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COLLIMATION OF THE RADIO JETS IN 3C 31

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ABSTRACT

Observations of the radio jets in 3C 31 using the VLA show that the rates of expansion of these jets transverse to their length decrease with increasing distance from the radio core. A rapid decrease in expansion rate in the northern jet occurs where its magnetic field appears dominated by an organized circumferential component. We use the supersonic beam model of Chan and Henriksen to show that the energy of this circumferential field need only be $\sim 1\%$ of the flow kinetic energy to produce the observed changes in expansion rate by an incipient magnetic pinch. If the beams in 3C 31 are described by the Chan-Henriksen model, their circumferential field strengths cannot significantly exceed their equipartition values, or pinches much stronger than those observed would result.

The observed changes in expansion rate in the jets of 3C 31 could also result from changes in the characteristic length scales of outward-decreasing confining pressures external to the beams. The pressure variations required for external confinement to be responsible for the observed collimation changes are plausible, given recent X-ray data on gaseous halos of massive elliptical galaxies.

Subject headings: galaxies: nuclei — magnetic fields — radio sources: galaxies

I. INTRODUCTION

Recent observations with the Very Large Array (VLA) of linear polarization in the jets of the radio galaxies 3C 31 and NGC 315 (Fomalont *et al.* 1980, hereafter FBWP) have shown that the dominant components of their magnetic fields change orientation with distance from the galactic nuclei much as predicted by models of expanding supersonic beams containing both relativistic and thermal particles and magnetic fields (e.g., Blandford and Rees 1974, 1978; Chan and Henriksen 1980, hereafter CH). On the axes of the brighter jets, the field component $B_{\parallel}$ parallel to the jets dominates for the first few kpc of their length, but the perpendicular component $B_{\perp}$ dominates at greater distances. There is also evidence from the variations of the degree and angle of linear polarization transverse to these jets that their organized field components are the projections of helical field structures whose pitch angles increase with increasing distance from the galactic nuclei.

In this *Letter* we show how the rates of expansion of the jets in 3C 31 vary with distance from the galactic nucleus; we also use the beam dynamics given by CH to examine how the observed variations in expansion rate could result from pinching of the beams by the helical magnetic field and/or from variations in an external confining pressure.

II. COLLIMATION AND MAGNETIC REGIMES IN 3C 31

The VLA observations of 3C 31 (FBWP) show that the transverse intensity profiles of the jets are approximately Gaussian in form. Figure 1 shows the variation with angle Θ from the central radio core of the angular diameter Φ of the intrinsic FWHM of the transverse profile of each jet. These values of Φ were derived by deconvolving the FWHM σ of the synthesized beam from the observed FWHM values Φ_o using the Gaussian relation $\Phi^2 = \Phi_o^2 - \sigma^2$. This deconvolution introduces negligible bias into the values of Φ, as the jets are well resolved; the uncertainties in Φ are $\sim 0\farcs2$ for the 6 cm data and $\sim 0\farcs5$ for the lower-resolution 20 cm data.

Figure 1 and Table 1 show that both jets in 3C 31 widen at decreasing rates as they leave the radio core. Table 1 lists the mean expansion parameters for the data in Figure 1, smoothing out apparent fluctuations in the expansion rate on scales less than 10″ (<5 kpc, $H_0 = 50$ km s^{-1} Mpc^{-1}). The smaller fluctuations are close to the uncertainties in the individual data and

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may not be real. To facilitate comparisons with expansion parameters given in the literature for other jets, Table 1 lists the expansion *rate* $\mu = d\Phi/d\Theta$, the expansion *angle* $\alpha = 2 \arctan (\mu/2)$ and the *cone angle* $\beta = 2 \arctan (\Phi/2\Theta)$, i.e., the angle subtended by the FWHM of the jet at the radio core. The behavior of the synchrotron-emitting material in these jets is evidently not that of a freely expanding supersonic flow with constant Mach number $M = 2/\mu$.

FBWP classified the polarization characteristics of

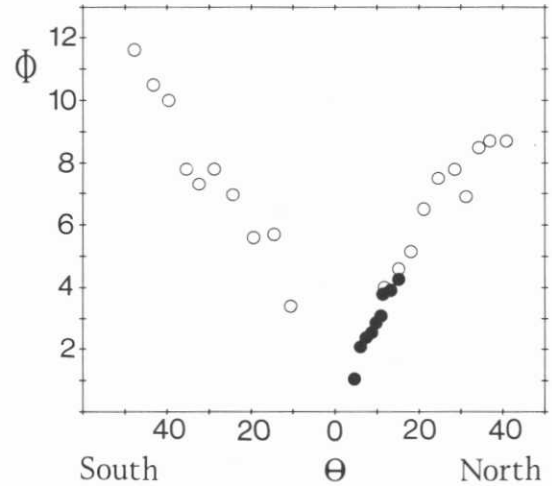

FIG. 1.—The observed FWHM Φ (arc seconds) of the jets in 3C 31 plotted against angular separation Θ (arc seconds) from the radio core, derived from the VLA observations at 20 cm wavelength (*open circles*) and 6 cm wavelength (*filled circles*).

TABLE 1

MEAN EXPANSION PARAMETERS IN THE JETS OF 3C 31

Angular Separation from Core Θ(arcsec)	Angular FWHM of Jet Φ(arcsec)	Expansion Rate (dΦ/dΘ) μ	Expansion Angle 2 arctan (μ/2) α (degrees)	Cone Angle 2 arctan (Φ/2Θ) β (degrees)
		North		
5.........	1.08	(0.22)	...	12.3
10.........	3.0	0.38	21.5	17.1
15.........	4.5	0.30	17.1	17.1
20.........	6.0	0.30	17.1	17.1
25.........	7.3	0.26	14.8	16.6
30.........	7.9	0.12	6.9	15.0
35.........	8.4	0.10	5.7	13.7
40.........	8.8	0.08	4.6	12.6
		South		
10.........	3.4	(0.34)	...	19.3
15.........	5.2	0.36	20.4	19.7
20.........	6.1	0.18	10.3	17.3
25.........	7.0	0.18	10.3	15.9
30.........	8.0	0.20	11.4	15.2
35.........	9.0	0.20	11.4	14.7
40.........	10	0.20	11.4	14.3
45.........	11	0.20	11.4	13.9
50.........	12	0.20	11.4	13.7

3C 31 and NGC 315 into three regimes: (1) a "base" regime, seen on only one side of the radio core in each source, in which the degree of linear polarization p increased with distance from the core, (2) a "transition" regime in which a dominant $B_{\parallel}$ established in the base evolved to dominant $B_{\perp}$, with an associated decrease of p, and (3) a "well-ordered" regime in which p increased with distance from the nucleus (with superposed oscillations) while $B_{\perp}$ remained dominant. In 3C 31, the base regime extends to $\Theta = 4''$ from the core, and the transition regime to $\Theta = 12''$. Our collimation data (Table 1) show that the jets in 3C 31 expand much more rapidly in these regimes than in the more-distant regime of well-ordered $B_{\perp}$.

Decreases in expansion rate imply decreases in the ratio V_r/V_z $(=\mu/2)$ of the transverse expansion velocity V_r to the longitudinal velocity V_z along the jets. Such decreases could either be due to changes in the pressure balance of a confined jet or to a change in the effective equation of state in a free jet. The slowness of the decline in intensity of the 3C 31 jets with distance from the radio core (Burch 1979, FBWP) requires relativistic particle reacceleration that is perhaps most readily accomplished in a "heavy" confined jet in which the relativistic particle energy is only a small fraction of the total energy. We therefore examine the heavy confined jet in more detail.

We adopt the dynamics of a supersonic, but nonrelativistic, magnetized beam given by CH for numerical estimates. CH treated a circularly symmetric beam which is self-similar with respect to $\boldsymbol{B}$, flow velocity $\boldsymbol{V}$, specific angular momentum L, and effective temperature T as functions of the coordinate r transverse to the flow direction z. As discussed by CH, such r-similar flows are likely to represent the asymptotic steady state of beams originating from, for example, magnetic dipole spinars. The CH results should therefore illustrate the dynamics relatively far (a few nozzle scales) from the radio core in beams that are not energetically dominated by the relativistic particles responsible for the observed synchrotron jets.

We have used the CH dynamics to generate examples of two classes of models which can simulate the collimation changes observed in 3C 31. In one class the observed changes are due to an incipient pinching of the beam by the organized circumferential component of the magnetic field; in the other they are entirely due to changes in the gradient parameters of an external confining pressure.

III. COLLIMATION BY MAGNETIC PINCHING

If the configuration of the ordered field in the 3C 31 jets far from the radio core is a helix of variable pitch angle, as suggested by FBWP, the $\boldsymbol{J} \times \boldsymbol{B}$ forces between the circumferential field components and the currents along the jets tend to pinch the currents toward the axes of the jets. The magnetic field strength that would produce the observed changes in expansion rate in the 3C 31 jets can be *estimated* using models where the observed changes are produced by this effect alone, in the absence of external confining pressures.

CH discuss a cold magnetized beam as an extreme case of their general formulation and their equation (47) can be used to estimate the ratio ϵ_B of the energy in the circumferential magnetic field to the kinetic energy of the flow that would produce the observed collimation changes in 3C 31. CH give

$$\frac{B_\phi^2}{4\pi\rho V_{z\infty}^2} = \epsilon_B = \frac{\pi}{4}\left(\frac{R_m}{z_{\max} - z_{\min}}\right)^2,$$

where $B_\phi(z)$ is the circumferential magnetic field strength at the edge of the beam, $\rho(z)$ is the density of thermal matter in the beam, and $V_{z\infty}$ is its asymptotic longitudinal velocity. Here R_m is the maximum radius achieved by the beam, and $(z_{\max} - z_{\min})$ should be approximately equal to the distance z from the radio core at which this maximum is achieved. The jets in 3C 31 deflect and merge with the lobe structure before achieving a clearly defined maximum radius, but because the northern jet appears to be approaching a maximum radius (Table 1) we can *estimate* $R_m/(z_{\max} - z_{\min})$ with the observed quantity $(\Phi_{\max}/2\Theta_{\max}) \times \cos i = (8.8/80) \times \cos i$, where i is the unknown angle between the axis of the jet and the plane of the sky. The greatest uncertainty in this estimate stems from identifying the observed HWHM $\Phi/2$ of the synchrotron-emitting *jet* with the parametric radius R of the CH *beam*. We then find

$$\epsilon_B \sim 0.01 \cos^2 i\,,$$

so that *magnetic pinching alone would produce the observed collimation changes if the energy in the circumferential field were as little as 1% of the kinetic energy of the flow down the beam.* If we assume flow velocities $V_{z\infty} \approx 1000$ km s^{-1} and beam densities 10^{-22} to 10^{-23} kg m^{-3}, which are typical of values estimated for the beams in 3C 31 and 3C 449 on other grounds by Blandford and Icke (1978) and by Perley, Willis, and Scott (1979), circumferential fields B_ϕ of order 3×10^{-6} to 10^{-5} gauss would produce the observed collimation change in the northern jet of 3C 31 as the initial stages of a magnetic pinch. Such field strengths are in the range which would be estimated by the usual equipartition calculations for the synchrotron-emitting material.

Curves *a* and *b* in Figure 2 show fits to our 3C 31 data of more realistic magnetically pinched beams with both internal and external pressures. These were obtained by numerical solution of the CH equations, assuming that the beam *pressure* is dominated by the relativistic particles, so that $P \propto \rho^{4/3}$ along the stream lines. In these models the observed HWHM of the jet where $B_\parallel \approx B_\perp$ has been used to constrain the parameter $R_1 = V_{z\infty}/\Omega$ of CH, where Ω is a characteristic angular velocity of the beam around its axis at the Alfvénic point (CH, eq. [16]). The values of ϵ_B in these models are 0.0063 (*a*) and 0.016 (*b*) and their sonic points are 1".45 (*a*) and 0".90 (*b*) (0.7 and 0.4 kpc) above the radio core. In both cases the sonic point would lie in unresolved structure at the base of the observed radio jet.

The model curves are extrapolated beyond the data to illustrate a test for a magnetic pinch as the *primary* mechanism for changes in the expansion rate of long jets: the radius of a magnetically collimated beam should exhibit long-wavelength oscillations around an equilibrium value far from the radio core, although the oscillations may be of small amplitude if the magnetic and thermal pressure are not too different where the beam achieves its first maximum radius, as in curve *a*. The jets in 3C 31 terminate instead by deflecting and forming the radio lobes; so we cannot determine directly whether these jets are collimated mainly by a magnetic pinch.

Curve *b* in Figure 2 illustrates the behavior of the beam radius far from the core if the pinching pressure significantly exceeds the internal particle pressure at the distance $z_{\max}$ where the beam first achieves its maximum radius; the beam collapses at $z > z_{\max}$ and its radius subsequently oscillates dramatically. Since such large oscillations in radius are not observed in any of the longer (>50 kpc) jets that we have studied at the VLA, *it is unlikely that magnetic energies in long jets with $B_\perp$ dominant are more than a few percent of their flow kinetic energies*, or equivalently, that their magnetic energies significantly exceed those corresponding to energy equipartition between the fields and relativistic particles.

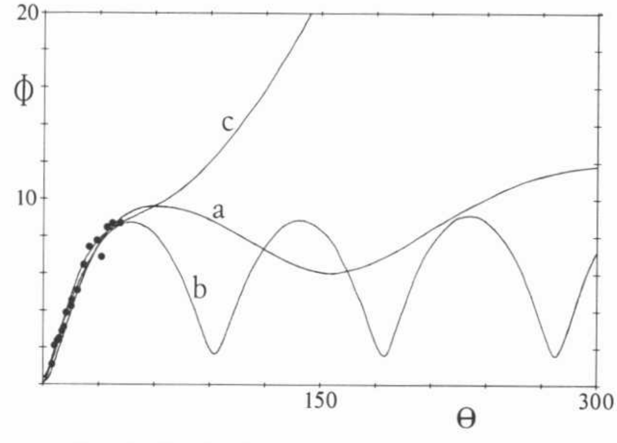

FIG. 2.—The data for the northern jet in Fig. 1 are superposed on three models obtained by numerical integration of the CH equations—curve *a*: a magnetically collimated model with $\epsilon_B = 6.314 \times 10^{-3}$ and sonic-point parameters $R_s = 0''.1$, $z_s = 1''.45$, and magnetic Mach number 1.10. The external pressure initially falls off with $m = 5$, and the collimation change beyond $\Theta = 15''$ results entirely from the incipient magnetic pinch; curve *b*: a stronger magnetic pinch with $\epsilon_B = 1.65 \times 10^{-2}$ and sonic-point parameters $R_s = 0''.18$, $z_s = 0''.90$, and magnetic Mach number 1.23. The external pressure falls off with $m = 4$; curve *c*: a model in which $\epsilon_B = 0$, and the change in expansion rate is produced by an external pressure variation (§ IV) with $z_s = 0''.64$, $m = 4$, $z_e = 9''$, H $= 21''$, and $m' = 3$. The beam radius at the sonic point is $R_s = 0''.07$. All three models provide an acceptable fit to the data; they have been selected to illustrate the divergent predictions of different model types at distances well beyond the expansion-rate maximum actually observed in 3C 31 (see text).

IV. COLLIMATION BY EXTERNAL PRESSURES

Given the X-ray detection of extended ($\sim$100 kpc), hot ($>10^7$ K) gaseous halos around M87 (e.g., Fabricant *et al.* 1978; Fabricant, Lecar, and Gorenstein 1979) and Cyg A (Fabbiano *et al.* 1979), it is now attractive to consider the possibility that the jets in low-luminosity radio sources such as 3C 31 may be confined over such scales mainly by external pressure. To match the decreasing expansion rates we have observed in 3C 31, the beam must initially be collimated by a dense "nuclear" atmosphere whose pressure decreases rapidly with z and is supplanted above some height z_e by a more slowly decreasing pressure with a characteristic scale $H \gg z_s$. Following CH, we write such an external confining pressure P as the sum of two contributions:

$$P = P_s\left[\frac{f}{1 + (f-1)(z/z_s)^m} + \frac{(1 - z_s/z)(z_s/z_e)^m}{1 + (z/H)^{m'}} \times \frac{f}{f-1}\right],$$

where $f(\gamma) = 1.85$ for $\gamma = 4/3$, and the subscript s denotes that a parameter is to be evaluated at the sonic point. The second term becomes significant at a distance $z_e \gg z_s$ and produces a pressure variation that is "flat" over a shoulder of width $H > z_e$. The model shown by curve c in Figure 2 provides an equally satisfactory fit to our observations of the northern jet and postulates a transition from a dominant "nuclear" atmosphere with $m = 4$ and $z_s = 0\rlap{.}''64$ at $z < z_e \approx 4/\cos i$ kpc to a general "galactic" atmosphere extending over several $H \approx 10/\cos i$ kpc. The radius of the nozzle in the model was $0\rlap{.}''07$ (34 pc). Although such a pressure structure for 3C 31 is entirely ad hoc, it is in no sense unlikely, as the required n_eT products in the hypothetical medium are only $\sim 10^5$ cm^{-3} K at $\Theta = 4''$ ($1.9/\cos i$ kpc) near the base of the 3C 31 jet and $\sim 10^4$ cm^{-3} K near $\Theta = 40''$ ($19/\cos i$ kpc). This class of model predicts an asymptotic ballistic expansion with a constant expansion angle α, in contrast to the oscillations of the beam radius predicted by *typical* magnetically pinched models. We may therefore be able to discriminate between these two classes of models with VLA data on radio jets which extend far from their first regime of slow expansion.

V. THE SOUTHERN JET IN 3C 31

We have also modeled the collimation of the southern jet; as shown in Figure 1, this jet expands more rapidly near the radio core and its expansion rate μ does not decrease as rapidly as that of the northern jet near $\Theta = 40''$. These properties can be fitted with only minor variations of the northern jet models shown in Figure 2. In particular, the externally confined model c of Figure 2 fits the data on the southern jet within their errors if the beam radius at the sonic point is increased by about 5% and the height of the sonic point above the radio core is decreased by about 3%, all other parameters being unaltered. Such small side-to-side differences in jet collimation as are seen in 3C 31 could therefore be attributed to very minor differences in conditions between the sonic points in the two sides of the flow.

VI. DISCUSSION

There is evidence that collimation changes similar to these in 3C 31 also occur in the jets of 3C 449 and NGC 315 near the boundaries between their "transition" and "well-ordered" magnetic regimes, so that the phenomena described here are important in other low-luminosity radio galaxies. Figure 3 of Perley, Willis, and Scott (1979) shows that for $\Theta > 10''$ the expansion rate μ in both jets of 3C 449 is ~ 0.14, but in the northern jet the limited data at $\Theta < 10''$ show a much faster initial expansion, with $\mu \approx 0.5$. The position angle of the 6 cm linear polarization in the northern jet of 3C 449 also changes rapidly with Θ for $\Theta < 10''$, as it does in the transition regime of 3C 31. Bridle *et al.* (1979) found a decreasing expansion rate in the brighter jet of NGC 315, where FBWP found changes in the magnetic field configuration closely resembling those in 3C 31.

The relation between expansion rates and magnetic structure, however, may be different in the more radio-luminous jets of 3C 219 (Perley *et al.* 1980), NGC 6251 (Willis, Perley, and Bridle 1981), and the quasar 2349+32 (Potash and Wardle 1980), where $B_\parallel$ remains dominant for large distances from the radio cores, but the jets are highly collimated until they disappear or enter the radio lobes. We are now undertaking high-resolution polarimetry of a variety of radio jets at the VLA to test whether models which account satisfactorily for the collimation of low-luminosity systems such as 3C 31 can also explain the phenomena observed in more powerful sources.

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REFERENCES

Blandford, R. D., and Icke, V. 1978, *M.N.R.A.S.*, **185**, 527.
Blandford, R. D., and Rees, M. J. 1974, *M.N.R.A.S.*, **169**, 395.
———. 1978, *Phys. Scripta*, **17**, 265.
Bridle, A. H., Davis, M. M., Fomalont, E. B., Willis, A. G., and Strom, R. G. 1979, *Ap. J.* (*Letters*), **228**, L9.
Burch, S. F. 1979, *M.N.R.A.S.*, **187**, 187.
Chan, K. L., and Henriksen, R. N. 1980, *Ap. J.*, **240**, in press (CH).
Fabbiano, G., Doxsey, R. E., Johnston, M., Schwartz, D. A., and Schwarz, J. 1979, *Ap. J.* (*Letters*), **230**, L67.
Fabricant, D., Topka, K., Harnden, F. R., Jr., and Gorenstein, P. 1978. *Ap. J.* (*Letters*), **226**, L107.

Fabricant, D., Lecar, M., and Gorenstein, P. 1979, *IAU Joint Discussion: Extragalactic High Energy Astrophysics*, ed. H. van der Laan (Leiden: Leiden Observatory), p. 64.
Fomalont, E. B., Bridle, A. H., Willis, A. G., and Perley, R. A. 1980, *Ap. J.*, **237**, 418 (FBWP).
Perley, R. A., Bridle, A. H., Willis, A. G., and Fomalont, E. B. 1980, *A.J.*, **85**, 499.
Perley, R. A., Willis, A. G., and Scott, J. S. 1979, *Nature*, **281**, 437.
Potash, R. I., and Wardle, J. F. C. 1980, *Ap. J.*, **239**, 42.
Willis, A. G., Perley, R. A., and Bridle, A. H. 1981, in preparation.

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