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EXTENDED RADIO SOURCES AND ELLIPTICAL GALAXIES
II. A SEARCH FOR RADIO CORES USING THE VLA

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ABSTRACT

Four antennas of the Very Large Array (VLA) have been used at 4.9 GHz to search for small-diameter radio components in extended radio sources whose optical identifications are uncertain. Thirteen of 21 systems studied have small components ($\lesssim 4$ arcsec in extent) with flux densities ≥ 5 mJy. Eleven of these small components are coincident with galaxies and thus confirm or establish the identification of the sources. In three systems previously identified with close pairs of galaxies (or double-nucleus systems), the position of the radio core lies within the nucleus of one of the two galaxies. The probability that a small-diameter radio source will be detected at random within an extended source is also discussed. The large angular size and the high redshift ($z = 0.2107$) of the identification of 0136+397=4C39.04 imply that it is a "giant" radio galaxy ~ 1.5 Mpc in linear extent. A compact component in 1522+546=3C319 coincides within errors with a very faint optical image that is not the usual identification.

I. INTRODUCTION

This paper is the second of a series describing radio and optical measurements of elliptical radio galaxies. In Paper I (Bridle and Fomalont 1978) we described observations made at 2.7 and 8.1 GHz with the NRAO 4-element interferometer which resulted in the detection of compact components within extended radio galaxies, and we discussed the implications of such observations for making reliable optical identifications of such extended systems. In this paper we report further observations made to improve the reliability of the identifications of 21 radio sources by detecting radio cores in the nuclei of their parent galaxies.

II. OBSERVATIONS AND REDUCTIONS

a) *Selection of the Program Sources*

The 21 sources observed are among those in a sample of several hundred sources (discussed in Paper I) which could not be reliably identified with an optical object on the evidence either of published high-resolution radio maps or of our observations with the 4-element interferometer at Green Bank. In most cases either several optical candidates lay within the radio structure, or the only optical object in or near the structure had a high probability of being a chance projection. Our aim was to resolve such ambiguities by detecting radio "cores" (i.e., small-diameter components coincident with a galaxy, see Paper I) in the true identifications. All 21 sources had already been mapped with reasonable sensitivity and resolution and were known to have (a) a well-defined major axis of elongation, (b) overall angular size $\gtrsim 20$ arcsec, and (c) possible relationship to an elliptical or SO galaxy. Thus, in order to detect radio cores at the mJy level, both high angular resolution (<5 arcsec) and good sensitivity were requirements for these observations.

b) *Instrumentation*

The Very Large Array (VLA), now being constructed by NRAO in New Mexico, will ultimately comprise 27 antennas, each of 25-m diameter in a Y-configuration providing baselines up to ~30 km. In March–May 1977 four elements of the array were fully operational at frequencies near 5 GHz with a maximum baseline of 4.739 km, providing a resolution of ~2 arcsec and (with 50 MHz bandwidth) an rms noise of ~1 mJy in less than 30 minutes of observing time.

We calibrated the gain and phase fluctuations in the electronics and the atmosphere by observing small-diameter radio sources with well-known flux densities and positions. Each radio source was observed alternately with one particular calibrator, usually less than 15° away, spending 13 min on source and 7 min on its calibrator with 1 min change time. Each source was observed about nine times spread in hour angle as conveniently as possible in order to maximize the (u,v) coverage. Ob-

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[a)] Operated by Associated Universities, Inc., under contract with the National Science Foundation.

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TABLE I. Calibrator sources.

Calibrator		$S(4.9)$ Jy[a]	RA (1950.0)	DEC	Sources calibrated
0106 + 013	P0106 + 01	4.23	$01^{h}06^{m}04^{s}.518$	$+01°19'00''.47$	2357 + 004
0134 + 329	3C48	5.35	01 34 49.827	+32 54 20.63	0136 + 397, 0158 + 293
0316 + 413	3C84	45.6	03 16 29.566	+41 19 51.92	0258 + 356
0430 + 052	3C120	6.85	04 30 31.603	+05 14 59.62	0356 + 102
0552 + 398	DA193	5.21	05 52 01.389	+39 48 21.78	0632 + 263
0736 + 017	P0736 + 01	1.90	07 36 42.517	+01 44 00.32	0819 + 061
0742 + 103	D0742 + 10	3.70	07 42 48.466	+10 18 32.67	0714 + 286
0923 + 392	DA267	7.30	09 23 55.314	+39 15 23.58	0915 + 320, 0916 + 342, 0936 + 361, 0938 + 349
1328 + 307	3C286	7.48	13 28 49.655	+30 45 58.65	1301 + 382, 1308 + 277, 1313 + 072, 1319 + 428, 1430 + 251
1641 + 399	3C345	7.05	16 41 17.608	+39 54 10.84	1522 + 546, 1707 + 344, 1726 + 318
2128 − 123	P2128 − 12	1.94	21 28 52.760	−12 20 23.30	2058 − 135

[a] 1 Jy = 1×10^{-26} w m^{-2} Hz^{-1}.

servations at elevations less than 15° were avoided. In Table I we list the parameters of the calibrator sources. The pointing of the antennas and their relative positions were measured using radio calibrators just prior to each run. The pointing accuracy was about 30 arcsec (1/20 half-power beamwidth) and the antenna positions were obtained with an accuracy of 2 mm.

c) *Data Reduction*

The data were accumulated for 10-s periods at the telescope. After editing the 10-s records for anomalous gain and phase behavior or unusual instrumental conditions, the data were vectorially averaged to 3-min samples. The observed visibilities for each source were then corrected by interpolating the long-term gain and phase performance of the array using the observations of the calibrators. The rms gain fluctuations on time scales ~10 min were ~3%; phase fluctuations varied from ~3° on baselines $\lesssim 1$ km to ~10° for the 4.7-km baseline.

Radio maps were made from the calibrated data by the usual Fourier methods. As some maps contained significant responses to the extended emission from the sources (which confused the search for weak small-diameter components), high-resolution maps were also made using only the baselines >2 km. Further reductions to determine flux densities and positions of possible radio "cores" depended on the nature of the resulting maps.

In some cases the maps were consistent with noise; upper limits to the flux densities of cores anywhere within the region near the extended emission could then be derived directly from the maps. For many sources a small-diameter component dominated the high-resolution (baselines >2 km) map and its position, intensity and angular size could be found by fitting an elliptical Gaussian model to the observed visibility data; the maps were used to guide the initial choice of model parameters. For a number of sources $\lesssim 40$ arcsec in extent, we mapped the entire structure using a CLEAN algorithm (Högbom 1974) to deconvolve the effects of our unfilled aperture. The core components could generally be recognized on the CLEAN maps, or upper limits could be set to their intensities as before.

III. RESULTS

a) *Positive Detections*

Table II shows the results for the 13 sources in which we detect small-diameter components. Column 1 gives the source designation (IAU convention and common name) and Column 2 the flux density and its standard error. The radio position and its error are tabulated in the upper row of Columns 3 and 4; if a galaxy lies within 2 arcsec of the radio position, the optical position of the galaxy center (generally from Goodson *et al.* 1978—Paper III in this series) is given in the lower row. The eleven entries with both radio and optical positions represent successful detections of radio "cores." Column 5 gives the angular size of the small component.

Column 6 codifies the overall radio morphology of the source and the relationship to this small-diameter component. The letter codes are those defined in Paper I—structures clearly bifurcated along their major axes are coded T (triple) or L (lobe brightening) according to whether the small-diameter component is located towards the center or the edge of the structure. Less clearly bifurcated structures are coded C (core) or H (head) on the same criterion. The galaxy morphology (E-elliptical, db-double-nucleus galaxy or double galaxy) and visual magnitude corrected for galactic absorption are given in Column 7. Column 8 gives references to finding charts for the identifications and maps of the extended radio source components. Individual sources are discussed in Sec. IV.

b) *Upper Limits*

The eight sources in which we did not detect small-diameter components are listed in Table III. The source names and the upper limit to the 6-cm flux density of any small-diameter component in the area covered by the extended source are given in Columns 1 and 2. Column 3 gives the nominal identification and Column 4 notes

TABLE II. Radio sources with detected small-diameter components.

Source	$S(4.9)$ mJy	RA (1950)	DEC	Diameter	Class	ID, m_v	References
0136 + 397 4C39.04	13 ± 2	$01^{h}36^{m}33^{s}.59 \pm 0^{s}.02$ 33.58 ± 0.03	$39°41'51''.5 \pm 0''.5$ 51.2 ± 0.7	<2″	T	db?, $18^{m}.5$	1, 9
0158 + 293 4C29.05	16 ± 3	01 58 43.43 ± 0.02 43.49 ± 0.04	29 19 17.4 ± 0.4 16.0 ± 0.4	<2	C(T)	db, 16.2	1, 10
0356 + 102 3C98	9 ± 3	03 56 10.20 ± 0.04 10.21 ± 0.04	10 17 32.1 ± 0.7 31.7 ± 0.4	<4	T	E, 15.0	2, 11
0632 + 263 4C26.23	21 ± 4	06 32 29.52 ± 0.02 29.60 ± 0.03	26 19 06.4 ± 0.2 06.4 ± 0.4	~3	T	E, 13.0	3, 9
0714 + 286 4C28.18	17 ± 2	07 14 48.02 ± 0.03 48.03 ± 0.03	28 40 35.4 ± 0.3 35.9 ± 0.4	<2	T	E, 15.6	4, 10
0915 + 320 B20915 + 32	8 ± 1	09 15 58.46 ± 0.05 58.53 ± 0.03	32 04 20.1 ± 0.7 20.8 ± 0.4	<2	T	E, 15.0	5, 12
0936 + 361 3C223	18 ± 4	09 36 50.92 ± 0.03 50.87 ± 0.06	36 07 35.8 ± 0.4 35.0 ± 0.5	<2	T	E, 17.4	6, 13
1313 + 072 P1313 + 07	22 ± 3	13 13 45.94 ± 0.01 45.97 ± 0.02	07 18 35.4 ± 0.2 35.6 ± 0.4	<2	T	E, 14.8	7, 14
1319 + 428 3C285	6 ± 2	13 19 05.20 ± 0.05 05.22 ± 0.04	42 50 56.7 ± 0.6 55.7 ± 0.3	<4	T	E, 15.7	6, 15
1430 + 251 4C25.46	24 ± 4	14 30 28.22 ± 0.05	25 09 25.4 ± 0.7	≲2	?	No ID	1, 9
1522 + 546 3C319	63 ± 5	15 22 47.68 ± 0.05	54 39 11.3 ± 0.5	≲2	?	ID: see text	6, 9
2058 − 135 P2058 − 13	23 ± 4	20 58 59.27 ± 0.12 59.38 ± 0.05	−13 30 35.8 ± 1.7 38.2 ± 1.0	<2	T	E, 14.3	8, 16
2357 + 004	12 ± 2	23 57 25.07 ± 0.03 25.00 ± 0.04	00 25 23.4 ± 0.6 24.5 ± 0.4	<4	C	db, 15.3	7, 9

references to suggested optical identifications and published radio maps.

c) *Radio Maps*

Seven radio maps obtained with the NRAO interferometer at 2.7 GHz or with the VLA at 4.9 GHz are shown in Figs. 1 and 2. We have included only those sources for which comparably detailed maps are not already published. Comments on the individual sources are given in Sec. IV.

IV. NOTES ON INDIVIDUAL SOURCES

a) *0136 + 397 = 4C39.04*

This source was first identified with a galaxy by Olsen (1970). Our inspection of the *Palomar Sky Atlas* showed the image marked by Olsen to be double; the positions of both optical features are given in Paper III. The small component detected by the VLA lies within 1.5 arcsec of the brighter South-preceding image. The redshift of 0.2107 for this system has been measured by Sargent (1973) although he does not state whether the redshift applies to both optical features. The optical field on the red print of the *Palomar Sky Atlas* is sketched in Fig. 1a, which also shows a 2.7-GHz map of the extended radio structure with 52 arcsec by 37 arcsec resolution. The data for this map were obtained by us with the NRAO 3-element interferometer as described in Paper I.

The overall linear size of the structure shown in Fig. 1a is ~1.5 Mpc using $H_o = 50$ km s^{-1} Mpc^{-1} and $q_o = 0.5$. This suggests that 0136 + 397 is a "giant" radio

TABLE III. Upper limits to small-diameter components.

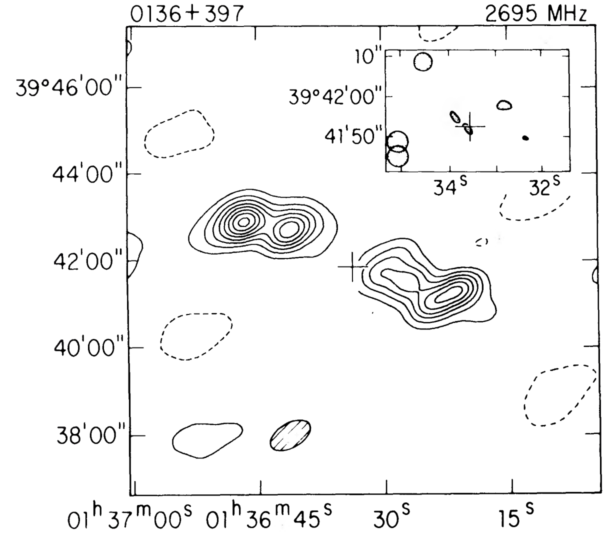
Source	$S(4.9)$ mJy	Nominal ID, m_v	References
0258 + 356 4C35.06A	<2	ambiguous	1, 17
0802 + 243 3C192	<5	E, 14.9	6, 18
0819 + 061 3C198	<1.5	E, 16.6	6, 14
0938 + 399 3C223.1	<5	E, 16.0	6, 13
1301 + 382 4C38.35	<3	ambiguous	5, 9
1308 + 277 3C284	<4	E, 17.4	6, 13
1707 + 344 4C34.45	<2	ambiguous	9, 19
1726 + 318 3C357	<3	E, 17.0	6, 13

References to Tables II and III
Finding Charts

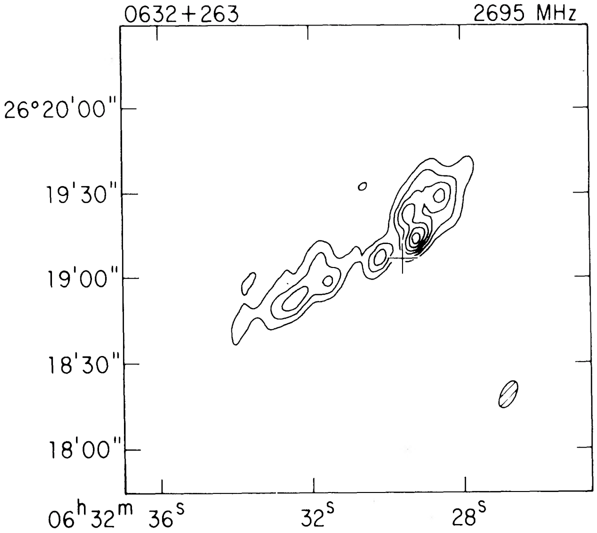
1. Olsen (1970)
2. Maltby, Matthews, and Moffet (1963)
3. Merkelijn, Shimmins, and Bolton (1968)
4. Willson (1972)
5. Colla *et al.* (1975)
6. Wyndham (1966)
7. Clarke, Bolton, and Shimmins (1966)
8. Schilizzi (1975)

Map of Extended Structure

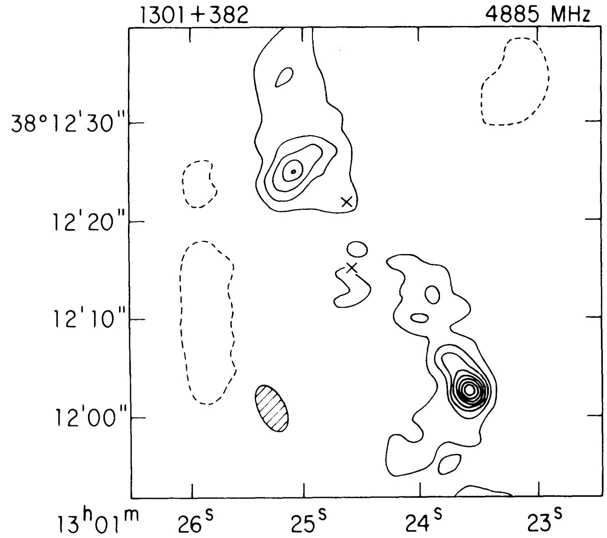
9. This paper
10. Bridle and Fomalont (1978). Paper I
11. Branson *et al.* (1972)
12. Fomalont and Bridle (1978)
13. Riley and Pooley (1975)
14. Fomalont (1971)
15. Miley and van der Laan (1973)
16. Schilizzi and McAdam (1975)
17. Rudnick and Owen (1977)
18. Högbom and Carlsson (1974)
19. Owen, Rudnick, and Peterson (1977)



(a)



(b)



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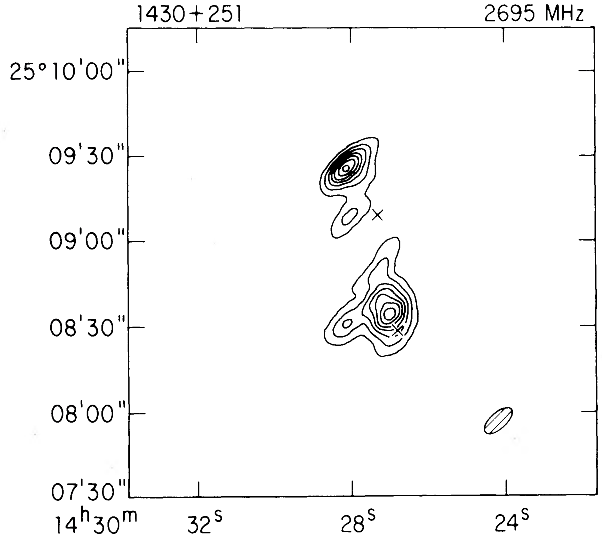


(d)

FIG. 1a. 0136 + 397: Each contour level is 9.0 mJy/beam. The location of a 12 mJy small diameter component detected at 4885 mHz is shown by the +. An inset of the optical field around this radio component is shown in the upper right.

FIG. 1b. 0632 + 263: Each contour level is 10.8 mJy/beam. The location of a 17 mJy small-diameter component detected at 4885 MHz, coincident with a $15\overset{\mathrm{m}}{.}5$ galaxy, is shown by the +.

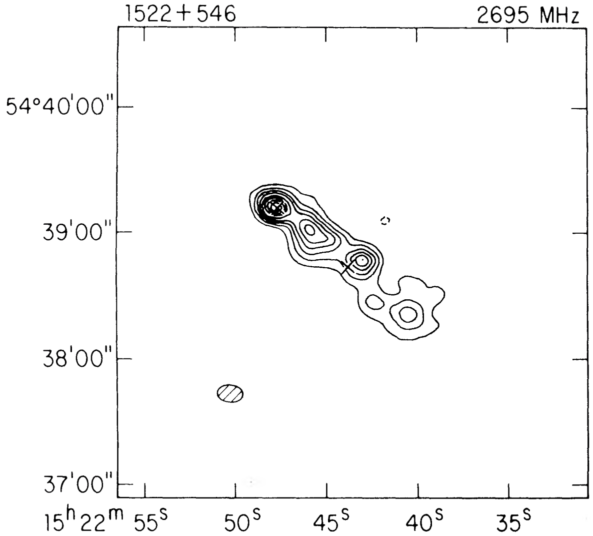
FIG. 1c. 1301 + 382: Each contour level is 3.4 mJy/beam. The location of two galaxies in the field are shown by the X's. No small-diameter component was found at 4885 MHz.

FIG. 1d. 1430 + 251: Each contour level is 8.7 mJy/beam. The small-diameter component found at 4885 MHz is the north component in its entirety. Two galaxies in the field are degnated by the *X*'s.

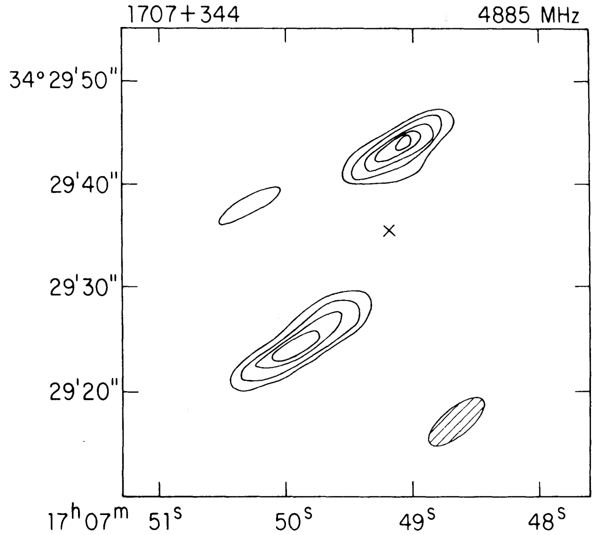
galaxy, similar in linear size to NGC 315 (Bridle *et al.* 1976). The monochromatic power emitted at 2.7 GHz is 1.1×10^{26} W Hz^{-1} making this source the most luminous radio source known with a linear extent greater than 1 Mpc. From the observed spectrum ($S \propto \nu^{-1.0}$) we estimate that the integrated luminosity between 10 MHz and 10 GHz is 2×10^{36} W. By the usual equipartition calculation the minimum energy in radiating particles and magnetic fields is 3×10^{52} joules and the equipartition field is of order 1 to 10 μG depending on the details of the radio structure which are not well- determined.

b) 0158 + 293 = 4C29.05

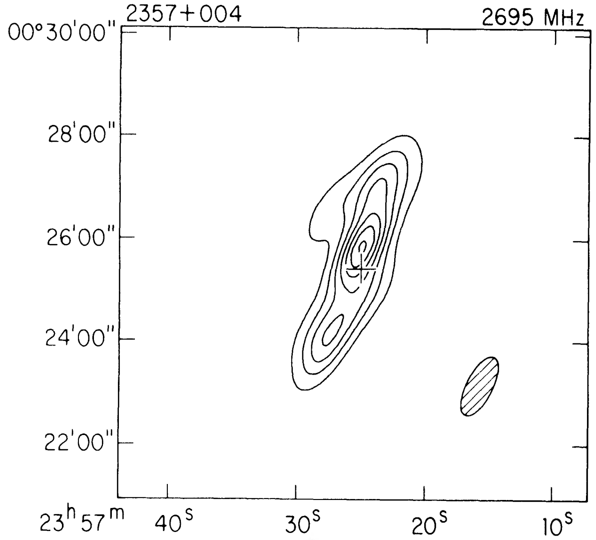
Olsen (1970) identified this source with a close pair of galaxies. The small-diameter component detected by



(a)



(b)



(c)

FIG. 2a. 1522 + 546: Each contour level is 31.1 mJy/beam. The location of a small-diameter component coincident with a 20^{m} optical object is shown by the *X* to the north. The identification suggested by Wyndham (1966), an $18\overset{\mathrm{m}}{.}5$ galaxy, is shown by the *X* in the center.

FIG. 2b. 1707 + 344: Each contour level is 1.6 mJy/beam. The location of a 16^{m} galaxy is shown by the *X*. No small-diameter radio component was detected and several other galaxies lie between the components. See Rudnick and Owen (1977).

FIG. 2c. 2357 + 004: Each contour level is 12.6 mJy/beam. The location of a small-diameter component, coincident with a 16^{m} galaxy is shown by the +.

the VLA is located in the eastern galaxy. The nuclei are separated by 6 arcsec and are of equal brightness. A map of the extended structure is given in Paper I.

c) 0356 + 102 = 3C98

This component would be very close to the noise in the map at 5 GHz given by Jenkins *et al.* (1977), so our detection is consistent with their observation. The optical position has been measured by Griffin (1963).

d) 0915 + 320 = B2 0915 + 32

The large-scale structure of this source has been mapped in a full synthesis with six VLA antennas at 4.9 GHz by Fomalont and Bridle (1978), who also discuss the optical identification and its implications.

e) 1301 + 382 = 4C38.25

The 4.9-GHz map obtained at the VLA is shown in

1978AJ.....83..725F

Fig. 1c. The positions of two 19^{m} galaxies possibly associated with the source are also plotted. The source has a roughly double structure and there may be low-level emission from the vicinity of both galaxies. Further sensitive mapping will be needed to detect any radio core associated with this system and so resolve the identification ambiguity.

f) 1319 + 428 = 3C285

Jenkins *et al.* (1977) give an upper limit of 10 mJy for a small diameter, 5-GHz component anywhere in the source. This is consistent with our detection.

g) 1430 + 251 = 4C25.46

A map at 2.7 GHz made from NRAO interferometer data is shown in Fig. 1d. The small component detected at 4.9 GHz by the VLA is the northern component on this map. The only two optical objects in the radio field are shown and no radio emission >3 mJy was detected at 4.9 GHz from them. The nature and identification of this source or sources are unknown.

h) 1522 + 546 = 3C319

Our 2.7-GHz map obtained with the NRAO interferometer is shown in Fig. 2a. The optical identification has generally been taken to be the $18\overset{\mathrm{m}}{.}5$ galaxy (Wyndham 1966) near the center of this structure. No radio core is detected in the $18\overset{\mathrm{m}}{.}5$ galaxy [1950 position: $15^{\mathrm{h}}\ 22^{\mathrm{m}}\ 43\overset{\mathrm{s}}{.}9 \pm 0\overset{\mathrm{s}}{.}1$, $54°\ 38'\ 42\overset{''}{.}8 \pm 1\overset{''}{.}0$ (Véron 1966)] to a limit of 4 mJy. The high-resolution map from the VLA shows, however, a small-diameter ($\lesssim 2''$) component containing ~8% of the total emission at 4.9 GHz at the position marked in Fig. 2a. This feature has also been reported by Jenkins *et al.* (1977). The identification is complicated by the fact that this component coincides within the errors with a feature near the Sky Atlas print limit whose position measured on the Queen's University X–Y engine (Bridle and Goodson 1977) is $15^{\mathrm{h}}\ 22^{\mathrm{m}}\ 47\overset{\mathrm{s}}{.}71 \pm 0\overset{\mathrm{s}}{.}05$, $+54°\ 39'\ 10\overset{''}{.}6 \pm 0\overset{''}{.}5$,—epoch 1950. The optical positions of other objects in the field are given by Jenkins *et al.* (1977).

Three possible interpretations must be considered. First, the field may contain two unrelated radio systems, the VLA component being associated with the $\sim 20^{\mathrm{m}}$ object but the rest of 3C319 being associated with the $18\overset{\mathrm{m}}{.}5$ galaxy. Second, the field may be a single radio system associated with the $18\overset{\mathrm{m}}{.}5$ galaxy, as is now generally assumed. In this case the nature of the very faint optical object near the VLA component is of interest. Possibly it is a background object unrelated to the radio structure despite its proximity to the small component. The alternative exists, however, that the faint image is optical emission from a compact radio feature in 3C319, in which case observations of its optical spectrum and polarization are of considerable astrophysical importance. A third scenario would also consider the radio source to be a single physical system, the 20^{m} object being the optical identification of a head-tail structure. In this scenario the $18\overset{\mathrm{m}}{.}5$ galaxy would be assumed to be protected against the radio structure by chance. The $18\overset{\mathrm{m}}{.}5$ galaxy is in fact the brightest member of a fairly rich cluster in the field of the source, so this interpretation cannot be ruled out.

Final identification of this source must await more detailed radio mapping of the field and clarification of the nature of the faint image near the VLA radio component.

i) 2357 + 004

The VLA component lies in the western galaxy of a close pair proposed as the identification by Clarke *et al.* (1966). The galaxies are separated by 8 arcsec and the western galaxy is $\sim 0\overset{\mathrm{m}}{.}6$ brighter on the O print of the Palomar Sky Atlas.

V. DISCUSSION

Except when the structural features of a source provide unambiguous morphological evidence for association with a galaxy (e.g., radio jets linking distant radio emission to a galaxy), identifications of extended sources are problematical. Two common criteria used to assist identifications—(a) small *a priori* probability of a particularly bright galaxy being situated within the radio emission and (b) small *a priori* probability of a galaxy positioned near the radio centroid or near a well-defined radio axis—may be insufficient to identify with confidence the galaxy associated with the radio emission. In many cases, however, detection of a radio core in an identification candidate can secure the identification of the extended source.

The utility of attempting to detect a small-diameter component which might indicate the location of the parent object (whether it is optically visible or not) depends on the *a priori* probability that the detected component lies within the extended area by chance. In Table IV we calculate for various source sizes the 5-GHz flux density at which there is less than 5% chance of random association. The source count used at 5 GHz (Fomalont *et al.* 1974) is

$$N = .027\, S^{-1.1},$$

where N is the number of sources per *square arc minute* with a flux density greater than S in *mJy units.* Although some of these weak sources will not be small in angular extent, we have shown in Paper I that some radio cores are extended so it may be appropriate to use the total source count to arrive at a conservative estimate of the probability of random coincidence. The "area covered by the source" was taken as the circular area whose angular diameter is the largest angular size (LAS). The "area near the centroid" was taken as a circular area

TABLE IV. Association of a radio core with an extended source with $>95\%$ confidence.

Largest angular size (arcsec)	Area covered by source (mJy)	Area near centroid (mJy)
300	>10.4	>1.2
60	>0.57	>0.06
15	>0.045	>0.005
3	>0.0024	>0.0003

centered on the source centroid with a radius of 0.15 LAS. In Paper I we showed that 90% of all bifurcated (double) sources are identified with galaxies in this latter area and this statistic can be used to limit the area of search for a radio core in a source whose detailed structure is adequately known.

Table IV demonstrates that if the angular extent exceeds several arcmin the detection of a random, small-diameter radio component within the source is not unlikely at the mJy flux density level. Confident identification of these extended sources will therefore require a combination of several of the morphological and brightness criteria used for the association of a radio source with an optical object unless the radio core is brighter than $\sim$10 mJy. On the other hand, there will be very little likelihood of detecting *unrelated* small-diameter components within extended sources smaller than $\sim$40 arcsec using the VLA in its completed state with a detection level of $\sim$0.2 mJy at 1.4 and 5.0 GHz.

Eleven radio sources in the present sample of 21 contain a radio core brighter than 5 mJy at 4.9 GHz. The probability that the radio core lies in the area covered by each source is greater than one percent for 0136 + 397, 0356 + 102, 0915 + 320, 0936 + 361, 1319 + 428, 2058 − 135, and 2357 + 004 which has the largest probability of 5.3%. If we use the additional morphological criterion from Paper I that the identification of a bifurcated source normally lies within 15% of the largest angular size from the centroid (which is true for all of the above sources), the probability of misidentification is less than 0.5% in all cases. In addition, in all eleven sources, the optical object is the brightest galaxy in the structure, further supporting the identification according to the results of Paper I. The identification of two sources, 1430 + 251 and 1522 + 546, in which the small-diameter radio components are not near the centers of the structures, are unknown or ambiguous. The small components are associated with the extended source with $\sim$99% confidence, however.

Of the eight sources in which no small-diameter component was detected, the identifications in the literature for 0802 + 243, 0819 + 061, 0938 + 399, 1308 + 277, and 1726 + 318 are probably reliable on the evidence of the brightness of the galaxies and their location near the centroids of the radio structures, although detection of a radio core would secure the identifications. The three sources 0258 + 356, 1301 + 382, and 1707 + 344 remain unidentified because there are several galaxies near the radio centroids.

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