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HIGH-RESOLUTION OBSERVATIONS OF COMPACT RADIO SOURCES AT 13 CENTIMETERS. II

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ABSTRACT

Observations made at 13 cm with a tracking interferometer 25×10^6 wavelengths long have been used to investigate the structure of the compact radio sources. The data show complex structure, so that, in general, it is not possible to discuss specific models with the limited data from this single baseline. It is established, however, that the compact components are confined to a region $\lesssim 1''$ arc.

I. INTRODUCTION

A previous paper on compact radio sources (Kellermann *et al.* 1970, hereinafter called Paper I) reported on observations at 13 cm made with an 81-million-wavelength interferometer consisting of the 210-foot (64 m) antenna at Goldstone, California, and the 85-foot (26 m) antenna at Tidbinbilla, Australia, both part of the NASA Deep Space Network. Although a total of 56 of the sources studied showed structure on a scale of 0".001 or less, the location of these telescopes severely limited their common sky coverage, so that for each source essentially only one point in the (u, v)-plane was sampled. In order to further study the brightness distribution of these sources, additional observations have been made on a shorter baseline giving a different coverage of the (u, v)-plane.

The new measurements were made using the 140-foot (42 m) telescope of NRAO in Green Bank, West Virginia, and the 85-foot NASA "Venus" telescope at Goldstone, California. The length of this baseline is 3260 km, or 24.9 million wavelengths at 13 cm, and gives at least 9 hours of common sky coverage for sources north of the equator.

II. THE OBSERVATIONS

The observations were made on 1970 November 23 and 24 at an observing frequency of 2296 MHz using the NRAO Mark I VLB[1] terminals and reduction programs described by Clark *et al.* (1968). This system has a 350-kHz bandwidth and records data for 3 minutes on a single magnetic tape. Rubidium-vapor frequency standards provided the time and frequency references at both sites. Right-circular polarization was used for the observations.

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[1] Very long baseline.

The system temperature at the 85-foot telescope was 17° K at high elevation angles and rose to 20°–30° K for elevation angles less than 30°; at the 140-foot telescope the system temperature was about 140° K. The overall sensitivity was about half that of the system described in Paper I.

The projected baseline ranged from 14.7×10^6 to 24.9×10^6 wavelengths with position angles between 42° and 137°. Most of the sources selected were known to have structure in the range 0".01–0".001 on the basis of observations reported in Paper I and in Kellermann *et al.* (1971). Observations were also made of Sgr A and Cen A to investigate the possibility that these relatively large sources might contain smaller structure.

The weakest source we were able to detect with confidence was about 0.25 flux unit (f.u.) of correlated flux density. This limit was achieved only when the source's position was sufficiently well known that it was possible to predict accurately the expected fringe frequency and time delay. The uncertainty in the correlated flux densities was computed from the scatter in different measurements of the same source at essentially the same values of u and v, and from the uncertainty found in fitting the observations to the delay pattern of the interferometer; this was about 0.07 f.u. plus 5 percent of the correlated flux density.

The correlated flux-density scale was established by assuming that PKS 2345−16 and NRAO 190 were unresolved on this baseline, as suggested by the data obtained on a longer baseline at the same wavelength reported in Paper I. This scale may be in error by up to 10 percent, as discussed in Paper I; but this will not affect the relative correlated flux densities for a given source.

III. RESULTS

The observational results are summarized in Table 1. Column (1) gives the source name; columns (2) and (3), the point in the (u, v)-plane sampled by the observation, expressed in polar coordinates. The magnitude d is in millions of wavelengths; the angle θ in degrees east of North. Column (4) gives the correlated flux density S_c in flux units; column (5), the total flux density S_t in flux units measured at Goldstone at the time of observations, with an uncertainty of 10 percent. Column (6) gives the fringe visibility γ.

For most of the sources observed, the data are still insufficient for the construction of models, since in general the resolved sources which were observed on both the 25- and 80-million-wavelength baselines appear to have brightness distributions more complex than simple disks or Gaussians. In some cases, such as 3C 273, CTD 93, PKS 2134+004, and VRO 42.22.01, there is evidence for a secondary maximum in the visibility function. These maxima are too high to be explained by simple disk distributions and indicate the presence of holes in the brightness distribution such as would occur, for example, in double or ring-type sources. Also, in general, it was not possible to fit our data with simple circularly symmetric models, suggesting either elongated ring or double structure as is found at comparable resolutions at other wavelengths (e.g. Clarke *et al.* 1969; Cohen *et al.* 1971).

The fringes were always found to be localized at one point in the (fringe frequency, time delay)-domain. This implies that there were no compact components with sizes smaller than 0".01 and stronger than 0.5 f.u. in a region beyond 1" but within 1' of the primary component; thus, the sources that we observed do not contain multiple compact components with ratios of separation to size $\gtrsim 10^2$. The individual values of these limits depend on the source declination and hour angle at which the source was observed (Cohen and Shaffer 1971). The lower size limit results from the inability to detect a double hump in the fringe-frequency distribution when the sources are closer than about 1"; the upper limit depends on the range of fringe frequencies and the number of delay channels investigated. Both limits are conservative estimates.

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TABLE 1

CORRELATED FLUXES

Source (1)	d (2)	θ (3)	S_c (4)	S_t (5)	γ (6)
PKS 0019−00....	17.2	83	0.99	2.0	0.50
	18.2	83	1.24		0.62
PKS 0237−23....	24.6	89	2.16	5.6	0.39
	24.7	88	2.36		0.42
	24.8	87	2.28		0.41
CTA 21..........	15.7	60	2.19	5.8	0.38
	17.1	64	2.63		0.45
	18.5	67	1.90		0.33
	23.8	90	0.38:		0.07:
3C 84............	18.5	130	4.83	12.4	0.39
	19.7	34	4.83		0.39
	22.8	104	4.72		0.38
3C 111...........	23.6	68	0.25	11.2	0.022
	23.9	70	0.32		0.028
3C 120...........	20.5	80	1.99	5.6	0.36
	21.7	81	2.12		0.38
	24.9	85	2.14		0.38
	24.9	85	2.17		0.39
NRAO 190.......	14.5	82	2.95	3.0	0.98
	19.3	84	2.98		0.99
PKS 0521−36....	24.7	89	0.89	13.1	0.07
	24.8	87	0.92		0.07
LHE 210.........	18.1	77	0.97	5.3	0.18
4C 55.16.........	24.5	96	1.42	7.7	0.18
4C 39.25.........	16.8	137	3.44	3.8	0.91
	23.6	99	3.11		0.82
	23.7	67	3.21		0.84
PKS 1127−14....	20.1	72	3.06	6.6	0.46
	20.7	73	2.98		0.45
PKS 1148−00....	16.5	82	1.05	2.8	0.38
	20.5	84	1.05		0.38
	22.6	84	0.78		0.28
3C 273...........	14.7	78	2.24	37.6	0.06
	17.2	80	6.86		0.18
	19.4	82	10.5		0.28
	21.2	83	12.6		0.34
	22.0	86	12.6		0.34
	22.7	83	13.8		0.37
	24.9	85	14.3		0.38
3C 274...........	15.5	65	1.38	131.	0.011
	17.4	69	1.28		0.010
	19.4	73	0.92		0.007
	21.3	92	1.07		0.008
	24.9	85	0.98		0.007
3C 279...........	15.4	89	10.1	13.6	0.74
	17.5	87	10.6		0.78
	19.7	88	10.4		0.76
	21.3	81	10.7		0.79
	21.5	88	10.5		0.77
	22.2	81	10.5		0.77
	22.9	87	10.9		0.80
	24.9	85	11.0		0.81
3C 286...........	14.3	131	2.40	5.6	0.43
	16.3	122	1.02		0.18
	16.9	120	1.06		0.19
PKS 1345+12....	12.9	58	0.70	3.9	0.18
	18.1	71	0.47		0.12
OQ 208..........	16.9	42	1.43	1.9	0.75
	20.6	60	1.40		0.74
	21.1	103	1.40		0.74

TABLE 1—*Continued*

Source (1)	d (2)	θ (3)	S_c (4)	S_t (5)	γ (6)
PKS 1510−08....	23.1	88	1.85	3.7	0.50
CTD93..........	14.5	123	0.94	3.2	0.29
	19.3	107	1.24		0.39
3C 345...........	18.0	130	3.87	7.7	0.50
	18.3	128	4.02		0.52
NRAO 530.......	20.6	93	2.35	4.3	0.55
	21.2	92	1.99		0.46
	24.8	86	2.25		0.52
3C 371...........	24.9	77	0.49	2.0	0.24
	24.9	79	0.46		0.23
PKS 2127+04....	16.4	77	2.08	3.2	0.65
	19.4	80	1.35		0.42
	22.5	82	1.20		0.38
	23.8	86	1.29		0.40
	24.1	86	1.12		0.35
PKS 2134+004...	18.9	83	4.02	5.9	0.68
	22.2	84	4.71		0.80
	23.9	85	5.32		0.90
	24.0	85	5.36		0.91
VRO 42.22.01....	19.7	32	3.97	5.8	0.68
	20.8	118	4.82		0.83
	23.9	99	5.15		0.89
CTA 102.........	16.9	69	2.82	5.0	0.56
	19.7	74	3.35		0.67
	21.9	78	3.39		0.68
	23.0	90	2.79		0.56
	23.6	80	3.00		0.60
	24.8	84	3.00		0.60
3C 454.3.........	15.8	60	7.08	12.2	0.58
	19.5	70	3.02		0.25
	24.1	87	3.50		0.29
PKS 2345−16....	22.1	75	1.88	2.1	0.90
	22.4	75	2.27		1.08
	22.8	77	2.20		1.05

IV. INDIVIDUAL SOURCES

The visibility functions for 3C 273, 3C 274, and 3C 279 were adequately sampled and had sufficiently simple dependence on the projected baseline to allow simple models to be constructed.

a) 3C 273

Observations of 3C 273 at 75 cm (Clarke *et al.* 1969), at 18 and 6 cm (Kellermann *et al.* 1971), and at 3.8 cm (Knight *et al.* 1971; Whitney *et al.* 1971; Cohen *et al.* 1971) show that it has complex structure with component sizes ranging from less than $0\overset{''}{.}0004$ to $0\overset{''}{.}08$.

The variation of correlated flux density with projected baseline at 13 cm (Fig. 1*a*) can be fit by an equal-double-source model with component size $0\overset{''}{.}002$ and flux density 11 f.u., or with the relative sizes and flux densities differing by up to 50 percent. The projected separation of the components is $0\overset{''}{.}007$ in the east-west direction. The datum at 86° position angle (Fig. 1*a*, *triangle*) suggests that the major axis has a position angle near 60°, but this is uncertain.

The minimum we observed must be the first minimum; otherwise, the effects of the next minimum would have been evident in the points at longer projected baselines.

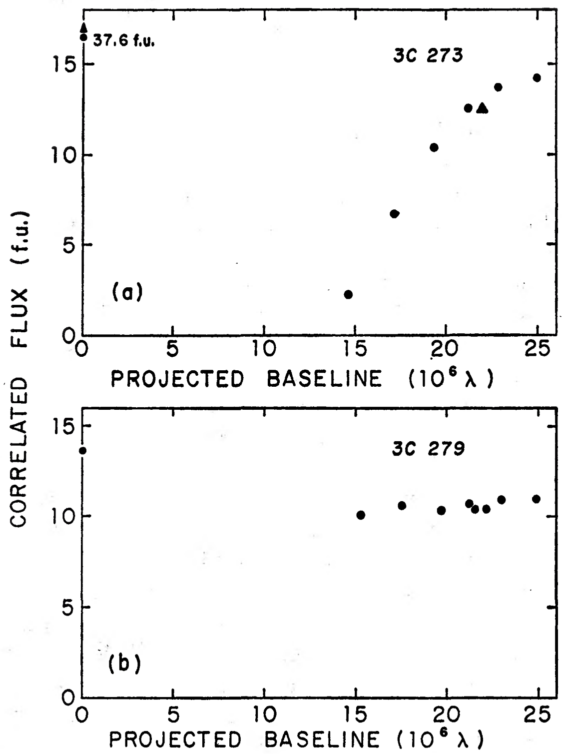

FIG. 1.—(*a*) Correlated flux of 3C 273 as a function of projected baseline. The triangle denotes the one observation made before the source crossed the interferometer meridian. Uncertainties in the correlated fluxes are about 5%. (*b*) Correlated flux of 3C 279 as a function of projected baseline.

The visibility is too high beyond the minimum for the source to be a disk. The visibility beyond the minimum is not too high for the source to be a thin ring, but this would require that the total flux at 13 cm come from the ring. In view of the complex spectrum for the source and the structure observed at other wavelengths, we regard this as being unlikely.

b) 3C 274

We find evidence that the small component in this source contains structure on two size scales. The simplest model gives 1 f.u. in a component 0".0008 ± 0".0001 and 2.5 f.u. in a component 0".010 ± 0".002. (These sizes are for Gaussian models; disks would have diameters nearly twice as large.) This model has taken into account the data from Paper I and assumes the flux density to be the same for both observing periods, although the source has been observed to vary at 6 cm (Graham 1971). At 3.8 cm this smaller component contains about 2 f.u. and has comparable size (Cohen *et al.* 1971).

c) 3C 279

The present data indicate a component of 10.6 f.u. which is unresolved between 15 and 25 × 10^6 wavelengths (Fig. 1*b*). It is difficult to tie in the point from Paper I because of the variability of this source. Observations at 3.8 cm (Knight *et al.* 1971; Whitney *et al.* 1971; Cohen *et al.* 1971) show evidence for a double source, although there is some ambiguity in deciding if the minimum observed is the first or second. If the minimum observed at 3.8 cm were the second, and this double contributed significantly to the 13-cm flux, then the first would appear at 35 × 10^6 λ at position angle

85° and the fringe visibility at $25 \times 10^6\ \lambda$ would be reduced to 0.5. We find no such evidence and can therefore rule out the second minimum model which has a separation of 0".0045.

d) 3C 111

Another source of particular interest is 3C 111. Previous observations at lower resolution have shown 3C 111 to be a triple source greater than 3′ in extent (Mackay 1969; Mitton 1970). The central component has a 2 f.u. core with a flat spectrum between 21 and 6 cm (Fomalont, private communication). At 3.8 cm with a spacing of $10^8\ \lambda$, observations with the "Goldstack" interferometer (Cohen *et al.* 1971) showed that this central component had 0.6 f.u. of correlated flux density; this is higher than the ~0.3 f.u. we observe at $\sim 24 \times 10^6\ \lambda$ at 13 cm and thus suggests that the small component is opaque between 3.8 and 13 cm. The interferometer measurements show that the central compact source has structure ≲0".007 at 13 cm and ≲0".001 at 3.8 cm. Thus 3C 111 is unique in that it is the only known extended double radio source which contains a compact opaque source at the center.

In addition to the sources listed in Table 1, we observed Sgr A and Cen A and did not detect any compact sources within the primary beam of the interferometer (~15′). The sensitivity limit of 1 f.u. was due both to the higher antenna temperature for these strong sources and to our *a priori* lack of knowledge of the positions of any compact components in these sources. For Cen A, the antennas were pointed toward a position midway between the two central components and included both peaks of the central component and the unresolved source seen with the NRAO interferometer at 3.7 cm (Kellermann 1970). For Sgr A we centered the search on the peak emission given by Maxwell and Taylor (1968). This includes the 2′ × 3′ source found by Maxwell and Taylor, the region where Dulk (1970) found a slight enhancement at 80 MHz, and Low and Auman's (1970) source Sgr IRA.

V. CONCLUSION

Paper I showed that many extragalactic radio sources contain compact components at 13 cm; the present observations show that the visibility functions are neither circularly symmetric nor monotonic. The high amplitudes of the visibility functions beyond the first minima often preclude simple elliptical-disk models. We cannot, however, distinguish between elliptical rings or double models without data from different baselines.

There is no evidence of compact components smaller than 0".01 occurring with separations between 1″ and 1′. This indicates that if compact sources separate, they must also expand at a similar rate.

For many sources the intensity, and possibly the structure as well, varies with time, so that simultaneous multistation observations are necessary to determine the structure of these sources.

The 13-cm radiometer used at Green Bank was developed for this experiment by John Payne. We thank him for his continual efforts on this program. We also thank P. Hemenway, S. Gulkis, G. Purcell, and W. Cannon for assistance in performing the observations; D. Spitzmesser, L. Skjerve, and M. Cohen for help at Goldstone; B. Clark for making available the fringe reductions programs; and W. E. Howard III and L. Matveyenko for helpful comments on the manuscript.

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