

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

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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 ~ 0.2 for the 6 cm data and ~ 0.5 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, $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$). The smaller fluctuations are close to the uncertainties in the individual data and

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

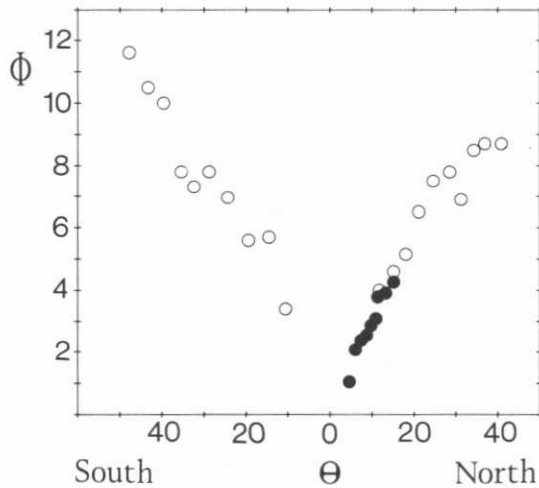


FIG. 1.—The observed FWHM Φ (arc seconds) of the jets in 3C 31 plotted against angular separation θ (arc seconds) from the radio core, derived from the VLA observations at 20 cm wavelength (open circles) and 6 cm wavelength (filled circles).

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 $(d\Phi/d\theta)$ μ	Expansion Angle $2 \arctan(\mu/2)$ α (degrees)	Cone Angle $2 \arctan(\Phi/2\theta)$ 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 non-relativistic, magnetized beam given by CH for numerical estimates. CH treated a circularly symmetric beam which is self-similar with respect to B , flow velocity 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 $J \times B$ 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 $V_{z\infty} \approx 1000 \text{ km s}^{-1}$ and beam densities 10^{-22} to $10^{-23} \text{ kg m}^{-3}$, 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 ($> 50 \text{ kpc}$) 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.

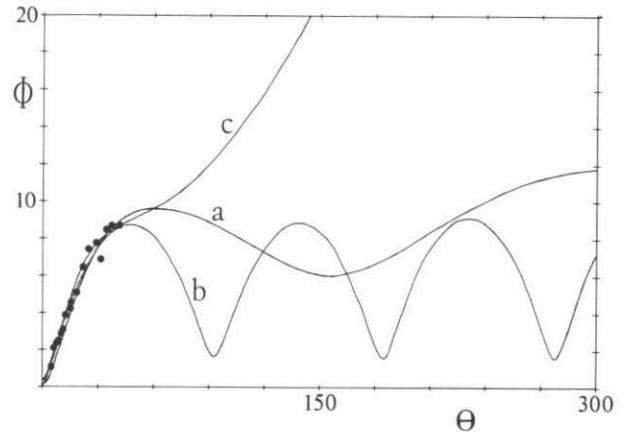


FIG. 2.—The data for the northern jet in Fig. 1 are superposed on three models obtained by numerical integration of the CH equations—curve *a*: a magnetically collimated model with $\epsilon_B = 6.314 \times 10^{-3}$ and sonic-point parameters $R_s = 0''.1$, $z_s = 1''.45$, and magnetic Mach number 1.10. 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 $z_s = 0''.64$, $m = 4$, $z_0 = 9''$, $H = 21''$, 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).