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Abstract

A theory of double radio sources which have a 'Z' or 'S' morphology is proposed, based on the refraction of radio jets in the extended atmosphere of an elliptical galaxy. The model describes a collimated jet of supersonic material bending self-consistently under the influence of external static pressure gradients. Gravity and magnetic fields are neglected in the simplest case except insofar as they determine the static pressure distribution. The calculation is a straightforward extension of the method used by Begelman, Rees, and Blandford (1979) to calculate a ram-pressure model for twin radio trails ('C' morphology). It may also be described as a continuous-jet version of the buoyancy model proposed by Gull and Northover (1973).

The model should be particularly relevant to S-shaped radio sources identified with isolated galaxies (such as 3C293), whose radio structures should be free of distortions resulting from motion relative to a cluster medium. One might expect it also to apply to 'internal' (dominated by the galaxy rather than the environment) small-scale S-shaped sources such as the inner jet structure of Fornax A. Finally, giant cD galaxies near the center of clusters which display 'C'-shaped morphologies may also fit this description (e.g., 1919 + 479).

The model has the added virtue of invoking a galactic atmosphere similar to those already indicated (1) by x-ray measurements of some other radio galaxies (Fabricant et al., 1978) and (2) by models for the collimation of other radio jets (Chan and Henriksen, 1980; Bridle, Chan, and Henriksen, 1981).

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I. Introduction

The beamed delivery of energy and particles to the lobes of radio sources associated with elliptical galaxies and quasars was first proposed in detail by Rees (1971) and subsequently elaborated by Blandford and Rees (1974) and recently by Wiita (1978). The first radio jets were observed by Hazard et al. (1963) in the quasar 3C273 and by Graham (1970) in the elliptical galaxy M87. Subsequent discoveries, most recently and with great clarity at the very large array (VLA) (e.g., Perley et al., 1979; Bridle et al., 1979; Potash and Wardle, 1980), have shown that radio jets are quite common in extragalactic radio sources and have led to the predominance of this continuous-beam model for energy transport in such systems.

'Straight' jets are thought to be responsible for the undistorted classical double (I-shaped) radio morphology, and these can be explained in terms of the basic nozzle mechanism (Blandford and Rees, 1974) and subsequent refinements [Wiita, 1978; Chan and Henriksen, 1980 (henceforth CH); Bridle, Chan, and Henriksen, 1981 (henceforth BCH)]. In sources where there are pronounced deviations from an overall I-shaped morphology, the proposed beams have been treated as 'ballistic,' and attempts have been made to account for the shapes of the observed radio jets in terms of the acceleration of a jet-carrying galaxy during a gravitational encounter with a near neighbor (e.g., Blandford and Icke, 1978). 'Trailing' jets are proposed to explain the head-tail (C-shaped) radio morphology. These may be understood as supersonic beams of material that are bent by the ram pressure of an intracluster gas as a result of the peculiar motion of the active galaxy (e.g., Begelman et al., 1979; Jones and Owen, 1980; Vallée, Bridle, and Wilson, 1981).

The 'S'- and 'Z'-shaped radio morphologies cannot readily be explained by such models, however, particularly when they are associated with isolated and presumably unaccelerated galaxies. Some of these sources have been cited as evidence for precession of the jet 'nozzle' when a galaxy is in a group of galaxies (Bridle et al., 1976; Ekers et al., 1978). We show here that for isolated galaxies they may be understood simply in terms of 'refracted' jets. Throughout this paper, we use the term "jet" to refer to the observed radio phenomenon and the term "beam" for the postulated directed flow.

In our model, the beams are refracted in the gaseous atmosphere (halo) of the elliptical galaxy, which we assume to be either spheroidal (§IIIA) or slablike (§IIIB). The argument would apply also to small-scale refraction in nuclear atmospheres. Two oppositely directed beams are supposed to be launched centrally at some nonzero angle to the minor axis of the pressure distribution. These beams then encounter pressure gradients which act to bend them parallel to the minor axis of the pressure distribution. This yields the 'S' or 'Z' morphologies very naturally. The necessary galactic atmosphere $(n \sim 10^{-2}$ to 10^{-4} cm^{-3}, $T >$ 10^7 K) has already been detected around M87 (Fabricant et al., 1978), Cygnus A, and Centaurus A (Fabbiano et al., 1979), and comparable atmospheres have been deduced from recent simulations of the confinement of radio jets (Bridle et al., 1980; BCH).

II. Theory

A. Generalities

We suppose a generally spheroidal centrally symmetric static galactic atmosphere to be associated with an active elliptical galaxy.

We further suppose that a 'narrow' beam (i.e., whose cross section subtends a small solid angle at the galactic center) emerges from a nozzle located at (ω_s, Z_s), as sketched in Figure 1a. The beam is for simplicity taken to have a circular cross section, to be coplanar with the minor axis of the background, and to bend only in its initial poloidal plane. Generally, it will bend in the plane containing the beam axis and ∇p (where p is the background pressure) and, for a narrow beam in the meridian plane of a spheroidal atmosphere, this should be the poloidal plane.

The buoyancy force per unit length of the beam is given by

$$\frac{dF_{\sim b}}{d\ell} = -\int_{X-\text{section}} \nabla p \; dA \tag{1}$$

so that its component toward the instantaneous center of curvature (see Figure 1a) is

$$z_{\sim} \cdot \frac{dF_{\sim b}}{d\ell} \equiv -\int_{X-\text{section}} \left(\hat{z}_{\sim} \cdot \nabla p\right) \; dx dz \approx -\left(\hat{z}_{\sim} \cdot \nabla p\right)_{\text{jet axis}} A \quad . \tag{2}$$

The unit vector $\hat{z}_{\sim}$ is given from Figure 1a as $(-\sin \phi, \cos \phi)$ and, moreover, $\tan \phi = dZ/d\bar{\omega} \equiv Z'$ so that, in the $(\bar{\omega}, Z)$ system,

$$\hat{z}_{\sim} = \left(1 + (Z')^2\right)^{-1/2} (-Z', 1) \quad . \tag{3}$$

The buoyancy force is thus determined when $\nabla p(\bar{\omega}, Z)$ is prescribed.

If $-\nabla \phi$ is the local gravitational acceleration produced by the background, then the beam has a weight per unit length obtained from

$$\frac{d\underset{\sim}{F}_W}{d\ell} = -\int_{X\text{-section}} \rho_j \underset{\sim}{\nabla}\Phi \ dA$$

and

$$\hat{\underset{\sim}{z}} \cdot \frac{d\underset{\sim}{F}_W}{d\ell} = -\int_{X\text{-section}} \rho_j (\hat{\underset{\sim}{z}} \cdot \underset{\sim}{\nabla}\Phi) \ dA \simeq -\rho_j (\hat{\underset{\sim}{z}} \cdot \underset{\sim}{\nabla}\Phi)_{\text{jet axis}} A \ .$$

In a static equilibrium background, $\underset{\sim}{\nabla}p = -\rho\underset{\sim}{\nabla}\Phi$ so

$$\hat{\underset{\sim}{z}} \cdot \frac{d\underset{\sim}{F}_W}{d\ell} = + \left(\frac{\rho_j}{\rho}\right) (\hat{\underset{\sim}{z}} \cdot \underset{\sim}{\nabla}p)_{\text{jet axis}} A \ . \tag{4}$$

Here, ρ_j, ρ are the beam and background mass densities, respectively. Consequently, (2) and (4) combine to yield the net force toward the center of curvature as

$$\hat{\underset{\sim}{z}} \cdot \frac{d\underset{\sim}{F}}{d\ell} = -(\hat{\underset{\sim}{z}} \cdot \underset{\sim}{\nabla}p)_{\text{jet axis}} A(1 - \rho_j/\rho) \ . \tag{5}$$

This force, being perpendicular to the beam axis, will produce a plane curvature of the axis with a radius of curvature r given by

$$r \equiv \left(1 + (z')^2\right)^{+3/2} \Big/ z'' \tag{6}$$

such that

$$\rho_j A V_j^2 / r = \hat{\underset{\sim}{z}} \cdot d\underset{\sim}{F}/d\ell \ , \tag{7}$$

where V_j is the local beam velocity. We may use mass conservation (continuity) and conservation of energy in the forms

$$R^2 \rho_j V_j = R_s^2 \rho_{js} V_{js} \tag{8}$$

and

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$$\frac{v_j^2}{2} + \frac{\gamma}{(\gamma - 1)} \frac{p}{\rho_j} = E \quad , \tag{9}$$

where R is the cross-sectional radius of the beam. Also, we will use pressure continuity across the beam boundary and an internal polytropic equation of state yielding

$$(\rho_j/\rho_{js}) = (p/p_s)^{1/\gamma} \tag{10}$$

to fully determine ρ_j, V_j, and R in terms of the prescribed p. We note that

$$d\ell^2 = d\omega^2 \left(1 + (z')^2\right) \quad . \tag{11}$$

Finally, in this section, we write equation (7) explicitly [using Eqs. (3), (5), and (7)] as

$$\left.\begin{array}{c} \rho_j v_j^2 \dfrac{z''}{1 + (z')^2} = - \left(1 - \dfrac{\rho_j}{\rho}\right)\left\{\dfrac{\partial p}{\partial z} - z' \dfrac{\partial p}{\partial \omega}\right\} \\[3ex] \rho_j/\rho_{js} = (p/p_s)^{1/\gamma} \end{array}\right\} \quad . \tag{12}$$

B.   Specialized Application

In the supersonic region of a beam that has been accelerated by a nozzle mechanism (e.g., CH, BCH), the dominant term on the left of equation (9) will be $v_j^2/2$. Consequently, we may replace equation (9) with V_j = constant, leaving only (7) and (10) to be solved together and (8) to yield subsequently $R(\ell)$. [This ignores entrainment which, at worse (constant surrounding density), would require $V_j \propto \ell^{-1}$ and $R \propto \ell$ in place of (9) and (8).]

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An analytical solution of equation (12) can be made in the slab approximation for the atmosphere as follows. When $\partial p / \partial \bar{\omega} = 0$ (slab approximation), we have [noting that $\sec^2 \phi = 1 + (z')^2$]

$$v_j^2 \frac{d}{dz} \ln \sec \phi = - \left(\frac{1}{\rho_j} - \frac{1}{\rho} \right) \frac{dp}{dz}$$

or, with equation (10) and assuming $\rho/\rho_s = (p/p_s)^{1/\Gamma}$, the first integral

$$\frac{\rho_{js} v_j^2}{p_s} \ln \left(\frac{\sec \phi}{\sec \phi_s} \right) = \left(\frac{\gamma}{\gamma - 1} \right) \left(1 - p^{(\gamma-1)/\gamma} \right) - \left(\frac{\Gamma}{\Gamma - 1} \right) \frac{\rho_{js}}{\rho_s} \left(1 - p^{(\Gamma-1)/\Gamma} \right) ,$$

(13)

where p is measured in units of p_s. We will suppose subsequently that the second term (the weight of the beam) is negligible compared to the first term so that the beam will always float 'up' from the central plane rather than falling 'down'. The other extreme would tend to produce a sinuous equatorial beam that is unlikely to be visible as a radio jet because of its low internal energy density. Hence, for a beam of light fluid,

$$\sec \phi = \sec \phi_s \exp \left\{ \left(\frac{\gamma}{\gamma - 1} \right) \left(\frac{p_s}{\rho_{js} v_j^2} \right) \left(1 - p^{(\gamma-1)/\gamma} \right) \right\} , \qquad (14)$$

and

$$\sec \phi = \sec \phi_s \exp \left\{ - \frac{p_s}{\rho_{js} v_j^2} \ln p \right\} \qquad \text{when } \gamma = 1 .$$

Asymptotically, then, as $p \rightarrow 0$ and for $\gamma \neq 1$,

$$\sec \phi \rightarrow \sec \phi_s \, \exp\left\{\left(\frac{\gamma}{\gamma-1}\right) \frac{p_s}{\rho_{js} v_j^2}\right\} \, , \qquad (15)$$

so that the argument of the exponential must be at least of O(1) to produce a substantial deflection. It is noteworthy that the existence of a nozzle at $P(\varpi_s, z_s)$ also requires $p_s/(\rho_{js} v_j^2)$ to be O(1). Thus, the ability to collimate the beam by external pressure and the ability to refract the beam result from the same environmental conditions.

III. Working Equations for Specific Forms of the Pressure

A. Spheroidal Distribution

We prescribe a spheroidal galactic atmosphere whose pressure has the form

$$\left. \begin{array}{c} p = \dfrac{p_s\left(1 - \sigma_s^\alpha\right)}{\left(1 + (p_s/p_{ig})\left(\sigma^\alpha - \sigma_s^\alpha\right) - \sigma^\alpha\right)} \\[20pt] \sigma \equiv \dfrac{z^2}{a_3^2} + \dfrac{\varpi^2}{a_2^2} \end{array} \right\} \, , \qquad (16)$$

where p_{ig}, p_s, α, a_3, and a_2 are the parameters of the distribution. We see that $p = p_{ig}$ at $\sigma = 1$ and $p = p_s$ at $\sigma = \sigma_s$, where σ_s labels the spheroid on which the beam first emerges. We obtain a planar or slab distribution by letting $a_2 \rightarrow \infty$. Such a distribution is not, in general, an exact solution to the self-gravitating hydrostatic equations unless an appropriate background stellar mass density is assumed. However, it has sufficient parameters to allow reasonable empirical fits over a limited range.

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Equations (12) now yield the one equation to be integrated as

$$z'' = - \frac{2\alpha}{(1 - \sigma_s^\alpha)} \left(\frac{p_s}{\rho_{js} v_j^2} \right) \left(\frac{p_s}{p_{ig}} - 1 \right) \sigma^{(\alpha-1)} (p/p_s)^{(2-1/\gamma)}$$

$$\cdot \left(1 + (z')^2 \right) \left(\frac{\alpha z'}{a_2^2} - \frac{z}{a_3^2} \right) . \tag{17}$$

B. CH Distribution

We consider also the two-component slab model introduced by CH and by BCH in their studies of jet collimation. We hope that this will eventually allow the collimation data and the bending data from the VLA to be combined for a given source, to simultaneously restrict the choice of parameters of the background pressure distribution. Einstein data provide direct constraints on the pressure distribution and should be employed wherever possible in the future.

The pressure law used by CH is

$$p/p_s = \frac{f}{1 + (f - 1)\left(\frac{z}{z_s}\right)^m} + \frac{(1 - z_s/z)(z_e/z_s)^{-m}}{1 + (z/H)^{m'}} \left(\frac{f}{f - 1} \right) , \tag{18}$$

where $f \equiv (\gamma+1/2)^{(\gamma/\gamma-1)}$ and $z > z_s$. The two power laws become equal near z_e, and there is an intermediate region determined by the quantity H. Such a law is also not, in general, a solution of the self-gravitating equilibrium equations unless there is an appropriate stellar distribution. In this case, equation (12) yields

$$Z'' = -\left(1 + (Z')^2\right)\left(\frac{P_s}{\rho_{js}V_j^2}\right)(p/p_s)^{-1/\gamma}\frac{d}{dz}(p/p_s) \qquad (19)$$

which has, of course, the first integral (14).

In both equations (17) and (19), we repeat that we have neglected the weight of the beam fluid.

C. Numerical Integration

We have numerically integrated equations (17) and (19) below, taking the beam to lie in the (Z,Y) plane so that $\omega \equiv Y$ in the formulae. Figure 1b shows the coordinates we have used to effect a projection onto the plane of the sky. The required formulae are

$$\begin{array}{l} Y_p = -Y \cos \phi \\[2ex] Z_p = -Y \sin \phi \cos \theta + Z \sin \theta \end{array} \Bigg\} \qquad . \qquad (20)$$

These give the coordinates Y_p, Z_p of the emission in the observer's sky plane (see Fig. 1b) in terms of the angle between the minor axis of the pressure distribution and the line of sight, θ, and $\pi/2 - \phi$, the angle between the planes through the minor axis containing, respectively, the radio jet and the line of sight (Fig. 1b).

IV. Application to 3C293

We discuss this source in particular because it is a _relatively isolated_ galaxy that has a jetlike large-scale radio structure originating at a nonzero angle to the principal optical axes of its parent galaxy but which becomes S-shaped by bending towards the minor axis of the galactic stellar distribution.

The peculiar $m_v = 14.3$ (Sandage, 1973) E6 galaxy VV5-33-12 identified with 3C293 lies within the boundaries drawn in the Zwicky Catalogue (Zwicky and Herzog, 1963) for two clusters--the "very distant" (0.15 < z < 0.2) cluster 1350.0 + 3148 and the "near" (z < 0.05) cluster 1352.0 + 3107. The redshift of VV5-33-12 (z = 0.0452) is sufficiently smaller than that of 1350.0 + 3148 that it is unlikely that the galaxy and the cluster are spatially related. Burns and Owen (1977) list 3C293 as a possible outlying member of 1352.0 + 3107. The separation of the galaxy from the center of the cluster is about 50 arc min (3.6 Mpc for $H_0 = 50$ km s^{-1} Mpc^{-1}), however, and the ratio of this separation to the cluster radius makes it unlikely that the galaxy is a cluster member, according to the statistics presented by Burns and Owen. Furthermore, Stocke (1979) notes that the source is in a region of exceptionally low galaxy density, which also suggests that it is not, in fact, a member of 1352.0 + 3107.

An INT plate of the galaxy shown by Argue, Riley, and Pooley (1978) indicates that it has complex internal structure; Wyndham (1966) suggests that there may be a dust lane oriented towards the northeast. Sandage (1966) classified the system as a possible Sb, but this is now unlikely in view of the large-scale radio structure revealed by the recent VLA observations (Bridle and Fomalont, 1981; this paper, Fig. 2).

A spherical diffuse image $\sim 3^m$ fainter than VV5-33-12 lies ~ 30" west and 15" south of the galactic nucleus (Argue et al., 1978). It is not clear whether this is a faint companion to VV5-33-12, a bright knot within VV5-33-12, or a background object. Apart from the ambiguity associated with the nature of this object, VV5-33-12 appears to be a

well-isolated and unusually flattened radio galaxy to which our model should therefore be particularly applicable.

Bridle and Fomalont (1981) obtained sensitive maps of 3C293 with the VLA at 1.47 and 15.1 GHz; these maps are reproduced in Figures 2a and 2b. The source contains an inner core with about 80% of the total intensity (Fig. 2b). This core is broadly double with a largest angular scale of ~3 arc sec and is clearly oriented in PA ~90°, i.e., ~60° from the minor axis of the galactic light which is in PA 151° ± 2° (Argue et al., 1978). The 1.47 GHz map shows a weak elongated large-scale bridge structure extending in both directions from the galaxy in PA ~125°, which is much closer to the optical minor axis. On both sides of the galaxy, this structure terminates in lobes whose major axes lie along PA ~30°. The overall radio structure therefore has an 'S'-shaped morphology whose overall linear size is about 290 kpc (about 4 arc min at $H_0 = 50$ km/sec^{-1}/Mpc^{-1}).

Table 1 gives the parameters of theoretical refracted jets which fit the observed large-scale bridge-lobe structure, allowing for uncertainties in the interpretation of the locus of its observed ridge line. We have not fitted each side separately, but rather our model parameters have been deduced from a fit to the mean of the NW and SE ridge lines. The fits are not shown therefore on Figure 2, but they lie roughly between the NW and SE ridge lines when, say, the latter is rotated through 180°. It should be noted that the position angle of the outer pressure term used to fit the radio structure is that of the minor axis of the outer stellar distribution of the optical galaxy. The end directions of the jet will approach the direction of the projected minor axis of the galaxy as $p_s/\rho_{js}v_j^2 \gg 1$, according to equation (15). Referring to

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Figure 1b and to equations (20), we see that only observers at $\phi = 0°$ and $\theta = 90°$ would avoid such projection effects. In this case, $\phi = 223°$. In fact, there are so many parameters (including the projection angles) and not all of them independent, that we regard these fits as illustrative rather than unique. In this preliminary account, we have made no attempt to define systematically the parameter space volume that is admissible. However, it appears that the projection angles cannot vary by more than ~10° and the relatively flat portion of the pressure distribution should not differ in scale by more than a factor of 2.

Equations (8) and (10) show that $R \propto p^{1/2\gamma} \propto p^{-3/8}$ for the models shown. Thus, we indeed expect the beam radius R to vary rapidly only when p does, which, in the distributions chosen above, is near a_3 and $(1/2)H_e$. Inspection of Figure 2a shows that the jet widths are indeed roughly constant outside the radio core until a projected distance of ~1' (75 kpc) from the galaxy, where they bend, broaden, and decay in intensity. Inverting equations (20) gives this deprojected scale as ~130 kpc, in rough agreement with the pressure scales used to fit the beam curvature (Table 1).

We have seen in Section II that at least initially the refracting pressure required is comparable to the confining pressure. The minimum confining pressures required for the radio components in 3C293 can be estimated from the usual equipartition calculations (Bridle et al., 1981). About 14 arc sec (17 kpc) from the core, the equipartition field strength is ~2 × 10^{-5} gauss and the minimum value of nT is ~10^5 K cm^{-3}. Near the middle of the Northwestern jet (or bridge) 45 arc sec (54 kpc) from the core, values of 1 × 10^{-5} gauss and 3 × 10^4 K cm^{-3} are obtained. The x-ray detectability of media with these minimum pressures

will depend strongly on the temperature; for temperatures of 10^7 K, the densities required would be comparable to those detected in a number of nearby radio galaxies (Fabricant et al., 1978; Fabbiano et al., 1979). It is then possible that x-ray observations of 3C293 will show whether there is indeed a galactic atmosphere with the appropriate parameters associated with the galaxy.

We have not attempted to fit the inner core-bridge misalignment of 3C293 with either of equations (17) or (19) because of the gap in scales between the 1.4 and 15 GHz VLA maps (Fig. 2). However, Bridle et al. (1981) have applied this model to the inner structure using additional data from the Jodrell Bank MERLIN network and find a fit with plausible parameters.

We will only give an order of magnitude argument here [as it might also be used for Fornax A (see below)]. Taking 'S' here to refer to a hypothetical nozzle near the center of the galaxy, equation (15) with $\phi_s = 0°$ and $\phi = 35°$ (the core-bridge misalignment) gives on setting $\gamma = 4/3$ that $\rho_{js} v_j^2 \approx 20 p_s$. The core equipartition pressure estimate (Bridle et al., 1981) gives $p_s \sim 10^{-8}$ dynes (nT $\sim 7 \times 10^7$ Kcm^{-3}) so that $\rho_{js} v_j^2 \sim 2 \times 10^{-7}$ dynes, whence $n_s \sim 10 v_{j8}^{-2}$ (and $T \sim 7 \times 10^6$ v_{j8}^2 K). However, taking $L_{core} \sim R_s^2 \rho_{js} v_j^3 \simeq 20 p_s v_j R_s^2$ gives $L_{core} \sim 2 \times 10^{42}$ $v_{j8} R_{100}^2$ ergs/s (R_{100} is in units of 100 pc). These numbers ($v_{j8} \sim \sqrt{(\gamma+1/\gamma-1)} = \sqrt{7}$, $R_{100} \lesssim 1$, $T \sim 5 \times 10^7$ K) appear very reasonable, are in good agreement with other estimates, and place these objects just in the regime of interest for X-ray detection (see Bridle et al., 1981).

V. Other Possible Examples of Buoyantly Refracted Beams

The inner structure of the radio galaxy 3C76.1 has recently been observed by Vallée (1981) with the VLA, and the results provide weak evidence for S-type morphology on a large scale ($\gtrsim 50$ kpc) when combined with the Westerbork map of Högbom and Carlsson (1974). Should this behavior be confirmed, then this galaxy merits theoretical attention as it is also a remarkably isolated galaxy (84' or 4.5 Mpc ($H_0 = 50$ km/sec/Mpc) from the center of Zwicky cluster 0254.7 + 1606).

A galaxy need not be strictly isolated for our model to apply to S-shaped _interior_ structure (assuming that the galaxy is not tidally disturbed). One such small-scale morphology may be the inner $\sim 45"$ radio structure of the galaxy Fornax A (Fomalont and Geldzahler, 1981). In this source, the innermost radio jet structure has a PA of 100°, but the outer jet appears refracted towards the minor axis of the spheroidal stellar component of the galaxy (NGC 1316) at $150 \pm 2°$, after emerging from a dust lane that passes through the central jet region. This galaxy is not as isolated as 3C293 or 3C76.1, so that its large-scale structure ($\sim 40'$) may well be dominated by environmental interactions. Nevertheless, the 45" structure remains an interesting example of the kind of bending that our model might describe.

A third category of sources which may show buoyancy refraction are the cluster 'C-type' sources. There may, in fact, be two subcases of these. Burns (1981) has studied the wide-angled tail radio source 1919 + 479 (4C47.51) and argued that it is associated with a cD galaxy near the center of a rich cluster. He further notes that the ram pressure interpretation of this source is incompatible with the galaxy's lack of observed peculiar motion and suggests a buoyancy model of the kind which

we have independently developed here in greater detail. We have not yet attempted to fit the shape of this source by integrating equations (17) or (19), but it is clear that a cluster atmosphere must be involved due to the enormous scale of the observed bending. The C-shape requires the cD galaxy to, in fact, not be at the center of the cluster pressure distribution.

A similar suggestion has been made for NGC 1265 by Jones and Owen (1979). However, as this galaxy is not thought to be at rest in the cluster, ram pressure effects can not be excluded. The essential distinction between the approach of Begelman et al. (1979) and that of Jones and Owen is that the latter postulate that a galactic atmosphere is retained (by nonhypersonic galaxies) to transmit the ram-pressure bending to the beam via static pressure gradients. This has the advantage of avoiding the fairly rapid ablation of a beam that might be expected in a direct interaction with an intergalactic wind, and again reduces the internal description to a model of the sort described here.

However, such central pressure gradients that are established in this way are likely to be transient (see, e.g., Lea and De Young, 1976), and one should estimate their spatial and temporal scales. When the Mach number of the galaxy's motion in the cluster medium, $\mathcal{M}$, is $\lesssim 1$, elementary considerations suggest that gas is retained (but for secular ablation in the tail regions) by a spherical galaxy of radius r_o, mass M_o if

$$q \equiv \frac{r_o}{GM_o} c_{ig}^2 \frac{\rho_{ig}}{\rho_s} \mathcal{M}^2 < 1 \quad . \tag{21}$$

Here, ρ_{ig} is the density of the cluster medium, C_{ig} is the sound speed in this medium, and ρ_s is the density in the interstellar medium beneath the contact discontinuity, and we assume throughout that $M(r) = (M_o/r_o) r$ in the stellar component of the galaxy, which also dictates the gravitational potential. In this limit, one obtains also that the shape of the contact discontinuity $r_s(\theta)$ is given (the result is insensitive to the equation of state to this order) by

$$\frac{r_s(\theta)}{r_o} \sim 1 - q \cos^2 \theta \ , \tag{22}$$

where θ is measured from the direction of the galaxy's motion. The time scale of the initial central pressure pulse may be taken roughly as $T_p \sim (r_o - r_s(0))/C_{is}$ or $T_p \sim q(r_o/C_{is})$, where C_{is} is the sound speed in the interstellar medium.

For $M_o \sim 10^{12} M_o$, $r_o \sim 15$ kpc, $C_{ig} \sim 10^8$ cm/sec, $\mathcal{M} = O(1)$, and $\rho_{ig}/\rho_s \lesssim 10^{-1}$, condition (21) is easily satisfied, and $T_p \sim 10^8 q$ years. Thus, our estimates are in essential agreement with those of Jones and Owen, with the caveat that one may require the radio activity to occur very soon after the encounter with the dense cluster medium. We note, moreover, that the quantity q should not be much different from one in either sense.

A beam in such a pressure-pulse event may be modelled by our equations (17) or (19) in the slab limit, and it could be interesting to compare the required bending scales in the central region with the quantity $r_o - r_s(0)$. We defer this to a future investigation.

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VI. Discussion and Conclusions

The bending of a supersonic beam by a static pressure gradient in the extended atmosphere of an elliptical galaxy has been studied theoretically in this paper. The beam is refracted towards the minor axis of the pressure distribution when its internal density is less than the background density. Heavy beams would be recognized by their oscillation about the equatorial plane of the pressure distribution. Although the bending is, in fact, due to the buoyancy of each section of the beam, this beam model should not be confused with the 'buoyancy-driven' beams of Gull and Northover (1973). The beam flows examined here are assumed supersonic, so that gravity may generally be neglected in calculating their speeds. We note that inferred beam speeds have fallen in the range 1000 to 10,000 km/sec [e.g., Perley et al., 1979 (for 3C449)], which is safely supersonic for background temperatures up to 10^8 K.

We have not discussed the influence of a beam magnetic field or the bending, largely because there is, as yet, no definite evidence that the magnetic field is dynamically important (BCH; CH) from fits to collimation data. In a source where the field is dynamically important, the present discussion would have to be expanded to include the magnetic contribution to the beam rigidity (provided here only by $\rho V_j^2/r$).

We see explicitly [Eq. (15)] that, in general, there is a close link between the ability of the pressure distribution to produce a beam (by forming a nozzle) and its ability to bend it. Refraction of low-luminosity beams is therefore likely to be quite common (and therefore also S or Z morphologies) for isolated galaxies. This may not be true for powerful radio jets emanating essentially unchanged from the nucleus of a galaxy since there is no necessary link between the jet pressure

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and that of the galactic atmosphere in such a case. Radio galaxies in denser regions will have their jets distorted by ram pressure into head tails (C-type). Moreover, it is likely that the extended galactic atmospheres will be themselves stripped by ram pressure or by gravitational encounters in dense regions.

Various independent lines of enquiry tend to support the basic hypothesis employed here of an extended gaseous galactic 'atmosphere'. These include the optical observations of Bertola and Perola (1973) and of Kormendy and Bahcall (1974) and the discovery of the x-ray atmospheres alluded to earlier--the collimation studies in CH, BCH, and the normal calculations of equipartition confining pressures. The parameter ranges necessary to fit the observed curvature of 3C293 by buoyant refraction in a similar atmosphere are sufficiently plausible to add weight to the hypothesis.

It seems, moreover, from our minimum energy estimates that the confining atmospheres may, in some cases, be detectable by the Einstein observatory. This would afford a truly independent probe of the parameters of this material and could lead to the confirmation or rejection of our model. Future work, which attempts a detailed comparison of VLA and Einstein parameters, should combine a consistent CH treatment of the radio collimation data with the refraction data. We note, however, that our preliminary parameter estimates (Table 1 and the equipartition arguments for 3C293) are already interesting in that they are very similar to the Einstein picture of the static atmosphere of M87 (Fabricant et al., 1980).

We have used the value 50 km/sec/Mpc in our calculations as a convention, but equations (17) and (19) are scale invariant, so that the

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calculated shapes will not vary with the assumed H_o. The length parameters in Table 3 may then simply be scaled with H_o, while the dimensionless quantities, of course, remain unchanged.

Acknowledgments

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    329, Vol. V, 305.

Table 1

MODEL CHARACTERISTICS FOR 3C293

Characteristics	Model	
γ (c_p/c_v)	spher.	1.33
	CH	1.33
$P_s/\rho v_j^2$	spher.	1.0
	CH	1.0
Y_s, Z_s, $\left.\dfrac{dZ}{dY}\right|_s$	spher.	3 kpc, 2.5 kpc, 0.8
	CH	3 kpc, 2.5 kpc, 0.8
α	spher.	5.0
P_s/P_{ig}	spher.	1.2
a_2/a_3	spher.	2.0
a_3	spher.	120 kpc
m	CH	1.0
m'	CH	1.5
Z_e	CH	6.7 kpc
H_e	CH	250 kpc
ϕ, θ	spher.	223°, 130°
	CH	223°, 130°

Figure Captions

1. (a) Geometry of the plane of curvature of the jet and a sketch of
    the spheroidal background.

    (b) Coordinates used in allowing for projection effects. See text.

2. The radio morphology of 3C293 at (a) 1.4 GHz and (b) 15 GHz
    observed with the Very Large Array [details in Bridle and Fomalont
    (1921)]. The centroid of the galaxy is marked by a cross in (a).

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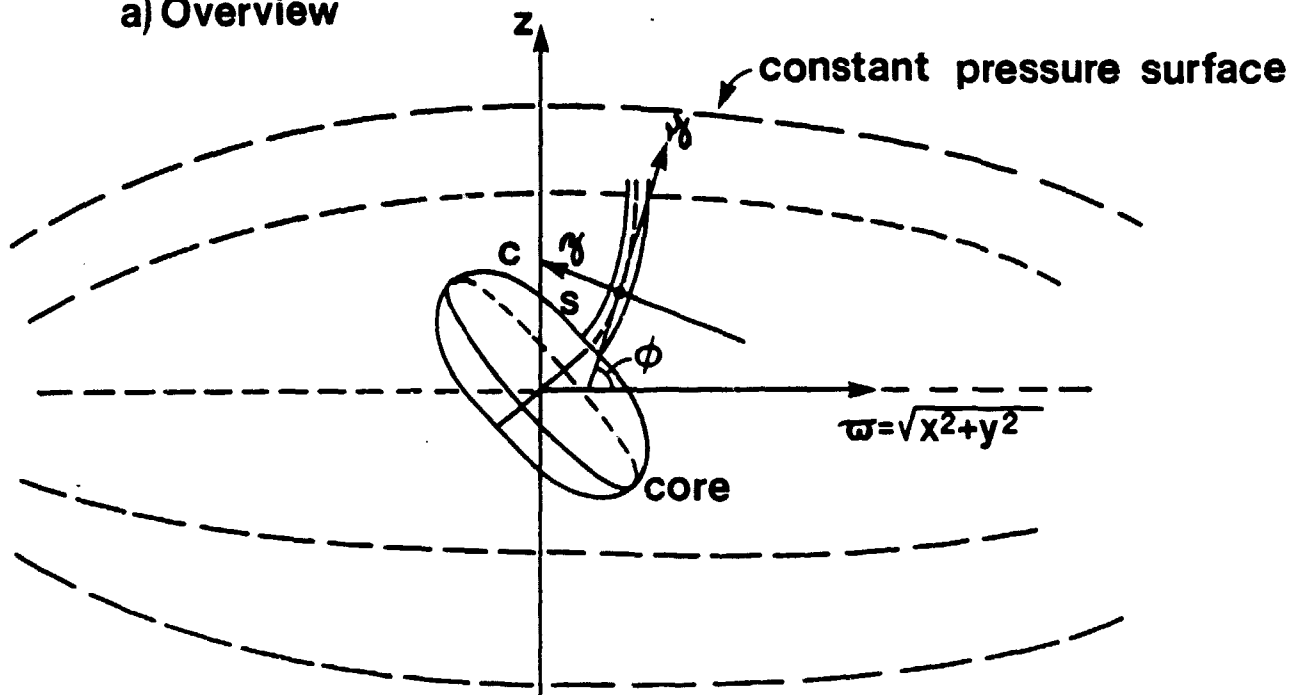CANADA

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a) Overview

constant pressure surface

$\varpi = \sqrt{x^2 + y^2}$

core

b) Coordinates

observer

3C 293   1465 MHz

/3C 293 CORE   15035 MHz