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THE RADIO STRUCTURE OF 3C 279

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ABSTRACT

Radio maps of the quasar 3C 279 have been made with resolutions between 0"06 and 3"5 at wavelengths of 1.3, 2.0, and 6 cm. At arcsecond resolutions, the source is a simple double with a component separation of 11"2 in P.A. −35°. At higher resolutions, the northern component resolves out while the compact component consists of an unresolved flat-spectrum core with a jet extending 4"7 in P.A. 205°. The jet is clearly resolved into numerous separate knots—in particular, two very compact knots are located 0"095 and 0"58 from the core. The jet displays notable curvature.

There is no measurable Faraday depolarization in the resolved regions of the source, but a small (~25°) rotation of the plane of the polarized emission is found in the unresolved core between 2 and 6 cm. The projected magnetic field is generaly aligned parallel to the jet, and the spectral index of the jet emission steepens with increasing distance from the core.

The presence of discrete components so well aligned invites an interpretation of repeated ejection from the core along a position angle which is highly stable over the lifetime of the source. The diffuse northern component does not easily fit into this interpretation, and its relation to the rest of the source is not clear.

Subject headings: polarization — quasars — radio sources: general

I. INTRODUCTION

The radio source 3C 279 is identified with a quasar of redshift 0.538 (Sandage and Wyndham 1965; Burbidge and Rosenberg 1965). The optical emission of 3C 279 is highly polarized (nearly 18% in P.A. 176°; Kinman 1967) and is highly variable, with m_v fluctuating from a low level of ~18 to as high as 11.3 over a 20 year interval (Eachus and Liller 1975). Changes in visual magnitude of 0.25 in times of less than a day have also been noted (Oke 1967). 3C 279 is also a luminous X-ray source (Tananbaum *et al.* 1979).

At radio wavelengths, Lyne (1972) used the method of lunar occultations to show that 3C 279 consists of three components, denoted by him as A, B, and C. The B components appeared to be steep spectrum and extended, located 11" in P.A. 330° from the core for A, and 5" in P.A. 210° for B. Lyne's data were not sufficient to map the components in any detail.

3C 279 is of particular interest because on the milliarcsecond (mas) scale (Cotton *et al.* 1979; Pauliny-Toth *et al.* 1981), it contains components which are expanding superluminally from the core. It is thus one of the six objects known to possess this characteristic (Cohen and Unwin 1982). The VLB observations of 3C 279 show that two different components were (circa 1972–1975) expanding at ~0.5 and ~1.0 mas yr^{-1} giving an apparent expansion velocity of ~20 to ~40 times the speed of light ($H_0 = 50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$)—so that 3C 279 is the "fastest" known of the superluminal sources.

Here we present maps of 3C 279 made from data taken with the VLA at 6, 2, and 1.3 cm. The resolutions obtained span the range from 3"3 to 0"06. These maps show the detailed structure of this source in both total intensity and polarization.

II. OBSERVATIONS

The observations of 3C 279 were made with the VLA at 1.3, 2, and 6 cm (22485, 14965, and 4885 MHz) in the C and A configurations on 1982 January 24/25 and February 15/16, respectively, while the source served as a calibrator source for observations of Saturn (I. de Pater and J. R. Dickel, in preparation). These configurations give maximum baselines of 3.5 and 35 km, respectively, and combined with the different frequencies give a wide range of possible map resolutions. The flux density calibration was based on the scale of Baars *et al.* (1977). The derived core flux densities of 3C 279 were found to be 10.6, 11.8, and 11.0 Jy at 1.3, 2, and 6 cm. There was no measurable change in flux density of the core at any frequency between the two observing dates. These flux densities are believed to be accurate to within 10%, 5%, and 3% at the three observing frequencies.

Since the initial phase calibration was based on 3C 279

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itself, the absolute positions of the structure are only as accurate as the assumed core position—about 0″.05. The position of the core of 3C 279 was assumed to be $\alpha = 12^h53^m35^s.838$, $\delta = -05°31'08''.04$ (Perley 1982). Further calibration proceeded via algorithms available with the AIPS package provided by NRAO. In particular, the self-calibration technique of Schwab (1981) was extensively used to improve the dynamic range of the maps. The final maps were cleaned in the standard way to remove the effects of beam sidelobes (Högbom 1974; Clark 1980).

III. RESULTS

Figure 1 shows a 3″.3 resolution map of 3C 279 at 6 cm. There are two dominant components, labeled A and B in the figure, corresponding to the nomenclature of Lyne (1972). Component A has an optically thin spectrum with power-law index of -0.95 and is well resolved at this resolution. At higher resolutions, it is completely resolved out and will not be shown in any of the subsequent maps. Component B is dominated by the unresolved core and has a flat, optically thick spectrum between 6 and 1.3 cm. It contains a short projection seen in P.A. ~210°. This projection (which is optically thin) is the jet and corresponds to Lyne's component C.

The highest resolution available to the VLA at 6 cm is 0″.40. Our map of 3C 279 at this resolution is shown in Figure 2. The jet is now clearly resolved into a number of knots which are arranged along a line extending out 4″.7 from the core in P.A. ~206°. This angle is only slightly different from the measured angle of the milliarcsecond jet (218°) as given by Cotton *et al.* (1979). (Both Cotton *et al.* 1979 and Pauliny-Toth *et al.* 1981 have 180° ambiguities in their maps. We have assumed that the VLB jets are directed to the southwest, rather than to the northeast.) The knots have been denoted by letters from D to G as they are found farther from the core. The missing knot C will appear in subsequent maps. It is clear from this map that the knots are not perfectly collinear. The measured position angles for the E, F, and G knots are 206°, 208°, and 205°. These differences are significant as the measurement error is about 1°. The inner knots (C and D) are also not collinear with the mean P.A. of the jet (see below).

The jet is 10%–20% polarized at 6 cm at all points with some indication that the polarization is higher on the edges, especially near knot E. The observed plane of polarization is the same at all frequencies for all points in the jet, so there is no evidence for Faraday rotation. Thus, addition of 90° to the observed electric vector position angle will give the projected direction of the source magnetic field. The result of this operation is shown in Figure 2*b*. No correction has been made for foreground Faraday rotation as this correction is only 3° at 6 cm with the listed rotation measure of 15 rad m^{-2}

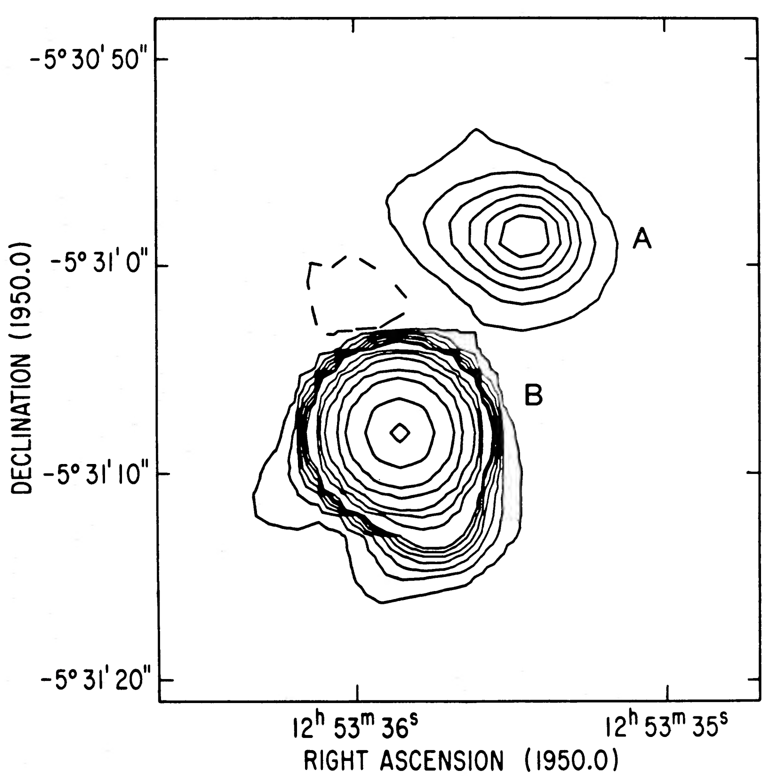

FIG. 1.—Map of 3C 279 at 6 cm with 3″.3 resolution. Contour levels are at −0.1, 0.1, 0.25, 0.4, 0.55, 0.7, 0.85, 1.0, 2.0, 3.0, 5.0, 10, 20, 50, and 90% of the peak brightness of 10.9 Jy per beam. Negative values are denoted by dashed lines.

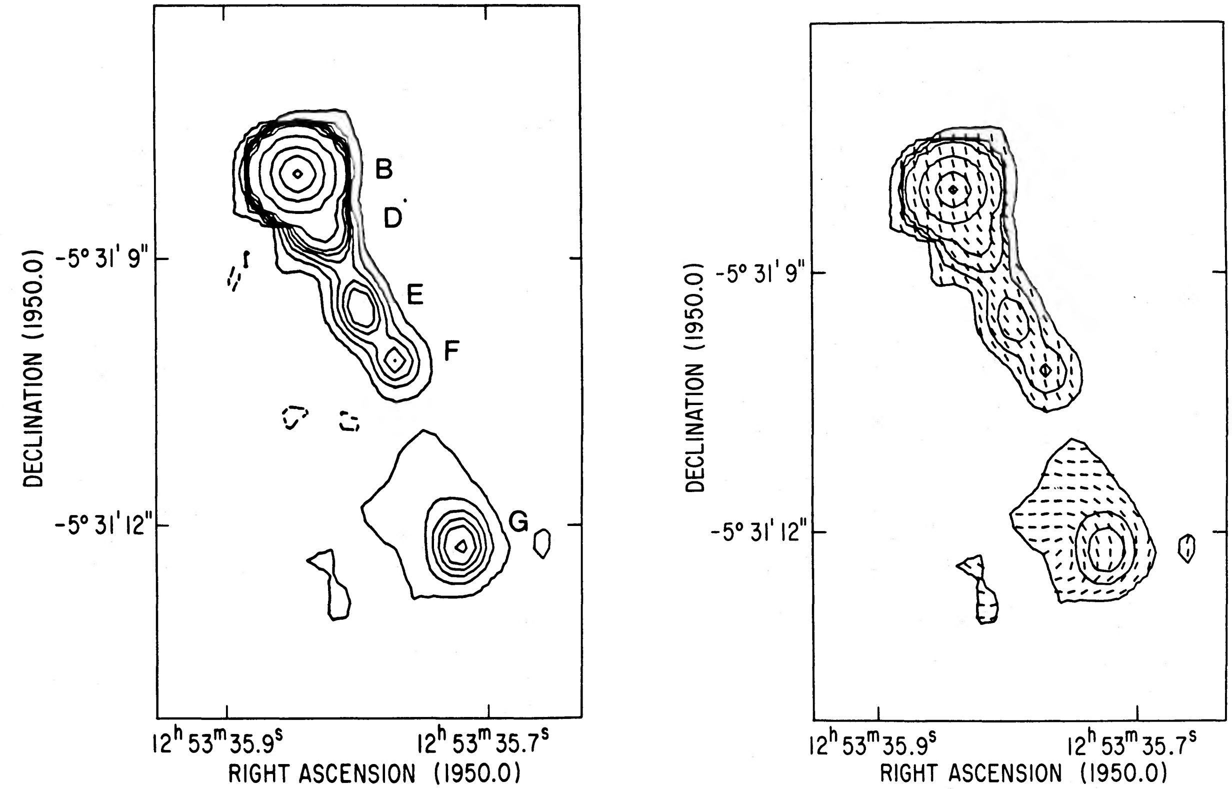

FIG. 2a FIG. 2b

FIG. 2.—(*a*) Map of 3C 279 at 6 cm with 0.″40 resolution. Contour levels are −0.05, 0.05, 0.15, 0.25, 0.35, 0.45, 0.6, 1.0, 5.0, 20, 50, and 90% of the peak brightness of 10.6 Jy per beam. (*b*) As in Fig. 2*a*, with the superposed directions of the projected magnetic field. Contour levels are 0.05, 0.2, 0.4, 1.0, 10, 50, and 90% of the peak brightness of 10.6 Jy per beam.

(Simard-Normandin, Kronberg, and Button 1981). The projected field is clearly longitudinal—along the jet—everywhere except in parts of knot G. Here the brighter emission displays longitudinal polarization, but the northern and southern extremities show significant deviations from this direction. The predominantly longitudinal field is a general characteristic of all milli-arcsecond jets found in D2 sources (R. A. Perley, E. B. Fomalont, and K. J. Johnston, in preparation).

The map of 3C 279 at 2 cm is shown in Figure 3 with 0.″11 resolution. The knot denoted D is now resolved and is centered 0.″58 at P.A. 208° from the core component. Note that this knot is resolved on the side opposite from the core. Subsequent observations at 2 cm with the A array confirm this feature. A 1.3 cm map with 0.″060 resolution is shown in Figure 4. The core has been removed from this map in order to show the appearance of yet another knot, only slightly removed from the core. This knot is denoted C and is located 0.″095 from the core in P.A. 215°. Note that this knot's position angle is the closest to that of the VLB jet as measured by Cotton *et al.* (1979). There is no evidence of any other knots. However, it is doubtful that structure within 0.″050 of the core could be separated unambiguously from the core.

As mentioned above, the jet is modestly polarized at all observed frequencies, and there is no evidence of depolarization anywhere in the jet. The core, however, behaves differently, showing 2%–3% polarization at 6 cm (higher at higher frequencies), with significantly different position angles of the electric vector at different frequencies. At 2 and 1.3 cm, the apparent P.A. is 82°, while at 6 cm the P.A. is 105°, a difference which is far greater than the measurement error. We cannot, however, infer the difference to be due to depolarization as the core is known to be composed of optically thin and optically thick components, each with different total and polarized flux characteristics as a function of frequency.

There is evidence of spectral steepening towards the end of the jet. The inner knots of the jet have a spectral index of −0.75, while the outer knots have spectral indices of −0.92 and −1.11 for F and G. The estimated error (1 σ) is ~0.1 in these measurements of spectral index. There is no evidence for spectral steepening in the jet as a function of frequency between 6 and 1.3 cm.

IV. DISCUSSION

Our data show that in most respects the structure of 3C 279 is fairly typical of the D2 or asymmetric class of double radio sources. This class was first defined by Miley (1971) to be distinct from the familiar double

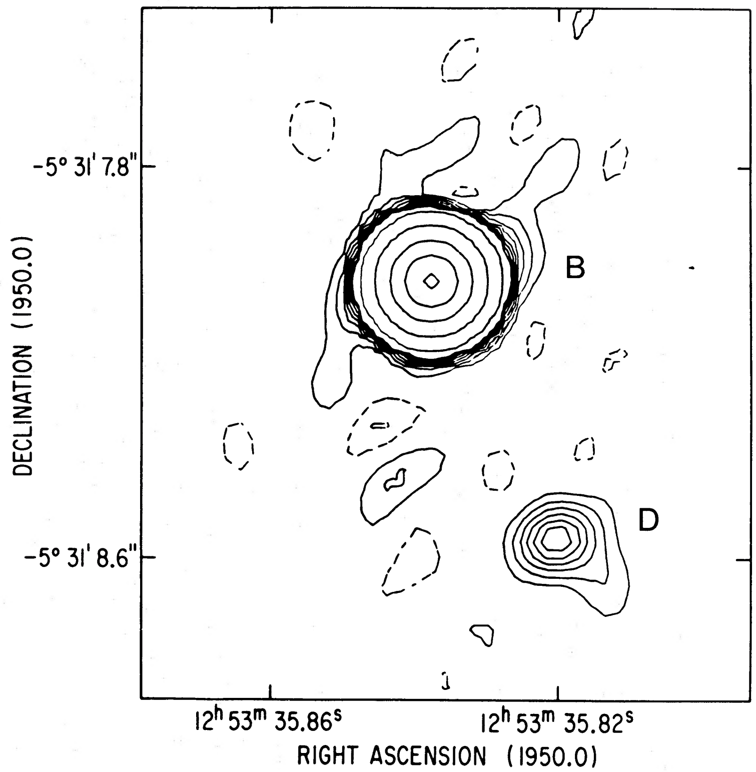

FIG. 3.—Map of 3C 279 at 2 cm with 0".11 resolution. Contour values are −0.05, 0.05, 0.10, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 1.0, 5, 20, 50, and 90% of the peak brightness of 11.8 Jy per beam.

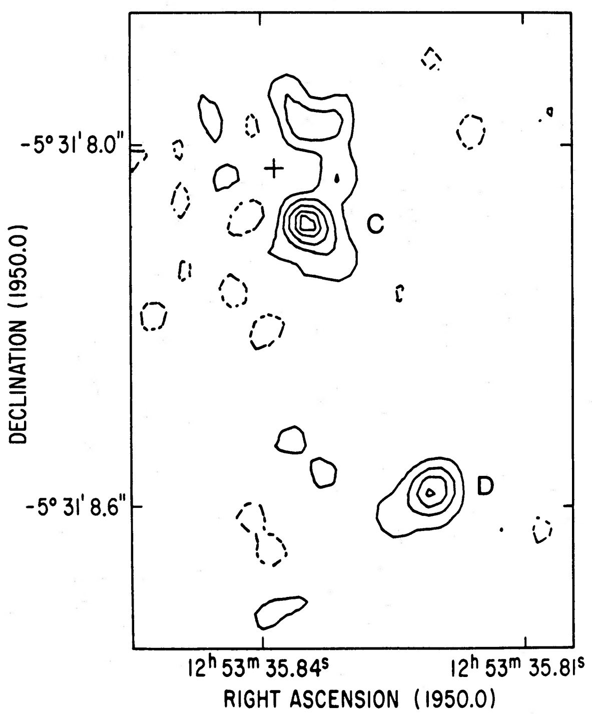

FIG. 4.—Map of 3C 279 at 1.3 cm with 0".060 resolution. The unresolved core has been removed to reveal the innermost knot, denoted C. The contour levels are −20, 20, 40, 60, 80, and 95% of the peak brightness of 25 mJy per beam. The position of the core is indicated by a plus sign.

sources (D1) characterized by two optically thin lobes straddling the identified optical galaxy. The D2 class differs in that one lobe, or component, is optically thick and identified with the optical object, while the other is an optically thin component. Generally there is only one optically thin lobe identified with the source, so D2 sources are usually considered to be asymmetric.

3C 279 is classified as a D2 source because of the dominant flat spectrum core coincident with the optical quasar. It is asymmetric only in that at a given resolution, the dominant secondary brightness is predominantly found on one side of the core. What makes 3C 279 unusual is that the predominant secondary at low resolution is not the predominant secondary at high resolution. As our maps show, at low resolutions (scales greater than 3"), the A component dominates, while the jet is hardly visible. At high resolutions (scales less than 1"), the A component vanishes (effectively), while the jet, with its many knots, is the dominant optically thin structure. This disparity of structure, while most evident in 3C 279, may be found in other core-dominated objects.

Recently, high dynamic range observations of D2 sources (Perley, Fomalont, and Johnston 1982; Browne *et al.* 1982*b*; Schilizzi 1982) have shown that they are often, and perhaps always, accompanied by considerable extended structure on both sides of the core. Thus, this class of sources may be asymmetric only in the brightness ratios of the fluxes of the optically thin components.

The striking differences between the D1 and D2 classes would suggest that these radio sources are fundamentally different. However, there may be only one class of sources, differing in appearance because of geometrical effects associated with relativistic motion of components of the structure. Such a unified scheme has been postulated by Perley, Fomalont, and Johnston (1981, 1982), and by Browne *et al.* (1982*a*). In this scheme, it is presumed that all strong radio sources contain two optically thin lobes, a core which is coincident with the optical source, and jets which link the core to the lobes. It is further presumed that at least in the vicinity of the nucleus, the jets flow with relativistic velocities. A small fraction ($\sim\theta^2/2$) of sources will be oriented so that the jet is aligned within an angle θ to the line of sight. The flux density received from the core and jet is then enhanced by the Doppler effect by a factor $\gamma^{-3}(1-\beta\cos\theta)^{\alpha-3}$, where $\gamma=(1-\beta^2)^{-1/2}$, $\beta=v/c$, and θ is the angle between the jet motion and the line of sight (Kellermann and Pauliny-Toth 1981). This function can exceed 10^4 if β exceeds 0.995. This flux enhancement is enough to reduce the relative contribution of the receding components of the normally present double structure below the noise in maps whose dynamic range is less than the enhancement factor. By this model, the D2 sources appear core-dominated simply because they contain jets aligned close to the line of sight. Observations of sufficiently high dynamic range and sensitivity should reveal two optically thin extended components lying near or perhaps around the core. Recent observations made by the VLA (R. A. Perley, E. B. Fomalont, and K. J. Johnston, in preparation), and WSRT (Schilizzi 1982), show that all the superluminal sources except 3C 273 contain considerably more structure than the arcsecond jets.

This model automatically explains the superluminal motion of the milli-arcsecond jets. The apparent expansion of motion is amplified by finite light-travel effects to be $\beta_{\rm app}=\beta\sin\theta/(1-\beta\cos\theta)$. In order to obtain high apparent expansion, the superluminal sources must be aligned close to the line of sight. This alignment will also give the tremendous flux enhancement needed to cause D1 sources to appear as D2. Thus we expect most D2 sources to show superluminal motion as well as faint diffuse structure.

At a given resolution, the brightness asymmetry of 3C 279 is fairly large, exceeding 20:1 between the jet and the missing "counterjet." Because the apparent super luminal motion of the milli-arcsecond components is so high, application of the relativistic model predicts that the small-scale jet must lie within 5° of the line of sight. With such a small angle, the expected brightness ratio between jet and counterjet is very high. Even jet velocities of $\beta\cos\theta=0.7$ will give flux density ratios of order 500:1 between approaching and receding components. So even with considerable deceleration of the motion of the jet, the lack of an observable arcsecond counterjet is not surprising. The combination of such a small inclination angle and modest redshift makes the arcsecond jet of 3C 279 of rather extreme length—$\sim$300 kpc. This is the largest of the superluminal sources. Generally, the D2 objects are not larger than D1 sources when modest ($\sim 10°$) inclinations are presumed.

The alignment of the knots labeled C to G strongly suggests a mechanism of repeated ejection from the core of 3C 279. The fact that the observed arcsecond position angle lies within the errors of the milli-arcsecond jet supports this hypothesis. Given that the milli-arcsecond motion is known to be superluminal and assuming outward motion of the knot, we feel that the arcsecond jet of this source is the manifestation of past activity of the core. The small misalignment in the knot position angles can be explained by assuming the jet precesses through a small angle much in the manner of SS 433 (Hjellming and Johnston 1981).

This hypothesis fails to directly explain the anomalous A component. We can imagine one of three explanations for this diffuse component. First, it could be the result of a greatly decelerated blob ejected from the (hypothetical) counterjet which itself is invisible over most of its length due to its relativistic motion. Second, it could be the actual end of the visible jet but which is seen on the "wrong" side of the core due to a combination of slight curvature and extreme projection. Third, it could perhaps be a lobe of the presumed large-scale underlying structure postulated by the unified scheme to be present in all D2 sources. These explanations are all somewhat unsatisfying. First, if the A component is the result of the counterjet, why can we not see any other feature of that jet? One would expect to see part of the counterjet leading into the component. Second, a very remarkable combination of source inclination and structure is required to provide such an apparent structure. However, since 3C 279 is such an extremely superluminal source, the inclination is probably a fact, and a very small curvature is all that is required to make a knot appear highly displaced. One then expects at least a tenuous connection between knots A and G but there is no evidence for this. Third, if knot A is really a "lobe," where is the other lobe? Every radio source is hypothesized (in this unified scheme) to have two symmetrical lobes, found on each side of the core. This does not seem to be the case in this object.

Thus, although the jet appears to admit a rather simple explanation, the presence of the diffuse A component does not seem to fit into a simple picture. If this source is actually a "double in disguise," higher dynamic range maps will be necessary to reveal remaining structure.

The discovery of very compact knots close to the nucleus in 3C 279 (knots C and D) raises the possibility of making an important measurement. The knots seen moving outward from the nuclei in VLB maps can only be traced a short distance before their expansion lowers the brightness below the sensitivity limits. Because these knots are moving through a galactic medium, they are expected to decelerate due to ram pressure acting at the leading surface. No deceleration of any knot has yet been observed by VLB. The knots in 3C 279, being very close to the nucleus of a source with very high apparent expansion, might still be expanding at a measurable rate. The fact that these knots are bright and compact will aid such a measurement. Observations of this source with the goal of measuring the knot motion have been started. However, even if the expansion is at the rate of the milli-arcsecond components (0.5 mas yr^{-1}), no definitive measurement of the motion of the C or D knots can be made for some years.

V. SUMMARY

The radio emission from 3C 279 is shown here to be comprised of three basic components as first revealed by Lyne (1972). There is a flat spectrum, compact core component (B) which is coincident with the optical object, a diffuse steep spectrum region (A), and a thin jet which is comprised of six knots aligned near P.A. 205° and extending out 4ʺ7 from the B component. The magnetic field in the jet is aligned parallel to the extension of the jet, and there is no measurable Faraday rotation or depolarization of the emission from the jet. The alignment of the jet coincides (within the errors) with the direction of the milli-arcsecond jet, and a light ($<10°$) transverse oscillation in the jet is seen.

The simplest interpretation is that the jet represents past outburst of the core via a collimator which has good long-term stability. The A component does not easily fit into this picture as it is not aligned with the jet knot components, nor is it morphologically similiar to the knots.

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