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DISTORTED STRUCTURE IN THE SMALL HIGH-REDSHIFT RADIO SOURCE 4C 29.50

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ABSTRACT

The powerful radio source 4C 29.50, which is identified with a quasar at redshift 1.927, has been mapped with a variety of instruments, frequencies, and resolutions. Our highest resolution is 30 mas, corresponding to about 150 pc at this redshift. The projected overall dimensions of the radio source are subgalactic, and the structure is very distorted. There are apparent sudden deflections of a jet emerging from the quasar core, and we propose that these are due to interaction with a dense, clumpy interstellar environment. The great power of the source and the small scales on which the deflections occur yield constraints on the properties of this environment.

Subject headings: galaxies: jets — quasars — radio sources: galaxies

I. INTRODUCTION

The radio source 4C 29.50 is identified with the quasar 1702+298 at a redshift of 1.927 and has been observed as part of a project in progress by the authors, investigating at kpc-scale resolution the radio morphology of quasi-stellar radio sources having $z > 1.5$. From a VLA study by Barthel *et al.* (1985) (see also Barthel 1984), it has become clear that a considerable fraction of luminous, steep spectrum quasars at high redshift cannot simply be classified as extended edge-brightened triple sources (Fanaroff and Riley 1974, Class II). Indeed, a surplus of distorted radio morphologies was detected. The dimensions of several of these distorted radio morphologies were found to be galactic, 4C 29.50 being one of these. The importance of such small, galactic size, steep spectrum radio sources, referred to as steep spectrum cores (SSCs) has been recognized previously (Kapahi 1981; Peacock and Wall 1982), and good examples of their morphologies may be found in Van Breugel, Miley, and Heckman (1984), Fanti *et al.* (1985), and Wilkinson *et al* (1984*b*). Although its morphology is certainly more extended and less complicated than other SSCs, 4C 29.50 might also be classified as such.

A detailed, multifrequency higher resolution study of the above mentioned distorted radio sources at high redshift was conceived by us, and the present paper describes the first results. Given the fact that the angular dimensions of these distant radio sources are generally small, the ideal instruments with which to investigate their morphologies are the VLA in its highest resolution A configuration, the Jodrell Bank Multi Element Radio Linked Interferometer Network (MERLIN) and the sensitive European VLBI Network (EVN). Using these instruments we obtain resolutions between 30 mas and 0\".5 which corresponds to linear resolutions of 150 pc and 2.5 kpc, respectively[2].

4C 29.50 had been observed previously by us with the EVN at 21 cm wavelength and the VLA at 6 cm wavelength (Barthel 1984). The EVN observations revealed the presence of complex compact structure, while the VLA map, at 0\".4 resolution, showed a distorted radio morphology with overall angular size of about 5\". In this paper we present the results of our more detailed high-resolution observations of 4C 29.50. The source properties thus revealed are unusual by the standards of lower redshift sources which have been studied in comparable detail, though they turn out not to be so unusual in the high-redshift environment (Barthel 1984).

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[2] We use $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ throughout.

II. OBSERVATIONS AND RESULTS

The VLA A array 6 cm map of 4C 29.50, taken from Barthel (1984), is reproduced in Figure 1, but with polarization vectors also plotted. Standard observing and reduction procedures were followed, and the angular resolution in the map is 0\".4. The position of the optical QSO (Barthel 1984) is marked. The main source components have been labelled A, B, C, and D. This map shows the following: (1) the basically double source seen on an early Cambridge map (Hooley, Longair, and Riley 1978) is resolved into a colinear triple (A, C, B), with extensive diffuse emission east and south of A, the peak of which has been labeled D; and (2) complex polarized emission is detected at several locations; particularly in component A the polarization structure is peculiar, with the direction of polarization being orthogonal and one side of the component to that on the other.

Higher angular resolution (0\".25) observations were obtained with MERLIN at 18 cm wavelength. All six antennas of the array (Davies, Anderson, and Morison 1980) were in operation, and the data were calibrated using known system parameters. The final map, shown in Figure 2, was produced at Jodrell Bank using the iterative Cornwell and Wilkinson (1981) self-calibration algorithm. At the time of these observations, it was not possible to guarantee accurate amplitude calibration, and from the way the mapping process behaved, it was clear that some baseline-dependent errors had crept in at some stage. The overall effect of this on the map was to introduce a ringlike sidelobe at the 1%–3% level, approximately 0\".8 from the peak of the map. As a result, the morphology of component

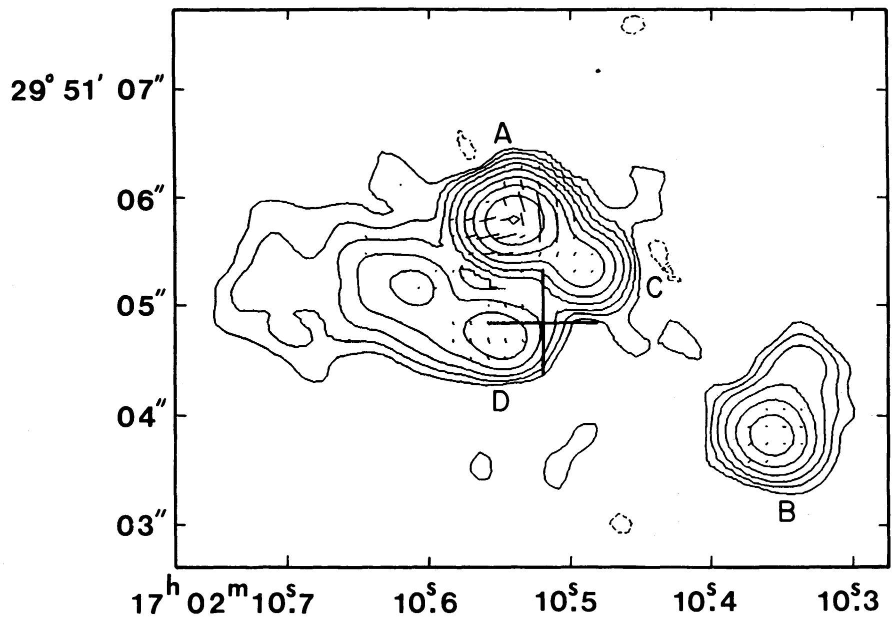

FIG. 1.—4C 29.50, 6 cm VLA. The restoring beam is 0″.45 × 0″.40 in position angle 70°. Contour levels are −0.4, 0.4, 0.8, 1.5, 3, 6, 12, 24, 48, 96% of the peak brightness, which is 238 mJy per beam. The lines represent the *E*-vector of the polarized emission, and the peak polarized intensity is 18 mJy per beam.

C must be considered as possibly seriously distorted, and the low-level structure of component D is suspect. All other features on the map are reliable. Noteworthy are the following: (1) the northern component A is elongated in p.a. 120° and thus may contain substructure; (2) the southern lobe and its northward extension (component B) match the structure from the VLA 6 cm map and the peak shows evidence of resolution; and (3) the diffuse region appears similar to the diffuse "trail" in the nearby subgalactic radio source 3C 305 (component B′ of Lonsdale and Morison 1980—see also Heckman *et al.* 1982).

Our next increment in resolution comes with the VLA 2 cm observations, made with 25 antennas of the instrument in the A configuration. Standard observation and mapping procedures were followed, and the resulting maps (Figures 3*a* and 3*b*) are the most revealing of those we present, due to a fortunate combination of resolution and sensitivity. In Figure 3*a* we have used a 0″.20 × 0″.18 beam to show the diffuse regions of emission to best advantage. We have used the maximum resolution of 0″.12 × 0″.14 in Figure 3*b* to show the compact regions to best advantage. It is found that: (1) component A consists of

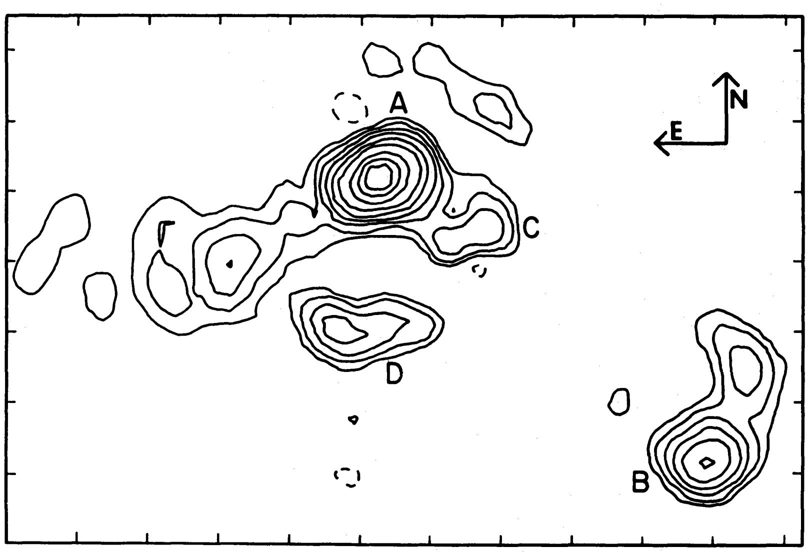

FIG. 2.—4C 29.50, 18 cm MERLIN. The restoring beam is 0″.25. Contour levels are −1, 1, 2, 4, 7, 12, 20, 40, 60, 80% of the peak brightness, which is 326 mJy per beam. The tick marks are spaced at 0″.5 intervals. Note that at the time of the observations, neither MERLIN nor the EVN allowed the determination of absolute positions for the radio maps, thus necessitating the use of relative coordinates as shown in Figs. 2, 4, and 5.

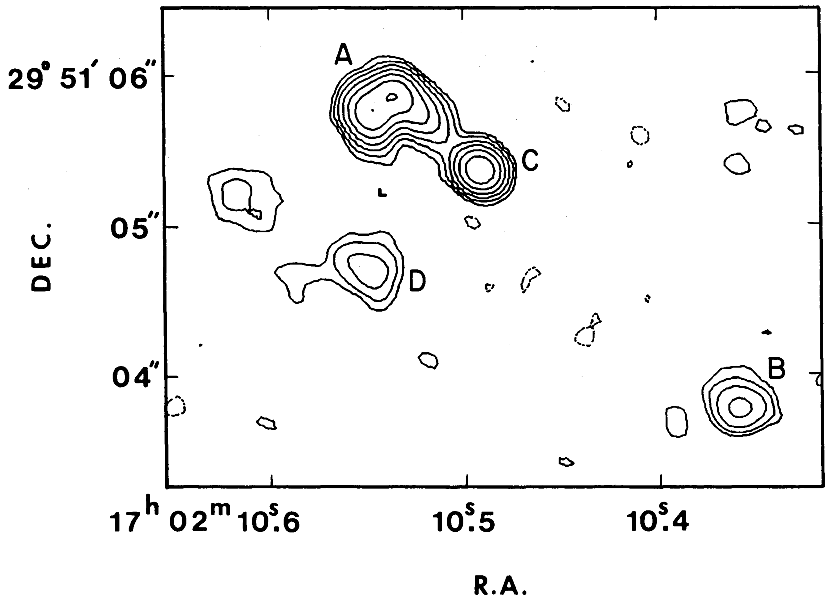

FIG. 3a

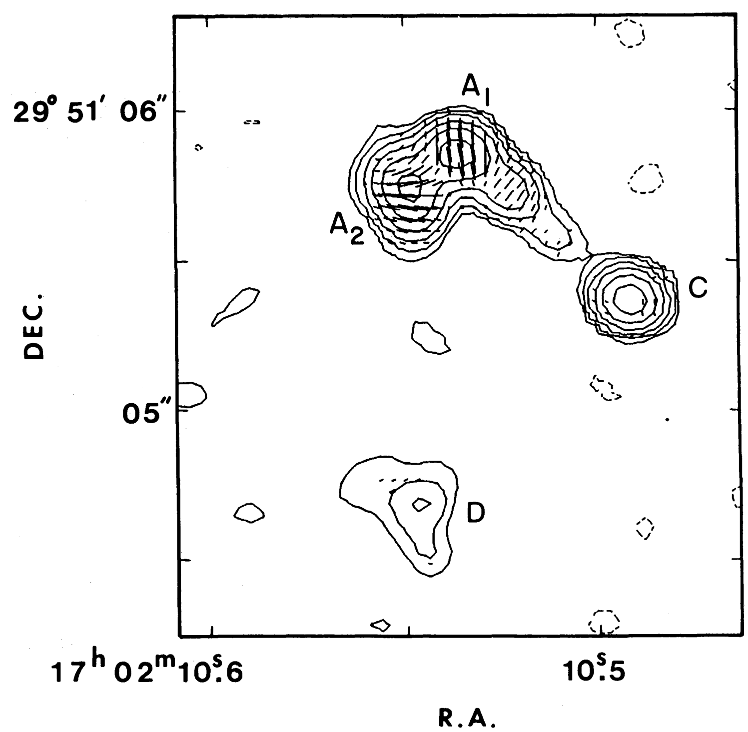

FIG. 3b

FIG. 3.—(*a*) 4C 29.50, 2 cm VLA. The restoring beam is 0″.20 × 0″.18, in p.a. 60°. The contour levels are −1.5, 1.5, 3. 6, 12, 24, 48, 96% of the peak brightness, which is 54.3 mJy per beam. (*b*) Core, jet, and hotspots of 4C 29.50, 2 cm VLA. The restoring beam is 0″.14 × 0″.12, in p.a. 70°. The lines represent the *E*-vector of the polarized emission which has a maximum intensity of 8.4 mJy per beam. The total intensity contour levels are −2, 2, 4, 8, 16, 32, 64% of the peak brighness, which is 48.5 mJy per beam.

two separate components, each with strong linear polarization, but with orthogonal inferred magnetic field directions; (2) labeling these components A1 and A2, we find that A1 is unresolved by our beam, whereas A2 is extended in a north-south direction; and (3) a jet links components C and A1, the former of which we infer to be the core (see below). Ignoring the effects of Faraday rotation at this wavelength (the emitted wavelength is 7 mm), the magnetic field in the jet is longitudinal.

Next, we obtained the MERLIN 6 cm map, with a resolution of 0″.1. This map, shown in Figure 4, was made using five telescopes of the array, and the calibration and mapping procedure were as described for the 18 cm map. Various features referred to in Figures 3*a* and 3*b* are shown in greater detail here: (1) component A1 is still unresolved and must therefore be smaller than 40 mas (200 pc); (2) component A2 is clearly resolved, and the measured dimensions of the peak of A2 from Figure 3*b* agree well with the size from Figure 4. However, on the MERLIN map there is no evidence for the southward extension of the component prominently visible in Figure 3. This is almost certainly due to the surface brightness sensitivity limitations of the MERLIN map, and emphasises the fact that component A2 has a "core-halo" type of structure; (3) there appears to be a prominent knot in the jet, about $\frac{3}{4}$ of the way from C to A1; (4) component C is unresolved and has a flat spectrum ($\alpha_6{}^2 = +0.1$, $S_\nu \propto \nu^\alpha$). Referring to Figure 1, C appears to coincide with the optical QSO nucleus within the errors; we therefore identify this component with the quasar core.

Finally, we obtained an EVN map of 4C 29.50 at a wavelength of 18 cm. The data used in producing this map were taken using standard Mk II equipment (Clark 1973), and the telescope network consisted of the Effelsberg, Dwingeloo, Onsala and Jodrell Bank telescopes. The resulting data were correlated at the Max-Planck-Institut für Radioastronomie, Bonn, FRG. The correlation coefficients were calibrated following Cohen *et al.* (1975), assuming the primary calibrator OQ 208 to be unresolved on all baselines with a flux density of 1.02 Jy and using known system parameters. The final map was produced using CIT VLBI algorithms and is shown in Figure 5. This map has an angular resolution of 30 mas and shows the unresolved core C, the knot in the jet, and component A1. Component A1 is found to be elongated in p.a. 120°, the same as that of the line joining A1 and A2.

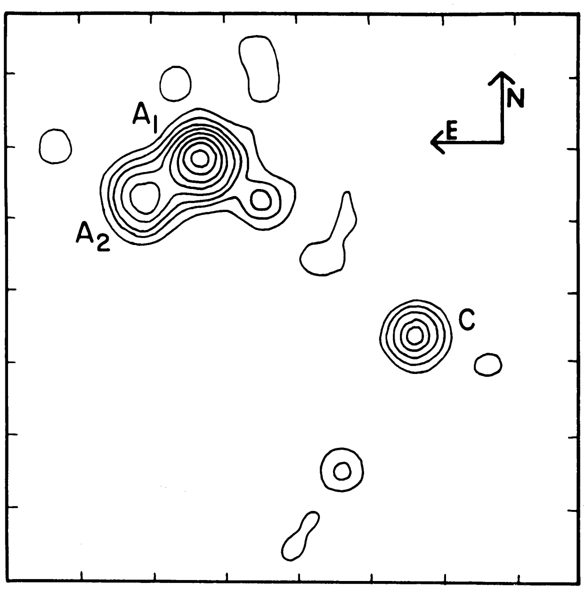

FIG. 4.—4C 29.50, 6 cm MERLIN. The restoring beam is 0″.1, and the contour levels are 4, 8, 12, 20, 30, 40, 60, 80% of the peak brightness, which is 93 mJy per beam. The tick marks are spaced at 0″.2 intervals.

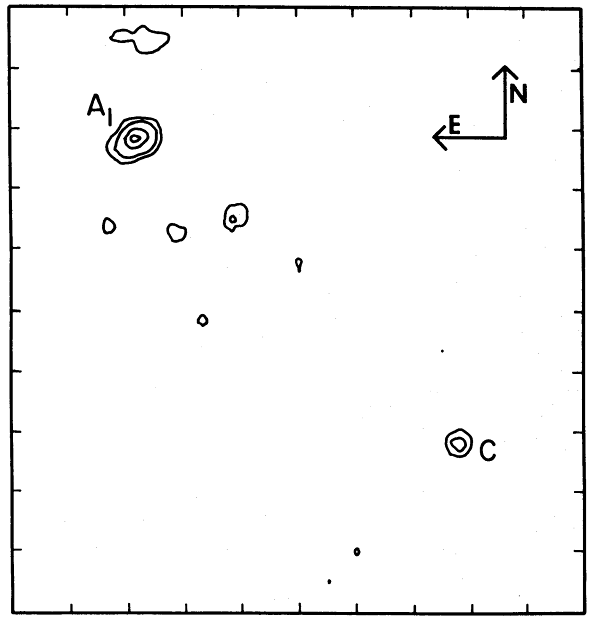

FIG. 5.—Central part of 4C 29.50, 18 cm EVN. The restoring beam is 0″.03. Contour levels are 10, 20, 40, 80% of the peak brightness, which is 156 mJy per beam. The tick marks are spaced at 0″.1 intervals.

The observational parameters obtained in this high resolution study of 4C 29.50 are summarized in Table 1.

It is not easy to derive accurate spectral indices for the components, due to differing resolutions and $u - v$ coverages. However, an attempt has been made, and the the results of our calculations are given in Table 2. We estimate that the errors in the spectral indices are generally ~0.1, but they may be somewhat higher for the jet and component D. We have also derived limits on the depolarization parameters of the various components, and give estimates of the minimum internal pressure in components A1, A2, and the diffuse component. It is not possible to distinguish between the spectral indices of A1 and A2, and the rotation measure of the A1–A2 hotspot complex is about 70 rad m^{-2}. The latter value is in agreement with the overall source value as listed by Simard-Normandin, Kronberg, and Button (1981).

TABLE 1

OBSERVATIONAL PARAMETERS

Instrument	Wavelength (cm)	Resolution (arcsec)	Month and Duration of Observation
VLA	6	0.4	1982 Aug; 10 minutes
MERLIN	18	0.25	1983 Feb; 20 hr
VLA	2	0.15	1982 Aug; 10 minutes
MERLIN	6	0.1	1982 Jun; 18 hr
EVN	18	0.03	1982 Apr; 11 hr

TABLE 2

MEASURED AND CALCULATED COMPONENT PARAMETERS[a]

Component	θ_{maj} (arcsec)	θ_{min} (arcsec)	Position Angle (degrees)	Flux Density 18 cm (mJy)	6 cm (mJy)	2 cm (mJy)	$\alpha_6{}^2$	p_{min} (dyn cm^{-2})	$\lambda_{1/2}$ (cm)
A1	0.03	0.02	120	250	100	45	−0.8	7×10^{-7}	≥25
A2	0.09	0.06	20	...	...	55	...	3×10^{-7}	≥25
A1+A2	...	...	...	630	300	100	−1.0	...	...
B	0.25	0.17	130	140	56	18	−1.0	2×10^{-8}	≥5
C	<0.02	<0.02	...	50	40	46	+0.1	...	...
Jet	...	...	...	...	~45	23	~ −0.6	...	≥10
D	~0.5	~0.3	~90	~80	~30	~10	~ −1.0	~6×10^{-9}	...
Trail	~2.0	~0.5	~120	~150	~60	...	...	~10^{-9}	...

[a] Radio window was taken from 10 MHz to 10 GHz; cylindrical geometry, unity filling factor, energy equipartition between electrons, protons and magnetic field, and random pitch angle distribution were assumed.

III. DISCUSSION

Despite the very powerful nature of this source, its morphology does not fit the Fanaroff and Riley (1974) type II classification, which requires a basically double, edge-brightened structure. Several other powerful sources have also been noted for their failure to conform to this classification scheme, which was formulated when only relatively large, nearby sources had been observed with sufficient angular resolution to delineate their structure. The powerful steep spectrum core (SSC) source 3C 380 (Wilkinson *et al.* 1984*a*) is a good example of a source whose luminosity lies well above the FR type II threshold, yet whose morphology is complex and not obviously edge-brightened. Other violators of the previously well established rule can be found in profusion amongst the small, steep spectrum high redshift sources under investigation in the present projects (Barthel 1984; Barthel and Lonsdale 1985), and it seems that powerful sources of subgalactic dimensions may form a complete separate class of objects which are not subject to the generally accepted morphological classifications of larger sources. This is hardly surprising in view of the markedly different environments in which radio sources of sub and supergalactic dimensions are probably embedded, and the discussions of Van Breugel, Miley, and Heckman (1984) and Wilkinson *et al.* (1984*b*), concerning strong interactions between the radio jets and a dense rotating interstellar medium are very likely of relevance.

The morphology of the jet and double hotspot in the VLA 2 cm map strongly suggests a U-turn in the flow toward the south. This is in part due to smearing of several features together by the 0''.14 beam (as indicated by the MERLIN 6 cm map and the EVN 18 cm map), but there can nevertheless be little argument that the ridge line from the core through the double hotspot curves through an angle of 150°. This curvature occurs abruptly in two very localized areas (the hot spots). The VLA 2 cm map just happens to have a resolution which is ideal for picking up the elongation of A2, as well as underemphasizing the discreteness of the hot spots. The result is that the curvature appears to be unrealistically smooth. However, the fact that the inferred magnetic field direction follows this ridge line accurately through all 150° from the jet to A2 is striking. Evidence has been steadily mounting to support the idea that double hot spots such as that in 4C 29.50 are the result of a jet deflection by a dense obstacle (Laing 1982, 1984*b*; Lonsdale 1984; Lonsdale and Barthel 1984, 1985) and, as pointed out in the latter paper, 4C 29.50 is a good example of a source for which the deflection hypothesis explains the observations well.

Next, we note that the weak northward extension from component B (seen to best advantage in Figs. 1 and 2) lends the source a slight degree of rotational symmetry about the core component C. Such symmetry in the diffuse regions of other, more nearby subgalactic sources has been cited as evidence that radio plasma is being swept away from hotspots and other bright regions by galactic rotation in the interstellar gas (Heckman *et al.* 1982; Wilson and Ulvestad 1982; Pedlar *et al.* 1983; Van Breugel *et al.* 1984). As previously mentioned, there is some similarity between the appearance of the diffuse regions in 4C 29.50 and 3C 305. For the latter source, associated with a nearby galaxy, a detailed investigation of the thermal–nonthermal relationships led Heckman *et al.* (1982) to infer interaction between radio jets and the emission-line gas.

Given the apparent curvature in the structure of the northern lobe, and the structure and position of the extended emission, we propose that interaction between the radio jet and a dense interstellar medium is responsible for the morphology of 4C 29.50. It should be emphasized here that this model is based on two assumptions: (1) we assume that radio emission occurs at places of lossy energy transport, and that efficient energy transport is characterized by the absence of radio emission along a beam path; although this assumption needs confirmation in other wavelength bands, we now adopt it as a working hypothesis; (2) we assume that 4C 29.50 is not far from the plane of the sky, i.e., that the apparent curvature in the jet is not caused by projection of an otherwise small intrinsic bending (e.g., Gower *et al.* 1982); this assumption is supported by the fact that the actual bending is localized in a region smaller than about 150 pc (A1), which is highly polarized (~20%): jets with a longitudinal field which are viewed end-on are unlikely to appear highly polarized.

The following model is proposed. Material is ejected from the quasar (component C) in a jet to the northeast. After travelling a few kpc with little interaction between the jet material and the surrounding medium, the jet strikes an obstruction and is deflected sharply to the east. Strong shocks and turbulence associated with the abrupt change in direction of the supersonic jet result in intense radio emission, thus producing A1. The presumed nature of the obstruction is a density enhancement, such as an interstellar gas cloud. After the deflection, the flow is less energetic and well collimated and is thus more easily influenced by the external medium than before. It is deflected again after traveling only about 1 kpc in its new direction and gives up nearly all its bulk kinetic energy. This generates component A2, and a weak flow continues on to the south to form the southern component D. At both A1 and A2, the radio emitting regions form after the shocks and redirection, and the magnetic fields in the hotspots are sheared to be primarily in the direction of the post-interaction flow. Relativisic electrons from the hot spots diffuse into the surrounding plasma, thus forming the diffuse regions of emission, which are in pressure balance with the ambient medium. Buoyancy forces and probably galactic rotation carry these diffuse emitting regions away from the hotspots, in the same way as is inferred to occur for the similar diffuse regions in 3C 305 (Lonsdale and Morison 1980; Heckman *et al.* 1982). Although the details of the above picture are necessarily uncertain, we think it is probable that the basic interaction processes as described above are responsible for the observed characteristics of this source.

We now briefly discuss the feasibility of the model proposed above and consider a few simple consequences of the scenario. 4C 29.50 is close to the top end of the luminosity distribution of steep spectrum radio sources, with an integrated radio luminosity of about 2×10^{45} ergs s^{-1}. Most of this power originates on one side of the source, and given the normal estimates of the efficiency of conversion of bulk kinetic energy to synchrotron radiation of $\leq 10\%$ (e.g., Begelman, Blandford, and Rees 1984), the jet power L_j on this side of the core must by $\geq 2 \times 10^{46}$ ergs s^{-1}. Referring to our first assumption, if all of this energy is being dumped in the surrounding medium, a few kiloparsecs from the nucleus, this must have severe consequences for the structure and energetics of the outer reaches of the presumed galaxy. For a given jet kinetic energy flux (power) the momentum flux is minimized for $v_j = c$ (see, e.g., Bridle and Perley 1984). Momentum conservation at A1 therefore implies a minimum rate of momentum transfer into the interstellar medium of $L_j/c \approx 7 \times 10^{35}$ g cm s^{-2}. Based on the overall source size of almost 10^5 lt-yr, we assume that the radio source has been active for at least 10^6 yr, and hence derive that the total momentum exchange with the interstellar medium corresponds to the acceleration of 10^8 $M_\odot$ to a velocity of 1000 km s^{-1}. While we have no idea how large a proportion of the interstellar gas content participates in interactions with the jet, it seems clear that the dynamical consequences for the ISM of such a powerful radio source of subgalactic dimensions can be far-reaching.

Is it reasonable to assume that the interstellar medium is substantial enough to sustain an interaction at the required level for long enough to contain and deflect the jet, as proposed above? The arguments of Lonsdale and Barthel (1984), concerning the presence of double hot spots, constrain the rate of advance of the primary hot spot due to the evidence (morphology, magnetic field direction) for directed flow between the primary and secondary hot spot. The flow can only exist while the primary is close to the secondary, and it must stay close for as long as it takes to build up the observed internal energy in and around the secondary hot spot. In the case of 4C 29.50, the total minimum internal energy of A2 is about 6×10^{57} ergs, and assuming a maximum energy supply rate of 10^{46} ergs s^{-1} from A1 (see above), we deduce an upper limit to the forward velocity of A1 of about $0.2c$. The usual ram pressure balance condition can be applied, using the minimum internal energy density of A1 which corresponds to a pressure of about 10^{-6} dyn cm^{-2}. We find that the ISM (around A1) must have a minimum density of 3×10^{-2} cm^{-3}, which is quite normal for nearby radio galaxies (e.g., Mirabel 1982). Note, however, that this is a lower limit, and the true value could be several orders of magnitude higher. The question of whether the conditions necessary for a deflection of the jet through 90° can be maintained for the required tens of thousands of years is more difficult. An essential part of a jet deflection model is that strong density gradients exist in the external ISM. If the diffuse regions in 4C 29.50 are in static pressure balance with the external medium, this medium may well contain cool clouds of density 10^3 cm^{-3} or more, which are responsible for the jet deflection. The problem of jet deflection in general is addressed at some length in Lonsdale and Barthel (1985).

We finally consider the polarization behavior of 4C 29.50. One of the key arguments for proposing a jet–ISM interaction in 3C 305 (Heckman *et al.* 1982) was the anticorrelation between the presence of optical narrow-line emission and radio polarization. The gas responsible for the line emission is believed to be directly responsible for Faraday depolarization of the radio emission. However, we find no significant depolarization in the hotspots of 4C 29.50. The requirement in any jet deflection model, that dense thermal matter is present at the deflection site, may at first glance indicate a problem, considering our failure to detect any depolarization. However, three points should be noted in this regard. First, as pointed out by Laing (1984*a*), the presence of many reversals in the line of sight magnetic field can greatly reduce the expected amount of depolarization, either from an inhomogeneous screen, or from a slab-type model of the emitting region itself. Second, given the fact that the EVN map (Fig. 5) indicates an angular size on the 10 mas scale for A1, our VLA resolution may not be sufficient to pinpoint the actual location of the deflection. The high percentage of polarized emission may reflect the periphery of the deflecting region, similarly as is the case in 3C 305, where polarization percentages exceeding 30% were detected. Finally, the covering factor or column density of the ISM could simply be insufficient to substantially depolarize the radio emission, at the high emitted frequencies of our observations. It is interesting to note, however, that the overall rotation measure for 4C 29.50 ($b^{II} = 35\overset{\circ}{.}1$) is quite high in comparison with nearby sources (Simard-Normandin, Kronberg, and Button 1981), probably indicating some Faraday rotation local to the source. We detect similar RM values in both A1 and A2, suggesting a Faraday screen associated with the radio source.

In summary, due to the high redshift of the source, the lack of depolarization does not yet pose extreme difficulties for the proposed model of jet deflection by interstellar gas clouds, but we only have a lower limit for $\lambda_{1/2}$, and lower frequency polarization measurements would be useful. Both MERLIN and VLBI arrays should soon have the capability for such measurements.

IV. CONCLUSIONS

The powerful distant radio source 4C 29.50 has been found to exhibit subgalactic dimensions and a distorted morphology. Interaction of a radio jet with a dense interstellar medium can explain the observed morphology. We propose a model of the radio source involving repeated deflections of the powerful radio jet. This model is supported by both the morphology and the polarization characteristics of the jet and hotspots. From the energetics of the radio source, we infer a minimum density for the interstellar medium close to the hot spots of $\sim 3 \times 10^{-2}$ cm^{-3}, although a collision of the jet with a cloud of higher density than this may be required to provide plausible longevity for the observed morphology. Our arguments illustrate the potential use of detailed radio observations of high-redshift sources as tools with which to probe the properties of early epoch galaxies. To further investigate the proposed interaction phenomena, both optical spectroscopy and deep imaging would be extremely useful.

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