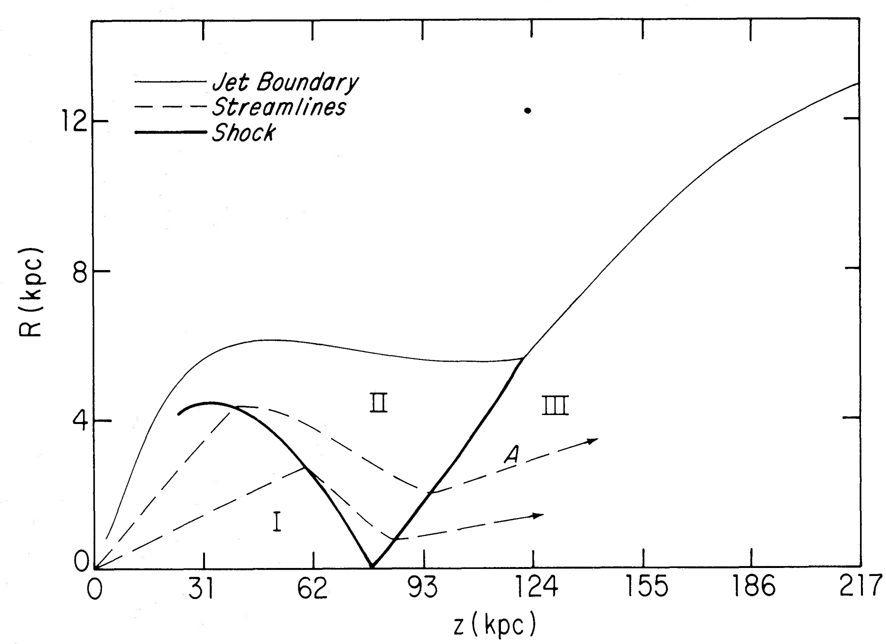

FIG. 2.—A steady state, inviscid jet in the presence of an ambient medium with a pressure distribution which is consistent with observed X-ray intensity profiles of galactic halos. Shown are the jet boundary (*thin solid line*), the conical shocks (*thick solid line*), and two stream lines (*dashed lines*) in a meridional plane; i.e., the structure is symmetric about the z-axis. The scale of the radial axis has been expanded by a factor of 10 over the z-axis. The free parameters of the model are given in the text. The three separate flow domains discussed in the text are indicated.

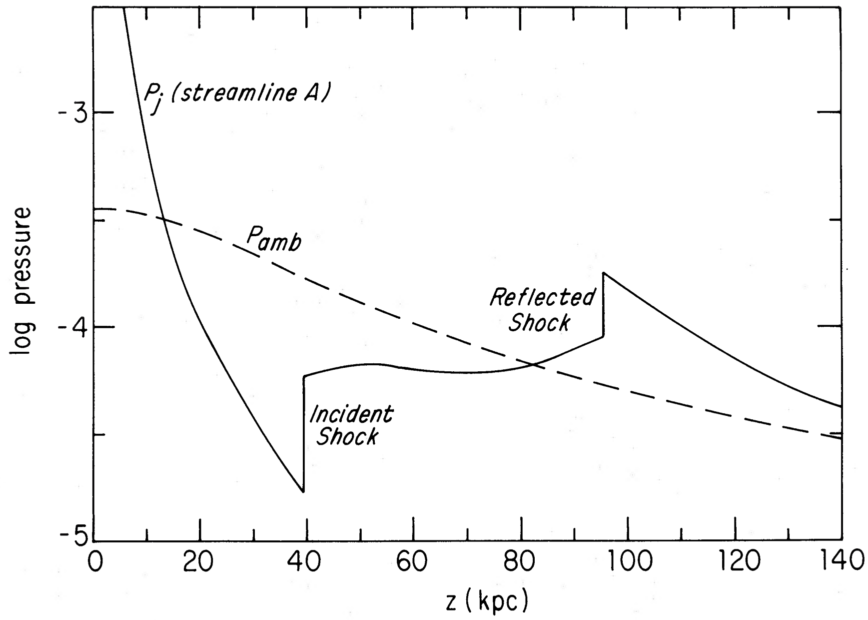

FIG. 3.—The pressure in the ambient medium (*dashed line*) and on streamline A (*solid line*) as a function of distance along the jet shown in Fig. 1. It is seen that the internal pressure of a free jet falls very rapidly with respect to that of a realistic ambient medium, but that the conical shocks reheat the jet sufficiently that it reexpands as a free jet. The units of pressure are arbitrary, but for the particular scaling discussed in the text would be 7.8×10^{-10} dyn cm^{-2}.

The structure would be more periodic if the pressure of the ambient medium were constant, as we see in Figure 4 which shows the same jet, but in constant density medium. This illustrates that the form of the transverse jet profile seen in Figure 2 is directly due to the relatively mild pressure gradient in the external medium.

As mentioned above, a problem with respect to the validity of these calculations is the fact that the postshock flow is not strictly irrotational. But it is true that entropy is constant along streamlines (between the shocks), and, as we see from Figure 2, the streamlines are essentially parallel to the symmetry axis. This means that the gradient of entropy lies primarily in the radial direction. Moreover, the same is true of the pressure gradient. Near the point of shock reflection,

$$\frac{\partial p_j}{\partial r} = 20 \frac{\partial p_j}{\partial z} .$$

Therefore, to a high order of accuracy it is the case that

$$\nabla \boldsymbol{P} \times \nabla \boldsymbol{S} = 0 ,$$

and this is a sufficient condition for irrotational flow. It is difficult to access the error resulting from the small deviation from irrotational flow, but a significant error might be indicated by nonconservation of the mass flux in the jet. In this calculation the mass flux

$$Q = 2\pi \int_0^r u\rho(r) r dr$$

is conserved to better than 5%, out to the point of conical shock reflection.

In Figure 5, the calculated jet boundary is compared to the observed transverse expansion profile of the brighter jet in NGC 315 (Willis *et al.* 1981). It is seen that this hydrodynamic reconfinement accompanied by internal shocks is consistent with this observed characteristic signature of jet structure. The physical value of core radius in this model is 35 kpc. Therefore, the potential in which the ambient medium sits is more representative of a dark, extended halo (as in M87) or a cluster or group potential. However, it is assumed in this model that the jet originally breaks free at $z_0 = 2.6$ kpc. Presumably, within 2.6 kpc of the nucleus there exists a higher pressure medium which confines the jet. This

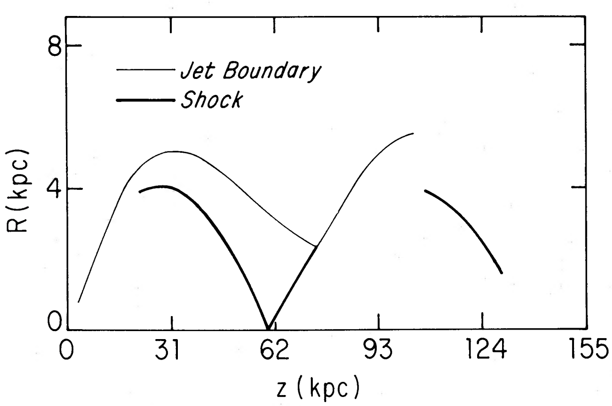

FIG. 4.—A steady state inviscid jet in the presence of an ambient medium with a uniform pressure; i.e., the only difference between this case and the jet shown in Fig. 1 is that the ambient medium pressure is constant. The jet structure is not strictly periodic because of irreversible entropy increase in the shocks.

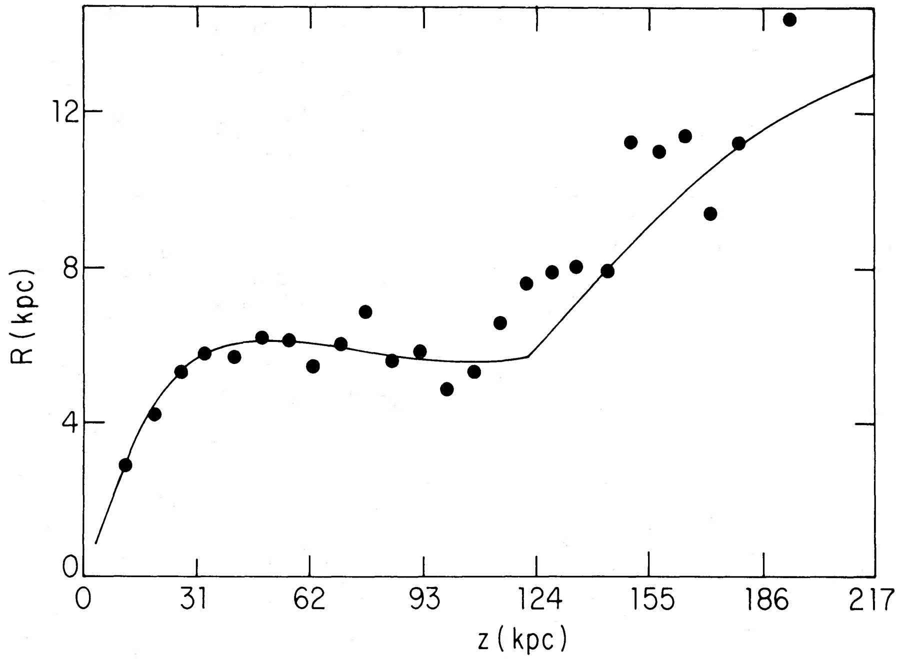

FIG. 5.—The jet boundary shown in Fig. 1 compared to the observed jet in NGC 315 (Willis *et al.* 1981). The solid points show the half-width at half-maxima of the 20 cm transverse intensity profiles of the brighter jet in NGC 315.

could be halo gas trapped in the deeper potential well of the visible galaxy.

Similar forms for the lateral expansion profile are derived from the self-similar MHD calculations of Chan and Henriksen (1980). In their calculations the reconfinement shoulder is also associated with the effect of an extended ambient medium, although magnetic self-pinching may also play a role. The essential difference between their work and the present calculation is that their assumption of transverse incompressibility does not permit the development of conical shocks, and such shocks will occur when the pressure imbalance between the jet and the ambient medium changes by a large factor over a Prandtl wavelength.

Smith and Norman (1981) have noted that a pressure confined jet is subject to transverse deformation by a global "centrifugal" instability whenever the ambient pressure gradient is not too steep. (i.e., $d \ln P/d \ln Z > -8/3$ as in this case). Again, one might expect this sort of instability to disrupt the jet on a length scale of several Prandtl wavelengths, or on a scale greater than the extent of the reconfinement shoulder in the present case.

In the context of this model, physical properties of the ambient medium can be estimated if we consider plausible limits on the jet velocity and mass flux. The power of the radio source is provided by the flux of kinetic energy in the jet, i.e.,

$$L_R = \epsilon \pi r_0^2 \rho_{j_0} v_{j_0}^3 , \tag{28}$$

where ϵ is the efficiency if transforming the energy in bulk motion to the energy in relativistic particles and magnetic fields. Since the flow is highly supersonic, the velocity in the jet v_{j_0} is essentially constant. The total mass supply rate for the jet is

$$\dot{m} = \pi r^2 \rho_{0_j} v_j . \tag{29}$$

Furthermore, given that

$$\rho_{j_0} v_j^2 = \gamma p_{j_0} M_0^2 \tag{30}$$

and

$$p_{a_0} = \tfrac{2}{3} \rho_{a_0} a_0^2 \tag{31}$$

for a hot ionized gas, we find, with some algebra, that

$$v_j = \tfrac{3}{2} L_R (\epsilon \pi \gamma z_0^2 \rho_0 a_0^2 f)^{-1} \tag{32}$$

and

$$\dot{m} = 4 \frac{\epsilon \pi^2}{9} \gamma^2 z_0^4 \rho_0^2 a_0^4 f^2 L_R^{-1} , \tag{33}$$

where $f = (p_j/p_a)_0$. For the model parameters of the NGC 315 jet discussed above and with $L_R = 3 \times 10^{41}$ ergs s^{-1}, equations (32) and (33) become

$$v_j = 1.3 \times 10^9 \left(\frac{0.01}{\epsilon}\right) \left(\frac{10^{-4}\ \mathrm{cm}^{-3}}{n_0}\right) \times \left(\frac{500\ \mathrm{km\ s}^{-1}}{a_0}\right)^2 \mathrm{km\ s}^{-1}$$

and

$$\dot{m} = 0.13 \left(\frac{\epsilon}{0.01}\right) \left(\frac{n_e}{10^{-4}}\ \mathrm{cm}^{-3}\right)^2 \left[\frac{a_0}{500}\ \mathrm{km\ s}^{-1}\right]^4 \mathrm{M}_\odot\ \mathrm{yr}^{-1}$$

where n_0 is the central particle density. We see that a physically reasonable jet flow velocity

$$a_0 < v_j < C$$

and a mass supply rate which is not too high,

$$\dot{m} < 1 M_\odot \text{ yr}^{-1}$$

are consistent with reconfinement of the jet by an ambient medium with a very low central density ($n_0 \sim 10^{-4}$ cm^{-3}). Indeed, if the central density were much higher ($\sim 10^{-3}$), the implied mass loss rate would become disturbingly large. The point is that a very low density, hot ambient medium, which would not be visible to present X-ray detectors, would affect the low-power jet in NGC 315 in the manner shown in Figure 5.

IV. DISCUSSION

A free jet in the presence of an extended ambient medium is likely to come into pressure equilibrium with the ambient medium due to the very rapid decrease of internal jet pressure with distance along the jet. Moreover, since the flow in free jets must be highly supersonic, the process of reconfinement will be accompanied by internal shocks—a conical shock from the boundary to the symmetry axis and a reflected conical shock from the axis back to the boundary. These shocks reheat the jet (increase the pressure, lower the Mach number) causing the jet to laterally reexpand as a free jet until at some greater distance, the jet pressure again becomes comparable to the ambient pressure. This process is not quasi-periodic if there is a mild pressure gradient in the external medium; i.e., the jet width generally becomes greater with increasing distance from the galactic nucleus, but not monotonically. Highly idealized (inviscid, steady state) gas dynamical calculations demonstrate that this process of reconfinement can account for the characteristic transverse jet profile exemplified by the radio jet in NGC 315. In the specific numerical model for the NGC 315 jet the ambient medium has a pressure distribution which is consistent with the X-ray intensity profiles of clusters of galaxies and hot galactic halos. In particular the density and pressure gradient is not too steep, with $p \sim z^{-1.36}$. For the low-power jet of NGC 315, an extremely tenuous ambient medium can cause the observed jet structure; the central particle density of the ambient medium need only be 10^{-4} cm^{-3} if the thermal velocity dispersion is taken to be 500 km s^{-1} ($T = 10^7$ K). In objects where both radio jets and extended X-ray halos are observed, it should be possible to determine whether or not the observed jet structure is consistent with the ambient pressure distribution implied by the X-ray intensity profile.

It should be emphasized that the internal shocks formed in this process of reconfinement are due to the overall dynamics of a free jet in an ambient medium. The shocks do not result from boundary irregularities generated by the Kelvin-Helmholtz instability as in the calculation of Norman *et al.* (1982). Indeed, an important implicit assumption in the present work is that boundary irregularities or entrainment of ambient material do not obliterate these global effects, and the only evidence supporting this assumption is the ability of this idealized model to reproduce the characteristic transverse jet profile (Fig. 4).

It is also evident that these internal shocks may be important not only in determining the overall structure of a jet but also for particle acceleration inside jets (Norman *et al.* 1982; Blandford and Ostriker 1978. It should be noted that in the above calculation the shocks are strongest near the point of reflection, therefore, we might expect associated particle acceleration to occur primarily in the very core of the jet and not near the boundaries. This would be consistent with the observation of no limb brightening in radio jets. Such particle acceleration might be particularly important in cases where the initial shock from the boundary makes such a large angle with the flow that regular shock reflection is not possible. Shock reflection would then occur at a Mach shock disk; i.e., a plane shock surface over some region perpendicular to the axis of the jet. The flow behind the Mach disk would be initially subsonic, but the contact discontinuity between the subsonic and supersonic flow would have the shape of a de Laval nozzle; that is, the flow along the axis would eventually again become supersonic. The important point is that this process of Mach shock reflection would create a region of high shear near the core of the jet—at the interface between the subsonic and supersonic regions, possibly resulting in turbulence and particle acceleration. Since jet reconfinement can occur several times (i.e., the rapidly falling free jet pressure keeps dropping below the ambient pressure) and since each reconfinement episode is accompanied by internal shocks, then this is a natural mechanism for producing bright knots in jets, as has been noted by Norman *et al.* (1982). But the significant aspect of shocks resulting from the global dynamics of the jet and not from surface irregularities, is that such knots would have a symmetric structure with respect to the radio galaxy if the galaxy were symmetrically placed with respect to the external ambient medium. Such detailed symmetry of knots is indeed observed in some objects (Ekers 1982).

The jets that we observe, the radiating jets, may, in general, be those jets with internal shocks which result either from the global effects discussed here (reconfinement), from boundary irregularities, or from the bending of highly supersonic beams by winds or pressure gradients. The jets that we do not observe (as in Cygnus A) may have contrived to avoid internal shocks, perhaps by being totally free or totally confined along their length.

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