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OVERPRESSURED COCOONS IN EXTRAGALACTIC RADIO SOURCES

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ABSTRACT

We show that the cocoons of shocked gas which surround powerful double radio sources can have significantly higher pressures than the surrounding intergalactic medium. The pressures can be high enough to confine the jets in these sources, obviating the need for magnetic confinement. The cocoon pressure and the age of a radio source may be estimated from observable quantities, as we demonstrate for the radio galaxy Cygnus A. We suggest that overpressured cocoons in high-redshift radio galaxies engulf and compress circumgalactic clouds, driving them over the Jeans limit and triggering star formation. Since overpressured cocoons have a much larger ratio of width to length than is indicated by the widths of observed radio lobes, they can trigger star formation at a much higher rate than can either the direct impact of the jet or entrainment in the radio lobe. We propose that this process leads to the observed alignments of optical continuum emission with radio source axes.

Subject headings: radio sources: extended — radio sources: galaxies — galaxies: jets — galaxies: intergalactic medium — hydrodynamics

I. INTRODUCTION

According to the standard evolutionary scenario for strong double radio sources (Scheuer 1974; Blandford and Rees 1974), jets boring through the intergalactic medium (IGM) are not in direct contact with the undisturbed IGM, but rather are enveloped in a "cocoon" consisting of shocked jet material and shocked IGM (Fig. 1). Scheuer (1974) showed that the cocoon around a pair of supersonic, low-density jets (i.e., low compared to the ambient IGM) acts as a "wastebasket" for most of the energy deposited by the jets, since relatively little of the energy is radiated away or used in lengthening the channels along which the jets flow. The lengthening of the cocoon is governed by the balance between the jet's thrust (the momentum flux) and the ram pressure of the ambient medium, while the width of the cocoon is determined by its internal pressure. The mean pressure inside the cocoon (away from the "hot spots" at the head of each jet) is of order the cumulative energy output of the jets divided by the cocoon's volume. If the cocoon expands at a rate faster than the rate at which the jets deliver energy, the pressure will drop until it reaches equilibrium with the pressure of the IGM.

However, we argue in this *Letter* that the cocoons in many observed sources have not yet had time to reach pressure balance through sideways expansion. These cocoons are overpressured with respect to the IGM, and are widening by driving a shock into the surrounding gas, as Scheuer (1974) suggested. We show how the existence of overpressured cocoons may resolve two outstanding problems in the theory of extragalactic radio sources: the confinement of high-pressure jets, and the alignment between radio and optical continuum structures in high-redshift radio galaxies.

In § II we develop a simple, approximate model to describe the evolution of a cocoon in a uniform density IGM. In § III we apply the model to the prototypical source Cygnus A and discuss the possible role of overpressured cocoons in triggering star formation along the source axes of high-z radio galaxies, which could explain the recently discovered alignments of optical and radio emission (Chambers, Miley, and van Breugel 1987; McCarthy *et al.* 1987).

II. EVOLUTION OF AN OVERPRESSURED COCOON

Consider a pair of jets advancing into a uniform ambient medium of density ρ_a and pressure p_a. As long as the pressure inside the cocoon (p_c) is much larger than p_a, the evolution of the cocoon is independent of p_a. Assume that the ends of the cocoon advance into the IGM with a speed v_h determined by balancing the thrust of the jet, Π_j, against the ram pressure force of the IGM, $\rho_a v_h^2 A_h$, where A_h is the cross sectional area of the bow shock at the end of the cocoon (Fig. 1). In early models of radio sources, A_h was assumed to be comparable to the cross sectional area of the jet itself, in which case v_h could be expressed in terms of v_j and the ratio of the jet density to ρ_a (Begelman, Blandford, and Rees 1984). However, observations of hot spots (Laing 1989) and the bow shock of Cygnus A (Carilli, Perley, and Dreher 1988) support Scheuer's (1982) suggestion that the jet direction fluctuates on a time scale which is short compared to the evolutionary time scale of the cocoon. As a result, the time-averaged momentum flux is spread over a much wider area than the instantaneous cross section of the jet. If the jet speed is supersonic with respect to its internal sound speed, we can express the thrust in terms of the jet power and the jet speed, $\Pi_j \sim L_j/v_j$, with the result that

$$v_h \sim \left(\frac{L_j}{\rho_a v_j^3 A_h}\right)^{1/2} v_j \, . \qquad (1)$$

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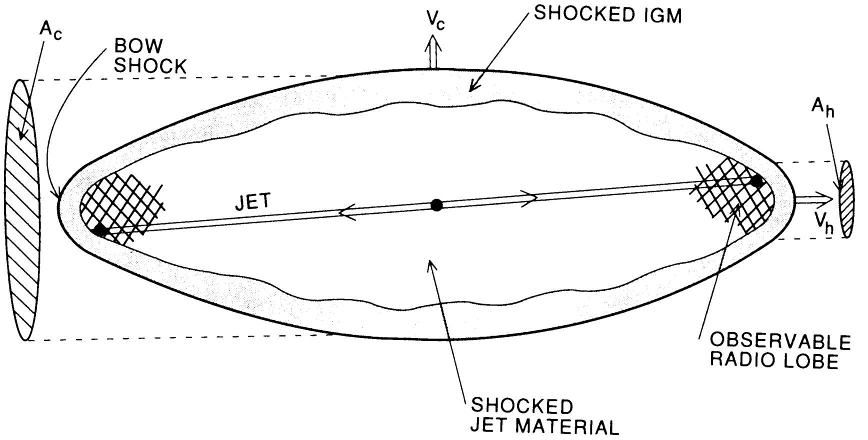

FIG. 1.—Schematic diagram of the overpressured cocoon surrounding a powerful double radio source. The shock bounding the cocoon expands into the IGM with speed v_h along the mean jet axis and $\sim v_c$ in orthogonal dirctions. The observable radio lobes constitute only a small fraction of the cocoon's volume near the ends of the jets, and the mean cross sectional area of the cocoon, A_c, is much larger than the area of the bow shock, A_h. Due to fluctuations in the jet directon, momentum is deposited over a much wider area than the instantaneous jet cross section. For Cygnus A, we estimate $A_h \sim 28$ kpc^2; the total projected length of the cocoon is ~ 120 kpc (for $H_0 = 75$ km s^{-1} Mpc^{-1}). In the multiphase IGM proposed for high-z radio galaxies, clouds could penetrate into the region of shocked jet material and star formation could occur throughout the interior of the cocoon.

The pressure inside the cocoon also drives a shock sideways into the IGM, at a speed v_c which is determined by balancing p_c against $\rho_a v_c^2$. The value of p_c is of order the total energy deposited by the jets over the lifetime of the source, $2\int L_j\,dt$, divided by the volume of the cocoon, V_c. If we denote the mean cross sectional area of the cocoon (transverse to the mean jet axis) by A_c, as illustrated in Figure 1, then $V_c \sim 2A_c \int v_h\,dt$. Note that A_c is generally *much larger* than the cross sectional area of the observed radio lobes, which are indicated on Figure 1 by cross-hatching. Although both L_j and v_h will depend on time, this crude model justifies our approximating $\int L_j\,dt \sim L_j t$, $\int v_h\,dt \sim v_h t$, and $A_c \sim v_c^2 t^2$, where t is the age of the source. These approximations lead to a second equation for v_h:

$$v_h \sim \frac{L_j t^2}{\rho_a A_c^2}\,. \tag{2}$$

Eliminating v_h between equation (1) and equation (2), we obtain a single relation among the remaining parameters, which we express as an equation for t:

$$t \sim \left(\frac{\rho_a}{L_j v_j A_h}\right)^{1/4} A_c\,. \tag{3}$$

Note that the cross sectional area of the cocoon increases roughly linearly with time; therefore its width grows $\propto t^{1/2}$ and its sideways expansion speed v_c decreases $\propto t^{-1/2}$. When v_c reaches the sound speed in the IGM, the cocoon ceases to be overpressured.

Next we extimate p_c. Substituting from equation (3), we have

$$p_c \sim \frac{\rho_a A_c}{t^2} \sim \frac{(L_j \rho_a v_j A_h)^{1/2}}{A_c}\,. \tag{4}$$

Comparing this value of p_c to p_a determines the self-consistency of our assumption that the cocoon is overpressured. Self-consistency also requires that $v_h > v_c$ (equivalently, that the cocoon's length exceed its width), which implies

$$L_j > \rho_a v_j^3 A_h \left(\frac{A_h}{A_c}\right)^2\,. \tag{5}$$

If condition (5) is not satisfied, then the static pressure in the cocoon (p_c) exceeds the time-averaged ram pressure of the jet. The cocoon then assumes a roughly spherical shape, and its radius evolves with time according to the formula for an adiabatic stellar wind bubble, $R \sim (L_j/\rho_a)^{1/5} t^{3/5}$ (Castor, McCray, and Weaver 1975).

III. APPLICATION TO EXTRAGALACTIC RADIO SOURCES

a) Confinement of Radio Jets

Jets detected in classical double radio sources often seem to have minimum pressures which are markedly higher than the maximum plausible pressure in the ambient IGM (Potash and Wardle 1980; Burns *et al.* 1984; Perley, Dreher, and Cowan 1984), making confinement by the thermal pressure of the surrounding gas unlikely. Yet the high degrees of collimation exhibited by these jets suggest that they are subject to some form of lateral confinement. This conclusion has led to the suggestion that magnetic tension is responsible for confining such jets. Here we suggest an alternative method of confining overpressured jets. We conjecture that these jets are in pressure balance with their cocoons, which in turn are overpressured with respect to the IGM.

The strong double radio source Cygnus A (3C 405) is an ideal candidate for testing our model not only because the jet appears to be strongly overpressured with respect to the ambient medium (Perley, Dreher, and Cowan 1984), but also because it is the only object in which the bow shock at the head of the cocoon has been traced observationally (Carilli, Perley, and Dreher 1988). From Figure 1 of Carilli, Perley, and Dreher (1988), we estimate that the radius of curvature of the bow shock is $\sim 3''$, corresponding to a cross sectional area of ~ 28 kpc^2 (for $H_0 = 75$ km s^{-1} Mpc^{-1}, which we assume throughout). We adopt this as the fiducial value of A_h, although it is best regarded as a lower limit. The IGM electron density in the vicinity of the bow shock is estimated from X-ray measurements to be $\sim 6 \times 10^{-3}$ cm^{-3} (Arnaud *et al.* 1984), and we assume $L_{45} \equiv L_j/10^{45}$ ergs s$^{-1} > 1$ and $\beta_j \equiv v_j/c \sim 1$ (Perley, Dreher, and Cowan 1984). Although ρ_a is not uniform but varies with distance from the nucleus $\propto r^{-1}$ (Arnaud *et al.* 1984), our order-of-magnitude analysis still applies if ρ_a is taken

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to be the ambient density near the ends of the cocoon. Since there are no observational estimates of A_c, we express our results in terms of the ratio of l_c to the half-width of the cocoon, $w_c \equiv (A_c/\pi)^{1/2}$. We find

$$p_c \sim 8 \times 10^{-11} L_{45}^{1/2} \beta_j^{1/2} A_{h,28}^{1/2} l_{60}^{-2} \left(\frac{l_c}{w_c}\right)^2 \text{ dyn cm}^{-2} , \quad (6)$$

where $l_{60} \equiv l_c/60$ kpc. Perley, Dreher, and Cowan (1984) estimate that the minimum pressure in the Cygnus A jet lies in the range (4×10^{-10})–(2.5×10^{-9}) dyn cm^{-2}, consistent with our rough estimate if $l_c/w_c \gtrsim 2$–6; narrower cocoons give larger pressures. According to X-ray measurements by Arnaud *et al.* (1987), $p_a \sim 8 \times 10^{-11}$ dyn cm^{-2}; therefore, the cocoon of Cygnus A would be overpressured for all values of $w_c < l_c$. To satisfy condition (5), A_h must not exceed $37 L_{45}^{1/3} \beta_j^{-1} l_{60}^{4/3}$ kpc^2. If A_h is much larger than the fiducial value, then Cygnus A must have a spherical rather than an elongated cocoon.

From equation (3), we estimate the age of Cygnus A to be

$$t \sim 10^8 L_{45}^{-1/4} \beta_j^{-1/4} A_{h,28}^{-1/4} l_{60}^2 \left(\frac{w_c}{l_c}\right)^2 \text{ yr} , \quad (7)$$

in agreement with other estimates that have appeared in the literature (Hargrave and Ryle 1974; Winter *et al.* 1980; Arnaud *et al.* 1984). Note that the minimum total energy in the radio lobes, $\sim 10^{60}$ ergs, places a lower limit on the age of Cygnus A of $3 \times 10^7 L_{45}^{-1}$ yr (assuming that L_j was not drastically higher in the past). We may therefore place a lower limit on the width of the cocoon, $w_c/l_c > 0.5 L_{45}^{-3/8}$, and an upper limit on the pressure, $p_c < 3 \times 10^{-10} L_{45}^{5/4}$ dyn cm^{-2}.

b) High-z Radio Galaxies

McCarthy *et al.* (1987) and Chambers, Miley, and van Breugel (1987) have discovered that the extended optical continuum emission in high-redshift radio galaxies tends to be aligned with the radio source axis. They argue that this emission comes from stars, and suggest that the expansion of the radio source is triggering star formation. Evidence for star formation resulting from the interaction of a radio jet with intergalactic gas has been observed in Centaurus A (Graham and Price 1981) and Minkowski's Object (van Breugel *et al.* 1985; Brodie, Bowyer, and McCarthy 1985). De Young (1981, 1986, 1989) and the above authors have suggested that star formation occurs when material is impacted by the jet and/or is entrained in the jet or in the backflow of the radio lobes. However, the star formation in high-z radio galaxies appears to occur over too large a volume to be explained in this way.

Here we wish to suggest a different mechanism: that star formation is induced by the sudden compression of preexisting intergalactic clouds which are overtaken and enveloped by the overpressured cocoon.

A high degree of inhomogeneity in the IGM surrounding high-z radio galaxies is indicated by Faraday depolarization studies (Pedelty *et al.* 1989) and studies of Lyman-α morphology (Spinrad 1989; McCarthy *et al.* 1989; McCarthy and van Breugel 1989). Suppose that the radio source is expanding into a two-phase medium consisting of cool ($\lesssim 10^4$ K) clouds of density $\rho_{\rm cl}$ and filling factor $f_{\rm cl} \ll 1$ in pressure balance with a hot ($\sim$few $\times 10^7$ K) intercloud medium (of density ρ_a). The sideways expansion of the cocoon is unimpeded by the presence of clouds provided that evaporation of cloud material can be neglected (McKee and Cowie 1975), and the lengthening of the cocoon is also unaffected if $f_{\rm cl} < (\rho_a/\rho_{\rm cl})^{1/2}$. Provided these conditions are met, the cocoon evolves as described in § II, and maintains an elongated shape if condition (5) is satisfied.

When the cocoon shock overruns and engulfs a cloud, the pressure on the cloud's surface jumps from p_a to p_c on a time scale much shorter than the sound crossing time across the cloud. As a result, a shock is driven into the cloud from all sides, with a speed $v_{\rm sh} \sim (p_c/\rho_{\rm cl})^{1/2}$. For the parameters we are considering, the shock will be radiative (Sgro 1975) and the postcompression temperature of the cloud will be $\lesssim$ the initial temperature. The cloud's Jeans mass will therefore decrease by a factor $(p_c/p_a)^{-1/2}$, or more (if the temperature decreases after compression). Clouds which initially have masses somewhat less than the Jeans mass will be driven gravitationally unstable by the compression.

We estimate the cocoon of Cygnus A to be increasing in volume at a rate $\sim 2A_c l_c/t \sim 10^{55} (L_{45}\beta_j)^{1/4}$ cm^3 s^{-1}; adopting this value, we find that cloud mass would be engulfed at a rate

$$\dot{M}_{\rm cl} \sim 10^7 f_{\rm cl} \left(\frac{p_a}{10^{-10} \text{ dyn cm}^{-2}}\right) \left(\frac{T_{\rm cl}}{10^4 \text{ K}}\right)^{-1} M_\odot \text{ yr}^{-1} . \quad (8)$$

Thus, even if the filling factor in clouds is as low as 10^{-3} and the star formation efficiency $\sim$1%, the star formation rate may be as large as $\sim 100\ M_\odot$ yr^{-1}, consistent with observations. Note that the radio hot spots (and perhaps the radio lobes) would track the instantaneous point of impact of the jet, and may not reflect its time-averaged behavior. Thus, if the jet is temporarily intercepted by a cloud in the cocoon's interior, the radio source may appear to be more compact than the elongated star formation region, as seems to be the case in some sources (e.g., 4C 41.17: P. J. McCarthy *et al.*, private communication). We would also expect the hot spot typically to lie closer to the nucleus on the side with a greater concentration of cool gas, in agreement with the results of Pedelty *et al.* (1989). A clumpier circumgalactic medium at high-z would lead to the greater incidence of asymmetric radio and optical structures found by McCarthy and van Breugel (1989).

IV. CONCLUSIONS

We have shown that the cocoons which surround powerful radio galaxies may have internal pressures which are considerably higher than the pressure in the ambient intergalactic medium. We suggest that the ubiquity of overpressured cocoons may help to explain two puzzling phenomena: (1) the high degree of collimation of luminous radio jets, despite their inferred overpressures; and (2) the alignment between radio and optical continuum structures in high-redshift radio galaxies.

Although we were able to apply our model to Cygnus A using observed quantities such as the area of the bow shock and the length of the jets, one crucial parameter—the cross sectional area of the cocoon, A_c—remains unobserved. We predict that the widths of cocoons in powerful radio sources should be much larger than the widths of typical radio lobes. In fact, the ratio of cocoon lengths to their average widths may only be of order $\sim$2–3. We suggest that the combination of large volume and high pressure enables the expanding cocoon to trigger star formation in preexisting circumgalactic clouds, at a rate sufficient to explain observed radio-optical alignments in high-redshift radio galaxies. In our model, the principal difference between high-z and low-z radio galaxies (which do not

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show the radio-optical alignment) lies in the nature of the circumgalactic medium, which is clumpier at high-z. This clumpiness leads to enhanced star formation, Lyα emission, and the increased incidence of asymmetric structure in the aligned radio-optical emission.

Except for the "lobe" regions, it appears that cocoons contribute little to the synchrotron surface brightnesses of powerful radio sources. Their emissivities must be far below the "equipartition" values associated with their internal pressures. This result seems to agree with the finding by Carilli, Perley, and Dreher (1988) that the sheath of shocked IGM which surrounds the bow shock of Cygnus A does not contribute detectably to the emission from the lobe. Support for our model could come from the detection of low surface brightness radio emission from the central portion of the cocoon, or the detection of a discontinuity in the rotation measure at the cocoon shock due to the compression of the intergalactic magnetic field (Carilli, Perley, and Dreher 1988). At X-ray wavelengths, the cocoon might show up as a very hot "bubble" in a cooling flow centered on the radio galaxy (Arnaud *et al.* 1984).

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