THE ASTROPHYSICAL JOURNAL, 248:499–503, 1981 September 1

VLA OBSERVATION OF RADIO/OPTICAL KNOTS IN 3C 277.3 = COMA A

A. H. BRIDLE[1]
National Radio Astronomy Observatory VLA Program; and Department of Physics and Astronomy, University of New Mexico

E. B. FOMALONT
National Radio Astronomy Observatory, Charlottesville, Virginia

J. J. PALIMAKA
Queen's University at Kingston, Ontario, Canada

AND

A. G. WILLIS
Netherlands Foundation for Radio Astronomy, Radiosterrenwacht Westerbork, The Netherlands
Received 1980 December 28; accepted 1981 March 17

ABSTRACT

The radio galaxy 3C 277.3 has been mapped at $\sim 1''$ resolution using the VLA at 4885 MHz. Its structure resembles that of the inner $\sim 50''$ of the radio emission from M87. A bridge or jet linking the unresolved central radio core to the southern lobe contains two bright radio knots. One of these coincides with a blue polarized continuum knot in the envelope of the galaxy. Minimum energy calculations for this knot demand *in situ* particle deposition there, as in the M87 optical-radio jet. If the flow velocity through the knots is of the same order as the 200–300 km s^{-1} peculiar radial velocity of an optical emission-line system detected in their vicinity by Miley *et al.*, two interpretations are possible. Either the magnetic field in the knots is well below its equipartition value, or *in situ* particle deposition occurs far from the radio core, and a large mass flux through the knots is needed to supply the observed luminosity of the source.

Subject headings: galaxies: individual — interferometry — radio sources: galaxies

I. INTRODUCTION

The radio source 3C 277.3 (= 1251+278 = Coma A) is identified with a $m_V \sim 15.5$ mag D2 galaxy projected against the outskirts of the Coma cluster (Wyndham 1966). The redshift of the galaxy is 0.0857, corresponding to a distance of 262 Mpc, for $H_0 = 100$ km s^{-1} Mpc^{-1}. It has a basically double structure $\sim 45''$ (50 kpc) in overall extent with wide radio lobes. The evidence for an elongated feature southeast of the center of the galaxy on a 5 GHz map by Pooley and Henbest (1974) suggested to us that there might be a weak radio jet in this source, so it was included in a radio-galaxy mapping program using the partially completed Very Large Array (VLA) (Thompson *et al.* 1980).

II. THE VLA OBSERVATIONS

The observations were made at 4885 MHz by tracking 3C 277.3 for 12.4 hr with 17 VLA antennas on 1979 14 July. Outputs from all antenna pairs were correlated, providing 136 baselines from ~ 0.6 to ~ 18 km in length. The data were calibrated by concurrent observations of 3C 287 and of 3C 286. The 4885 MHz flux density of 3C 286 was assumed to be 7.41 Jy.

[1] On leave from Queen's University at Kingston, Ontario, Canada.

Figure 1 (*left panel*) shows a CLEANed (Högbom 1974) map on the distribution of the total intensity (Stokes I) over 3C 277.3 at $1''.27$ by $0''.54$ resolution (FWHM), the direction of least resolution being in p.a. 146°. The overall morphology of the source resembles that of the inner $\sim 50''$ of M87 (Turland 1975; Owen, Hardee and Bignell 1980); the lobe morphology is similar to that of 3C 388 (Burns and Christiansen 1980). An unresolved ($< 0''.4$ by $< 0''.2$, 532 by 216 pc) 13 ± 1 mJy central component (C) at 1950.0 position $12^h51^m46^s.29 \pm 0^s.01$, $+27°53'49''.3 \pm 0''.1$ coincides to within the positional errors with the optical center of the galaxy as measured by Griffin (1963) and by Goodson, Palimaka, and Bridle (1979). Two bright radio knots (features K1 and K2) lie on a gently curving faint emission bridge (B) extending southward from the core source toward a broad emission peak (A) that dominates the emission from the southern lobe. The northern lobe is generally more diffuse than the southern, but it contains a resolved "hot spot" (D) near its northern edge. The peak of this feature is $20''.0$ (22 kpc) from the core in p.a. $-21°$. It lies approximately opposite the two knots, which are $5''.8$ (6.3 kpc) from the core in p.a. 154° (K1) and $7''.7$ (8.3 kpc) from the core in p.a. 163° (K2). There is a hint of a curved ridge in the northern lobe linking the core (C) to feature D, but

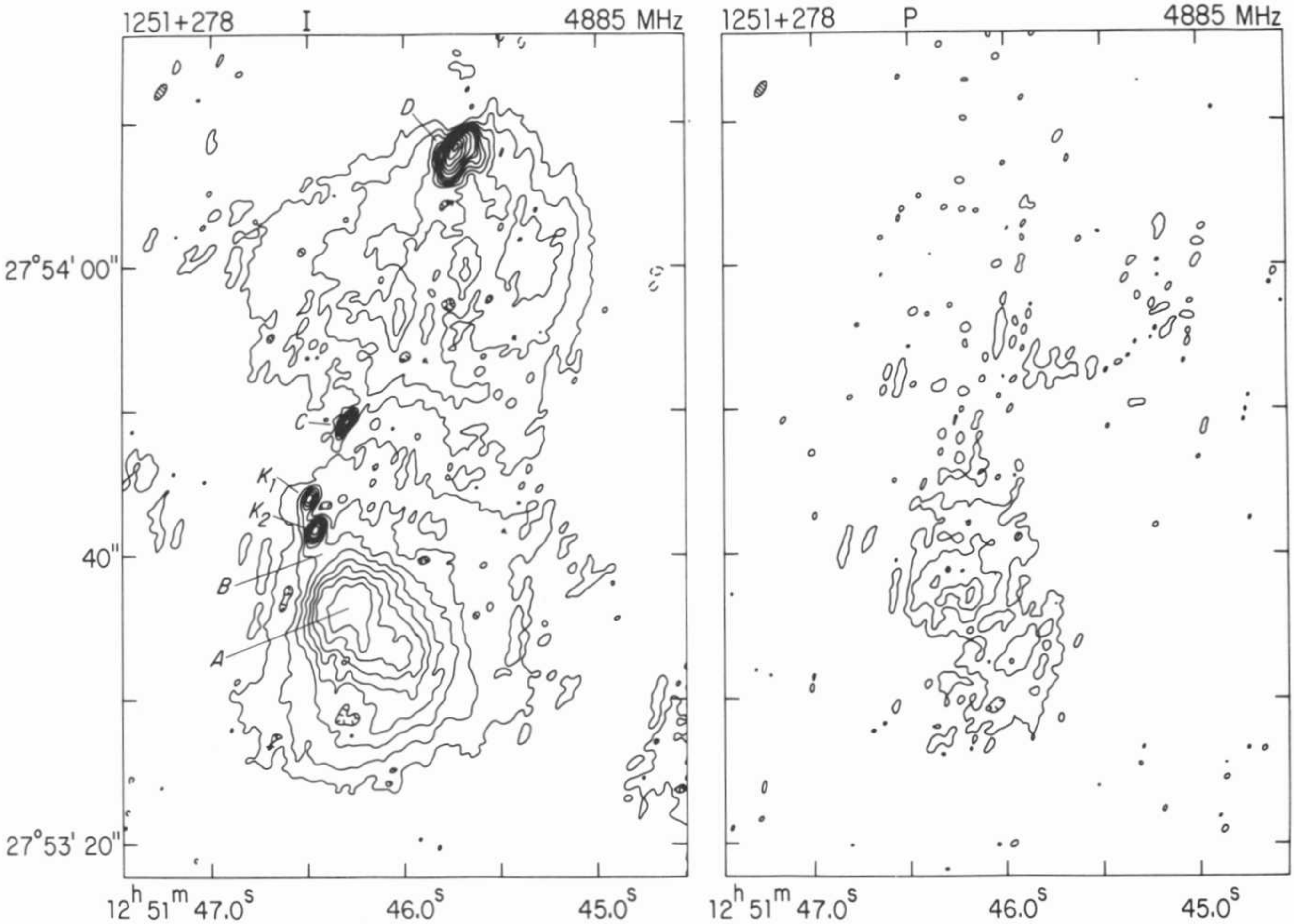

FIG. 1—*Left*, contours of total intensity (Stokes *I*) over 3C 277.3 at 4885 MHz with resolution (FWHM) 1″.27 by 0″.54 (major axis in p.a. 146°). Contours are drawn at −1, 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 14, 16, and 18 times 0.8 mJy per beam. The FWHM of the beam is shown by the shaded ellipse at upper left. The weak outer extensions of the lobes are confirmed by observations at lower resolution. The width of the lobes and the gap between them resemble features of the fainter structure of 3C 388 (Burns and Christiansen 1980, their Fig. 2). *Right*, contours of polarized intensity $P = (Q^2 + U^2)^{1/2}$ over 3C 277.3 at 4885 MHz with same resolution as in left panel. Contours are drawn at 1, 2, 3, and 4 times 0.4 mJy per beam.

the excess emission associated with this ridge is close to the *peak* fluctuations of 0.8 mJy on the map, and further observations are needed to confirm that it is real.

The distribution of the polarized intensity $P = (Q^2 + U^2)^{1/2}$ (Fig. 1, *right panel*) is strikingly asymmetric between the two lobes. The brighter features of the northern lobe, near D, are essentially unpolarized ($p = P/I \lesssim 2\%$), whereas the brighter emission from the southern lobe, around A, has $5\% \lesssim p \lesssim 35\%$. There is weak extended polarized emission in the diffuse southern part of the northern lobe, with $5\% \lesssim p \lesssim 35\%$; this emission is close to the noise (0.18 mJy per beam rms) in Figure 1 (*right*) but is clearly present in Figure 2, which shows the polarized intensity distribution at 2″.30 by 1″.22 resolution.

The distribution of the position angles of the *E*-vectors over 3C 277.3 is shown in Figure 3. The *E*-vectors tend to be arranged radially around the peak of feature A, but we cannot determine the magnetic field structure near this feature as the Faraday rotation of these vectors is unknown.

III. THE UNRESOLVED CORE

The core corresponds in position with a 16 ± 10 mJy small-diameter feature reported at 8.1 GHz by Goodson, Palimaka, and Bridle (1979). The large uncertainty in this 8.1 GHz measurement makes the spectrum of the core very uncertain, but a spectral index $\alpha = 0$ that would be typical of small-diameter cores in radio galaxies is compatible with the data. Assuming that the spectrum extends from 10 to 10^5 MHz with such an index, we find the lower limits to the equipartition parameters given for the core in column (1) of Table 1. Column (2) gives the same parameters for the assumption $\alpha = 0.7$ ($S_\nu \propto \nu^{-\alpha}$). The 5 GHz luminosity of the core in 3C 277.3 is similar to that of

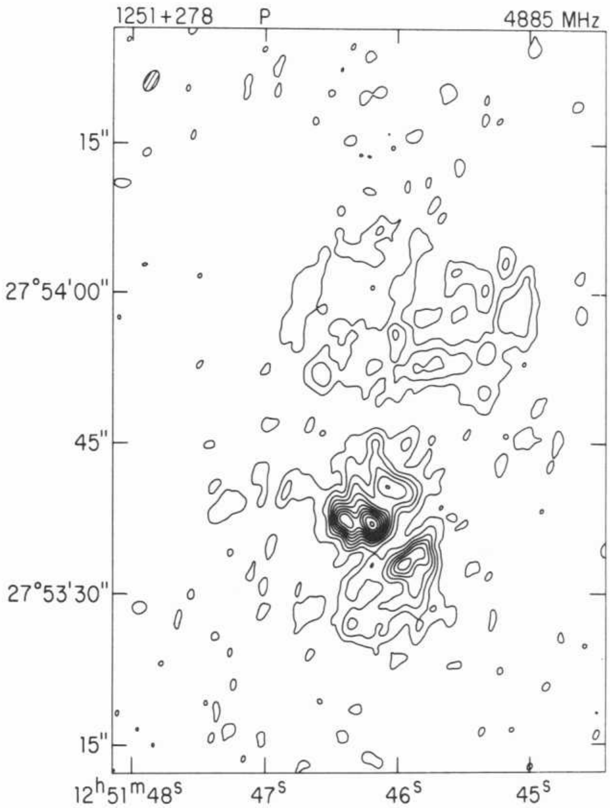

FIG. 2.

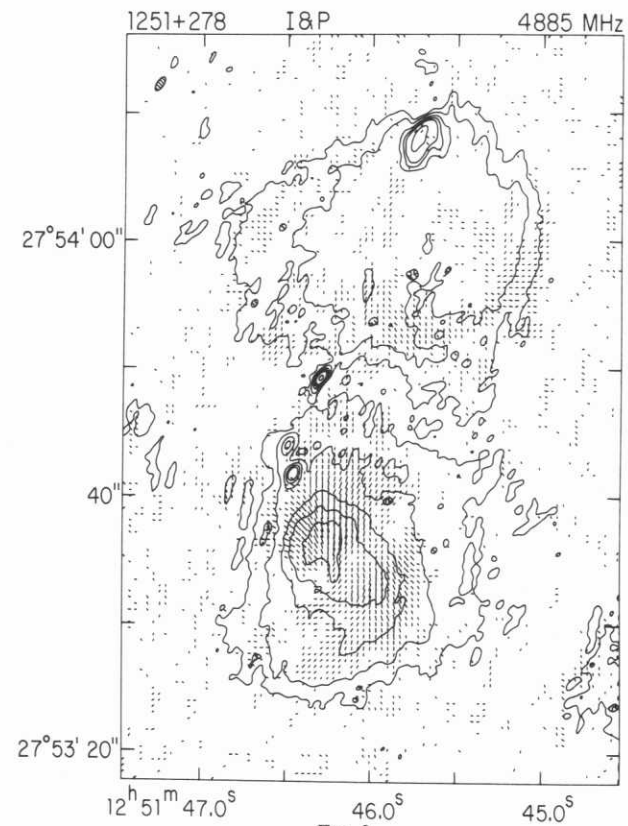

FIG. 3.

FIG. 2—Contours of polarized intensity $P = (Q^2 + U^2)^{1/2}$ over 3C 277.3 at 4885 MHz with resolution (FWHM) 2".30 by 1".22 (major axis in p.a. 150°). Contours are drawn at intervals of 0.33 mJy per beam. The FWHM of the beam is shown by the shaded ellipse at upper left.

FIG. 3—The distribution of orientations of the *E*-vectors of linear polarization over 3C 277.3 at 4885 MHz (resolution as in Fig. 1), superposed on contours from the total intensity map. The lengths of the vectors are proportional to the linearly polarized signal and their position angles are those of the observed *E*-vectors. The FWHM of the beam is shown by the shaded ellipse at upper left.

the emission within 0".5 of the center of M87, which is 1.2×10^{23} W Hz^{-1} for an M87 distance of 15.7 Mpc (Mould, Aaronson, and Huchra 1980).

IV. THE RADIO KNOTS

The peak of knot K1 at 4885 MHz is at 1950.0 position $12^h51^m46^s.49 \pm 0^s.01$, $+27°53'43".6 \pm 0".1$, within 1" of the optical position of a blue knot apparently within the envelope of the galaxy on the Palomar Sky Atlas prints (Goodson, Palimaka, and Bridle 1979). Both a polarized optical continuum and excited oxygen and other emission lines (Miley *et al.* 1981) have been detected from this blue optical knot; the radial velocity of the oxygen emission line system relative to that of the nucleus of the galaxy is 200 to 300 km s^{-1}. Both the positional coincidence between these optical features and the radio

TABLE 1

MINIMUM-ENERGY PARAMETERS FOR BRIGHT COMPONENTS OF 3C 277.3[a]

Parameter	Core		Knot 1	Knot 2	A	D
Total flux density (4885 MHz)	13 mJy		14 mJy	19 mJy	370 mJy	100 mJy
Angular diameters	<0".4 × <0".2		1".7 × 0".8	1".1 × 0".8	5".7 × 5".7	2".5 × 1".4
Spectral index α	0.0	0.7	0.56	0.75	0.7	0.7
ν_{max} (MHz)	10^5	10^5	10^9	10^9	10^5	10^5
L (watts)	1.0×10^{34}	3.9×10^{33}	2.8×10^{35}	6.4×10^{34}	1.2×10^{35}	3.1×10^{34}
E_{min} (joules)	1.2×10^{47}	1.6×10^{47}	1.1×10^{48}	1.2×10^{48}	6.0×10^{49}	6.0×10^{48}
B_{eq} (gauss)	1.6×10^{-4}	1.8×10^{-4}	5.8×10^{-5}	7.5×10^{-5}	3.3×10^{-5}	6.4×10^{-5}
U_{min} (joules m^{-3})	2.4×10^{-10}	3.2×10^{-10}	3.2×10^{-11}	5.2×10^{-11}	1.0×10^{-11}	3.9×10^{-11}
nT_{min} (cm^{-3} K)	6.1×10^6	8.0×10^6	8.0×10^5	1.3×10^6	2.6×10^5	9.8×10^5

[a] Equal energies are assumed in relativistic protons and electrons, and the source volume is assumed to be fully filled. The spectrum of each component is assumed to be a power law of index α between 10 MHz and ν_{max}. The depth of the component in the line of sight is assumed equal to its smaller diameter.

knot K1 and the polarization of the optical continuum strongly suggest that this continuum is nonthermal light from the radio feature, analogous to the blobby optical-radio jet in M87. In what follows we explore some consequences of this identification.

The 4885 MHz emission from knot K1 is resolved, with a peak intensity of 5.2 mJy and intrinsic FWHM (after deconvolution of the beam) of $\sim 1''.7$ by $0''.8$ (1.8 by 0.9 kpc). The greatest elongation of the knot is within 30° of the major axis of the synthesized beam, so the true orientation of the knot is difficult to determine. The integrated flux density of the knot is 14 ± 2 mJy. A major uncertainty in this estimate and in those of the FWHMs arises from the presence of the faint bridge B around the knot. The flux density of the optical knot at K1 is 23 μJy at 6.67×10^{14} Hz (Miley *et al.* 1981); if the optical and 4885 MHz emissions arise from the same region, the spectral index of this emission must be 0.56 between these frequencies. Column (3) of Table 1 gives equipartition parameters for K1 based on these estimates. The integrated luminosity is ~ 4 times that of knot A in M87, using the parameters of that system given by Owen, Hardee, and Bignell (1980). The knots in M87 are considerably more compact than K1, however, so the equipartition magnetic field in K1 is ~ 8 times smaller than that obtained with the same assumptions for M87. The 5 GHz luminosity per unit length in K1 (6×10^{22} W Hz^{-1} kpc^{-1}) is less than that in the M87 knots but is greater than those in other radio galaxies with detectable optical emission from their radio jets (Butcher, van Breugel, and Miley 1980). Both the luminosity per unit length and the equipartition parameters derived for K1 are similar to those for the jet embedded in the western lobe of 3C 388 (Burns and Christiansen 1980), whose lobe morphology closely resembles that of 3C 277.3.

K1 has a 4885 MHz linear polarization $p < 2\%$. This is well below the polarizations of 18% and 14% at this frequency in the bright bases of the jets in 3C 31 and NGC 315 (Fomalont *et al.* 1980) and lower than that of the knots in M87, whose 4885 MHz polarizations range from 4% to 24% (Owen, Hardee, and Bignell 1980). The low polarization in knot K1 could be due to thermal depolarization or to a highly disordered field structure. Given the large size of K1 relative to the M87 knots, it is also possible that it contains several smaller structures with misaligned magnetic fields; if this is true, the energy density and field strength estimated in Table 1 may be underestimated. Similar arguments may apply to the jet in 3C 388, which also has little polarization at 4885 MHz ($p < 5\%$, Burns and Christiansen 1980).

The lifetime against synchrotron radiation for an electron radiating at 6.7×10^{8} MHz in the equipartition field strength of 5.8×10^{-5} gauss in K1 is only 2910 years, while the light travel time over the projected distance of 6.3 kpc from the radio core to K1 is 20,500 years. Unless the field strength in K1 is $\lesssim 1.6 \times 10^{-5}$ gauss, there must therefore be *in situ* particle deposition in K1, as in the M87 knots. Such *in situ* deposition could be accomplished either by local particle acceleration within K1 or, if the magnetic configuration between K1 and the core permitted, by low-loss streaming of particles from the core into a region within K1 where pitch-angle scattering became significant (e.g., Spangler 1979).

The peak of knot K2 is at 1950.0 position $12^{h}51^{m}46^{s}.46 \pm 0^{s}.01$, $+27°53'41''.8 \pm 0''.1$ at 4885 MHz. Although the peak intensity (8.3 mJy) exceeds that of K1, the flux density of this knot at 6.67×10^{14} Hz is only $\lesssim 3.7$ μJy. Its spectral index between these frequencies must therefore be $\gtrsim 0.75$. (We use the optical flux density given by Miley *et al.* 1981 for K2 as an upper limit as it may contain a contribution from the emission lines.) Column (4) of Table 1 gives equipartition parameters for K2 on the assumption that its spectral index is 0.75 from 10 to 10^{9} MHz. The minimum light travel time from the core to K2 is 27,000 years, whereas the synchrotron lifetime for electrons radiating at 6.7×10^{8} MHz in the equipartition field strength of 7.5×10^{-5} gauss is only 2000 years. Unless the optical emission from K2 is mainly line emission or the field strength there is $\lesssim 1.3 \times 10^{-5}$ gauss, *in situ* particle deposition must also occur in K2.

V. THE RADIO LOBES

Columns (5) and (6) of Table 1 give equipartition parameters for features A and D of the lobes of 3C 277.3, assuming that the spectral indices of these features are $\alpha = 0.7$ from 10 to 10^{5} MHz. The minimum energy density, and hence the minimum confining pressure, is approximately the same for feature D as for K1 and K2. As D is about 3 times farther from the core than these knots, it is unlikely that an external thermal pressure due to a gaseous atmosphere of 3C 277.3 could actually have similar (and high) values at all three locations. It is more likely that some of these features are not in pressure equilibrium with their surroundings or that the assumptions implicit in the equipartition calculations do not hold for some of them.

If we assume that feature A is powered by a flow of energy through K1 and K2, then $\epsilon Uav = L$, where ϵ is the efficiency of conversion of the flow energy density U to synchrotron radiation, a is the flow cross section and v is the flow velocity at a point where the energy density is U, and L is the total synchrotron luminosity beyond that point. As L for K1, K2, and A is of order 4.6×10^{35} W, the parameters estimated for K1 and K2 in Table 1 require a flow velocity greater than $(2.0/\epsilon) \times 10^{4}$ km s^{-1} if $U = U_{\rm min}$. Energy balance therefore requires either a relativistic bulk motion or $U > U_{\rm min}$. If the flow velocity is actually of the same order as the 300 km s^{-1} peculiar radial velocity of the emission line system near K1 (Miley *et al.* 1981), then $U = (66/\epsilon)U_{\rm min}$ is needed. This could be achieved either with $B \lesssim 2.6 \times 10^{-6}$ gauss in the knots or in a "heavy" jet in which the thermal energy density $U_{\rm th} \sim (66/\epsilon)U_{\rm min}$. At a bulk velocity of 300 km s^{-1} the latter would require $n_{\rm th} \sim (37/\epsilon)$ cm^{-3}, i.e., a mass flux from the core of $\sim (160/\epsilon)\ M_{\odot}$ yr^{-1}.

The distributions of polarized 4885 MHz emission and of O III λ5007 emission (Miley *et al.* 1981) over both radio lobes are broadly anticorrelated. The region of low polarization at and south of feature D corresponds to the O III emission-line features N1 and N2, whereas the polarized signal at the southern edge of the northern lobe is a region where no O III emission was detected. The polarized signal from the southern lobe comes mainly from beyond the region S2 where O III emission was detected by Miley *et al.* (1981). This anticorrelation suggests that Faraday depolarization by thermal gas in the line-emitting regions may be occurring at 4885 MHz.

VI. DISCUSSION

Three extreme interpretations are possible for the parameters of the flow through the knots in the optical/radio jet of 3C 277.3.

The first is to postulate a light ($U \sim U_{rel}$) flow at $v \sim c$. The equipartition energy flux in such a flow could supply the luminosity of K1, K2, and feature A provided the efficiency of conversion to synchrotron radiation was $\epsilon \gtrsim 0.08$. *In situ* particle deposition would be required at K1 and K2 but not at A. If the flow were of this kind, the observed optical emission lines must arise in material excited by the passage of the relativistic flow but not moving with it. The brightness asymmetry between knots K1 and K2 and the faint ridge between the core and feature D could be attributed to Doppler favoritism of the approaching side of such a flow.

The second is to postulate a light ($U \sim U_{rel}$) flow with $v \sim 300$ km s^{-1}. In this case the energy density U must be $\sim 66/\epsilon\, U_{min}$ to provide the observed luminosity. A low-field model of this kind could have $B \sim 2.6 \times 10^{-6}$ gauss in the flow, in which case no *in situ* particle deposition would be required.

The third is to postulate a heavy ($U \gg U_{rel}$) flow in equipartition also with $v \sim 300$ km s^{-1}. In this case, large internal thermal densities ($37/\epsilon$ cm^{-3}) and mass flows from the core ($160/\epsilon\, M_\odot$ yr^{-1}) are required, and *in situ* particle deposition must occur throughout the source. The substantial energy reservoir associated with the thermal mass flow in such models might be available for particle acceleration.

Models of the second and third kind would be supported if studies of the velocity field and line strengths in the optical emission lines suggest that the lines originate from material that participates in the flow through the radio knots. In this case, constraints on the thermal densities within the flow from studies of the optical emission lines and of the radio polarization properties of the source could distinguish between models of the second and third kind.

The coincidence of optical and radio features in the jet of 3C 277.3 therefore holds attractive possibilities for studying the dynamics of a jet in a moderately luminous radio galaxy, and further observations of the source are planned at the VLA and at Kitt Peak to distinguish between the various alternative models described above.

We thank the staff of the VLA for their valuable contributions to the success of these observations. This research was partially supported by grants to A. H. B. from the Natural Sciences and Engineering Research Council of Canada (NSERC) and from the Advisory Research Committee of Queen's University at Kingston. A. H. B. also thanks the National Radio Astronomy Observatory and the University of New Mexico for their hospitality during a sabbatical leave in which this work was completed. J. J. P. acknowledges the support of an NSERC postgraduate scholarship.

The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

REFERENCES

Burns, J. O., and Christiansen, W. A. 1980, *Nature*, **287**, 208.
Butcher, H. R., van Breugel, W. J. M., and Miley, G. K. 1980, *Ap. J.*, **235**, 749.
Fomalont, E. B., Bridle, A. H., Willis, A. G., and Parley, R. A. 1980, *Ap. J.*, **237**, 418.
Goodson, R. E., Palimaka, J. J., and Bridle, A. H. 1979, *A.J.*, **84**, 1111.
Griffin, R. F. 1963, *A.J.*, **68**, 421.
Högbom, J. A. 1974, *Astr. Ap. Suppl.*, **15**, 417.
Miley, G. K., Heckman, T. M., Butcher, H. R., and van Breugel, W. J. M. 1981, *Ap. J.*, in press.
Mould, J., Aaronson, M., and Huchra, J. 1980, *Ap. J.*, **238**, 458.
Owen, F. N., Hardee, P. E., and Bignell, R. C. 1980, *Ap. J. (Letters)*, **239**, L11.
Pooley, G. G., and Henbest, S. N. 1974, *M.N.R.A.S.*, **169**, 517.
Spangler, S. R. 1979, *Ap. J. (Letters)*, **232**, L7.
Thompson, A. R., Clark, B. G., Wade, C. M., and Napier, P. J. 1980, *Ap. J. Suppl.*, **44**, 151.
Turland, B. D. 1975, *M.N.R.A.S.*, **170**, 281.
Wyndham, J. D. 1966, *Ap. J.*, **144**, 459.

A. H. BRIDLE: National Radio Astronomy Observatory VLA Program, P.O. Box O, Socorro, NM 87801

E. B. FOMALONT: National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901

J. J. PALIMAKA: Department of Physics, Stirling Hall, Queen's University at Kingston, Ontario K7L 3N6, Canada

A. G. WILLIS: Netherlands Foundation for Radio Astronomy, Radiosterrenwacht Westerbork, Schattenberg 4, 9433 TA Zwiggelte, The Netherlands