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HIGH-RESOLUTION OBSERVATIONS OF COMPACT RADIO SOURCES AT 13 CENTIMETERS

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ABSTRACT

Two antennas of the NASA Deep Space Network at Goldstone, California, and Canberra, Australia, have been used as elements of an interferometer. The baseline length is 10592 km, or 81×10^6 wavelengths ($\lambda = 13.1$ cm). Sources larger than 0".001 are well resolved.

Fifty-six sources show clear interference fringes, which indicate the presence of structure on a scale of 0".001 or less. Five sources appear to be completely unresolved; seven others probably have a relatively simple structure and are assigned an angular size. The other forty-four have more complex structure. Twenty-four sources are reported as showing no fringes, and a lower limit to their diameter is given.

It is estimated that about 15 percent of the stronger sources at decimeter wavelengths have appreciable structure 0".002 or smaller in angular size.

I. INTRODUCTION

We have previously reported measurements made with very-long-baseline interferometers at wavelengths of 6, 18, and 49 cm (Clark *et al.* 1968*a*, *b;* Kellermann *et al.* 1968; Jauncey *et al.* 1970). The sensitivity of these observations was typically 2–4 f.u., except at 49 cm, where, with the 306-m (1000-foot) Arecibo reflector, it was possible to measure fringe amplitudes down to 1 f.u. On the other hand, the limited sky coverage of the Arecibo reflector limited the number of sources observed, and the relatively long wavelength limited the resolution to about 0".01. Similar sensitivities at long wavelengths were obtained by Broten *et al.* (1969).

To obtain both higher resolution and increased sensitivity, we have used the 64-m (210-foot) antenna at Goldstone, California, and the 26-m (85-foot) antenna at Tidbinbilla, near Canberra, Australia, as a two-element interferometer. These antennas are part of the NASA Deep Space Network, and both are equipped with low-noise systems for operation at 13.1-cm wavelength. The baseline is 10592 km long, or 81

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million wavelengths at the operating wavelength of 13.1 cm. Sources larger than 7×10^{-4} seconds of arc are resolved with this interferometer. This pair of antennas has also been used as a very-narrow-bandwidth interferometer by Gubbay *et al.* (1969*a*, *b*); their 1969 June 8–9 observations were made simultaneously with ours (Gubbay *et al.* 1969*b*).

II. THE OBSERVATIONS

The observations were made on 1969 June 1–2 and 8–9. The data-recording system and reduction procedure have been described previously (Clark *et al.* 1968*b*). The signal in a 350-kHz band is recorded digitally, with one-bit samples, on magnetic tape. Each station had a rubidium-vapor frequency standard which controlled the local oscillator and also controlled the clock which started the tape and determined the sample rate. The clock at Tidbinbilla was synchronized to the one at Goldstone by transmitting a radar signal from one antenna to the other via the Moon. This procedure, which is a routine operation of the Deep Space Network, is accurate to a few microseconds. Each observation of a source lasts 3 min. The correlation of the pairs of tapes was done on an IBM 360/75 computer at Caltech, where reduction of one pair typically required about 10 min.

The phase of the interference fringes is lost with this interferometer, because the rubidium oscillators do not have the requisite stability. The fringe frequency, however, can be measured with an accuracy of a few millihertz. The interval between arrival times at the two stations can also be measured with an accuracy of a few tenths of a microsecond. These two quantities can give source positions accurate to 1″ or 2″. The position of the compact source in 3C 274 derived this way has already been published (Cohen *et al.* 1969); positions for others will be published later.

The observations were made at 2296 MHz, with right-circular polarization. The system temperature at the 64-m telescope was usually about 25° K but increased to 40° K for observations near the horizon. The power received from the source 3C 274 raised the system temperature by more than a factor of 3. At the 26-m telescope, the system temperature varied from 35° to 45° K. The resulting interferometer pair was equivalent in sensitivity to two 40-m antennas each operating with a system at 30° K. The minimum detectable flux for a 3-min observation with a bandwidth of 350 kHz was about 0.3 f.u. In most cases, the pointing of the 64-m telescope was checked by peaking up on the source just prior to the observation. This was not necessary with the 26-m antenna, since its beam width is 21′ and the pointing was measured to an accuracy of $\pm 1'$ prior to the experiment.

Since the antennas were located nearly diametrically on the Earth, the time of common source visibility was short and all observations were made near the interferometer meridian. The effective baseline was about 80 million wavelengths. The position angle of the baseline projected on the sky was between 30° and 50°.

Sources were chosen for observation because we suspected that they contained small components. In many instances, they had been observed previously with high-resolution interferometers at other wavelengths, and we wished to study the dependence of the small-scale structure on wavelength. In other cases, the form of the radio spectrum, the presence of time variations, or the presence of interplanetary scintillations had suggested small-scale structure. A total of eighty sources were observed, of which fifty-six showed fringes.

Most sources were observed twice in succession, with a 10-min interval between successive runs. The difference in the two measurements of fringe amplitude was typically about 0.05 f.u. rms for the weak sources (fringe amplitude $\lesssim 2$ f.u.) and about 2 percent for the strong sources. The scatter for the weaker sources is due to receiver noise and is consistent with the system parameters. Differences for the stronger sources are due mostly to errors introduced in determining the cross-correlation coefficient.

Eleven sources were measured both on June 1–2 and on June 8–9. Differences between fringe amplitudes taken a week apart are usually no greater than those taken 10 min apart, so in most cases all observations on a source were averaged together. In two cases (3C 120 and PKS 1116+12), one member of a pair of observations shows fringes and the other does not; and in two more cases (3C 345 and PKS 0734−006), there is a large difference ($\gtrsim$30 percent) between the members of a pair. In these cases, we have assumed that there was a gross local oscillator instability or error in oscillator frequency, and we have rejected the smaller value from the pair. The source 3C 120 may also have been affected by interplanetary scintillations. On June 2 its scintillation index was observed to be 7 percent and the measured fringe amplitudes were 0.74 and $\leq$0.3 f.u. On June 9 it appeared normal; the two measured values of fringe amplitude were in good agreement. This is the only discordant case for observations taken a week apart, and the June 2 values were rejected. One other source with fringes, NRAO 140, showed scintillations, but it was only observed 1 day and the effect of the interplanetary medium on the observed fringe amplitude is unknown.

There are also errors in fringe amplitude due to the uncertainty in the determination of system temperature, since the correlated flux measurement is proportional to the product of the cross-correlation coefficient and the geometric mean of the two system temperatures. At both stations, an uncertainty in system temperature of up to $\pm 1^\circ$ K was probable, and rather large errors may have been introduced occasionally. These errors thus run up to $\pm$5 percent and affect equally both measurements in a pair. In most cases, we regard the error in one measurement as $\pm$(0.05 f.u. +5 percent). In some cases, the errors quoted in the visibilities are increased to reflect imperfect knowledge of the total flux density.

The largest source of error in interpreting the results comes from the difficulty in calibrating the interferometer sensitivity. At this resolution (10^{-3} seconds of arc), there are no sources which, a priori, can be assumed to be unresolved and therefore used to determine the fringe intensity scale. The scale is bounded by the fact that fringe visibilities cannot exceed unity, and in fact the five sources of highest visibility, DW 1555+00, NRAO 512, PKS 1741−03, PKS 2131−02, and PKS 2345−16, have approximately the same visibility, so it is tempting to conclude that this visibility is indeed unity. This is confirmed by the visibilities of other sources whose structures are known approximately from previous high-resolution measurements and the radio spectra. The calibration is consistent with the measured system temperatures and cross-correlation coefficients. The fringe visibilities quoted below are not systematically low by more than 10 percent, and we believe that they are not too high by more than 20 percent.

III. RESULTS

The results of the observations are presented in Table 1. Column (1) gives the source name, column (2) the number of observations, column (3) the measured fringe amplitude in flux units, and column (4) the total flux density either measured from the Goldstone total power records or estimated from interpolation of the spectrum. Column (5) gives the fringe visibility and its uncertainty, and column (6) gives the angular size and its uncertainty, if it can be inferred (width at half height of a circular Gaussian). Complex sources have an asterisk in column (6), while the completely resolved sources are indicated by an *R*. Column (7) lists previously published diameters or limits of some of the resolved sources. These are based on previous interferometer measurements (Clark *et al.* 1968*a*, *b;* Kellermann *et al.* 1968; Clarke *et al.* 1969; Cohen 1969; Jauncey *et al.* 1970; Heeschen 1970) or on the observation of interplanetary scintillation (Harris and Hardebeck 1969). Data obtained from interplanetary scintillations are shown in parentheses in column (7). The errors given in column (5) include only the uncertainty in the relative fringe amplitudes and do not include the uncertainty in the calibration

TABLE 1

RESULTS OF THE INTERFEROMETER OBSERVATIONS

Source (1)	No. of Obser-vations (2)	Correlated Flux (f.u.) (3)	Total Flux (f.u.) (4)	γ (5)	θ (seconds of arc) (6)	θ (seconds of arc) (7)
PKS 0019−00.......	1	<0.30	2.1	<0.14	*R*	0.015
NGC 253............	2	<0.30	3.7	<0.08	*R*	...
PKS 0048−09.......	1	0.70	1.3	<0.54 ±0.07	*	...
PKS 0056−00.......	1	<0.30	2.0	<0.15	*R*	...
PKS 0106+01.......	2	1.42	1.8	0.79 ±0.07	*	...
PKS 0122−00.......	1	0.36	1.4	0.26 ±0.05	*	...
3C 48...............	2	<0.30	13.5	<0.02	*R*	0.35
3C 49...............	1	<0.30	1.8	<0.17	*R*	(≤0.04)
DW 0202+31........	2	0.33	0.9	0.36 ±0.06	*	...
PKS 0202−17.......	2	0.32	1.2	0.27 ±0.05	*	...
PKS 0229+13.......	2	0.30	1.4	0.21 ±0.05	*	...
CTD 20.............	2	0.71	1.3	0.55 ±0.08	*	...
PKS 0237−23.......	2	0.64	5.8	0.11 ±0.02	0.0020±0.0002	...
NGC 1052...........	3	<0.30	0.6	<0.50	*R*	≤2
3C 71...............	2	<0.30	3.3	<0.09	*R*	(≲0.3)
NRAO 140..........	2	1.32	2.8	0.47 ±0.05	*	...
CTA 26.............	2	1.32	2.0	0.66 ±0.06	*	...
PKS 0420−01.......	2	0.88	1.6	0.55 ±0.06	*	...
2C 120..............	2	1.12	7.0	0.16 ±0.02	*	...
PKS 0438−43.......	2	4.22	5.7	0.74 ±0.05	*	...
NRAO 190..........	2	1.80	2.9	0.62 ±0.05	0.0009±0.0002	...
PKS 0451−28.......	2	0.77	2.2	0.35 ±0.04	*	...
PKS 0605−08.......	2	1.89	3.1	0.61 ±0.05	*	...
PKS 0607−15.......	2	0.76	2.3	0.33 ±0.04	*	...
3C 161..............	2	<0.30	13.5	<0.02	*R*	0.4
PKS 0727−11.......	2	1.43	2.1	0.68 ±0.07	*	...
PKS 0735+17.......	2	0.74	2.3	0.32 ±0.04	*	...
PKS 0736+01.......	2	0.88	2.1	0.40 ±0.04	*	...
LHE 210............	1	<0.30	5.2	<0.06	*R*	≲0.06
DW 0742+10........	2	0.85	3.7	0.23 ±0.04	*	...
PKS 0743−006......	1	0.56	1.1	0.51 ±0.08	*	...
PKS 0818+17.......	1	0.30	1.2	<0.25	*R*	(≤0.08)
PKS 0829+18.......	2	<0.30	1.1	<0.27	*R*	(≲0.17)
PKS 0834−20.......	1	<0.30	3.1	<0.10	*R*	≲0.06
PKS 0920−39.......	1	<0.3	1.7	<0.18	*R*	...
4C 39.25............	2	2.55	3.8	0.67 ±0.05	*	0.0007
PKS 1015−31.......	2	<0.30	2.5	<0.12	*R*	...
PKS 1055+01.......	2	1.46	2.8	0.52 ±0.05	*	...
PKS 1116+12.......	1	0.50	1.8	0.28 ±0.05	*	...
PKS 1127−14.......	2	0.99	6.2	0.16 ±0.02	*	...
PKS 1148−00.......	2	0.39	2.8	0.14 ±0.03	0.0019±0.0003	...
PKS 1151−34.......	2	<0.30	4.3	<0.07	*R*	...
PKS 1213−17.......	2	0.75	1.5	0.50 ±0.07	*	...
NGC 4278...........	2	<0.30	0.5	<0.60	*R*	≤0.25
3C 273..............	5	1.90	39.0	0.05 ±0.01	*	...
3C 274..............	4	0.70	138	0.005±0.001	*	...
PKS 1245−19.......	2	<0.30	3.9	<0.08	*R*	<0.06
PKS 1252+11.......	2	0.71	1.0	0.71 ±0.10	*	...
3C 279..............	2	3.18	12.2	0.26 ±0.02	*	...
3C 287..............	2	<0.30	5.2	<0.06	*R*	0.025
3C 286..............	2	<0.30	11.2	<0.03	*R*	0.03
PKS 1345+12.......	2	<0.30	3.9	<0.08	*R*	(≤0.2)
OQ 208.............	2	0.30	1.7	0.17 ±0.04	0.0018±0.0003	...
3C 298..............	2	<0.30	3.2	<0.09	*R*	(≤0.2)
PKS 1504−167......	2	0.41	2.4	0.17 ±0.03	*	...
PKS 1508−05.......	2	0.39	2.8	0.14 ±0.04	*	...

* Complex sources.

TABLE 1—*Continued*

Source (1)	No. of Obser-vations (2)	Correlated Flux (f.u.) (3)	Total Flux (f.u.) (4)	γ (5)	θ (seconds of arc) (6)	θ (seconds of arc) (7)
PKS 1510−08	4	1.39	3.4	0.41± 0.03	*	...
4C 05.64	2	1.00	2.5	0.40± 0.04	*	...
DW 1555+00	2	2.00	2.2	0.91± 0.07	≲0.0009	...
CTD 93	2	0.48	3.4	0.14± 0.02	0.0019±0.0002	...
DA 406	4	1.60	2.9	0.55± 0.05	*	...
PKS 1622−29	2	0.65	1.7	0.38± 0.05	*	...
NRAO 512	2	0.57	0.7	0.81± 0.19	≲0.0013	...
3C 345	3	2.54	6.1	0.41± 0.03	*	...
PKS 1645+17	2	<0.30	1.4	<0.20	*R*	...
NRAO 530	4	0.39	4.3	0.09± 0.02	*	...
PKS 1741−038	2	1.90	1.9	1.00± 0.10	≲0.0008	...
PKS 1821+10	2	0.58	0.8	0.73± 0.10	*	...
PKS 2127+04	2	0.45	3.2	0.14± 0.02	0.0019±0.0002	...
PKS 2128−12	2	0.30	1.8	0.16± 0.05	*	...
PKS 2131−021	2	0.40	0.4	1.00± 0.30	≲0.001	...
PKS 2134+004	4	2.05	6.4	0.32± 0.03	0.0015±0.0002	...
PKS 2145+06	2	2.11	3.3	0.64± 0.04	*	...
VRO 42.22.01	2	1.32	6.0	0.22± 0.02	*	...
PKS 2203−18	1	<0.30	5.2	<0.06	*R*	0.05
PKS 2210+01	1	<0.30	1.9	<0.16	*R*	(≤0.2)
3C 446	2	1.04	5.5	0.19± 0.02	*	...
CTA 102	4	0.94	5.2	0.18± 0.02	*	...
3C 454.3	4	6.38	15.2	0.42± 0.02	*	...
PKS 2345−16	2	3.40	3.3	1.03± 0.07	≲0.0007	...

of the fringe intensity scale. The quoted uncertainty in the angular size (col. [6]) does, however, include this.

Fifty-six sources show clear interference fringes, of which all but five appear to be partially resolved. It is difficult to interpret uniquely these partially resolved sources, since there are no observations of lesser resolution near our wavelength and we have only one point on the visibility function. Seven of the partially resolved sources have a simple radio spectrum, which indicates that they may consist of a single component which has a reasonably well-defined size. In such cases, the single measurement was used to estimate the source diameter. These diameters are given in column (6) of Table 1.

These seven resolved sources all have brightness temperatures near 10^{11} ° K; the magnetic-field strength, estimated from this measured brightness and the spectrum cutoff frequency, is between 10^{-2} and 10^{-5} gauss. These quantities do not differ significantly from those determined in our earlier measurements (Kellermann *et al.* 1968; Kellermann and Pauliny-Toth 1969). Two of the seven sources, PKS 2134+004 and CTD 93, have been studied by previous interferometer observations at very high resolution. The sizes given in Table 1 are in reasonable agreement with the earlier measurements: CTD 93 at 18 cm has angular size $\theta = 0''.003 \pm 0''.001$, and PKS 2134+004 at 6 cm has $\theta = 0''.0010 \pm 0''.0005$ (Kellermann *et al.* 1968). This supports the interpretation that they are simple sources whose brightness distribution is independent of wavelength. The other sources in Table 1 either have never been studied before at high resolution or else have upper limits to the diameter which are an order of magnitude greater than the values reported here (cf. Cohen 1969; Clarke *et al.* 1969).

The remaining forty-four sources with detectable fringes show fringe visibilities less than unity; they also have complex radio spectra and are thought to have a complex brightness distribution consisting of two or more components. These sources all contain structure on a scale of 0".001, but a detailed description is not possible without observations over shorter baselines. Generally, the observed fringe amplitude may be considered an estimate of the flux density contained in components less than 0".001.

In six cases, observations have been made to comparable resolution at 6 cm. In each of these cases, the fringe visibility is bigger at 6 cm than at 13 cm, which supports the hypothesis that these sources are complex, with the higher-frequency components having the smaller diameters. Most of these sources are also variable, so that a complete discussion cannot be made without having synoptic data as well.

One source in Table 1, CTA 102, had previously been assigned a diameter (0".004 ± 0".0015) based on observations at 18 cm and the assumption that it was a simple source. The present observations, however, show that it is complex, with some structure on the order of 0".001 or smaller.

The results for 3C 274 have already been reported by Cohen *et al.* (1969). It was shown there that the compact radio component is coincident with the nucleus of M87 and has a linear diameter of 3 light months or less. The fringe visibility listed in Table 1, 0.005, is based on the total flux density of 3C 274. The fringe visibility of the compact component by itself is 0.2 or greater.

Three sources listed in Table 1, 3C 273, 3C 279, and PKS 1510−08, have also been observed at the same frequency and spacing by Gubbay *et al.* (1969*b*), who used a much narrower recording bandwidth. In fact, their measurements on 1969 June 8–9 were made simultaneously with those reported here. The intermediate-frequency signal was split and fed to independent recording systems, so the same fringe amplitudes should be seen in the two observations. Comparison of their results with those given in this paper for these three sources and for three others also observed by Gubbay *et al.* but not yet published (private communication) indicates that their fringe amplitudes are about 40 percent higher than those in Table 1. As noted above, it is very unlikely that the amplitudes in Table 1 can be systematically raised by more than 10 percent.

IV. COMPLETELY RESOLVED SOURCES

In Table 1 we also list twenty-four sources which did not show interference fringes and which were not close enough to the Sun to show interplanetary scintillations. In previous reports, we did not list such negative results, because their reliability was low. In this case, however, the internal consistency is very good. A measure of reliability is obtained by examining the sources which did show fringes. There are sixty-four cases where a source was observed twice (or three times) in succession. As discussed above, four of these had something wrong with one measurement (both measurements for 3C 120 on June 2); thus, the "error rate" is five per 129 observations. Table 1 contains nine undetected sources with only one observation (col. [2]); it is unlikely that more than one of these is erroneous. The remainder have two or three observations each; the chance that both results are false is negligibly small. Systematic errors in observation, such as telescope pointing errors on the 26-m antenna, are unlikely but would affect both observations of a pair. A more serious possible cause for failure to observe fringes from a source is bad position. The reduction typically searched 10"–30" around an assumed position; if the position error were greater, any fringes may have been missed. However, this could have happened in only a few cases, since most of these sources are well known and usually have positions in the literature that are probably more accurate than 15".

We conclude that nearly all the sources in Table 1 with upper limits to correlated flux in column (3) show no fringes because they are resolved. Most of the flux density of these sources must come from a region greater than about 0".002.

V. CONCLUSIONS

These observations show that many extragalactic radio sources, including both quasi-stellar sources and radio galaxies, contain significant small-scale structure on a scale of 0″.001 or less. It is not possible to quote accurate statistics on the occurrence of small components of radio sources, because the sources we observed were chosen, on the basis of other data, as likely to have components of small angular size. However, for the stronger sources, the angular sizes have been extensively investigated by other interferometers of lower resolution, and it is improbable that the strong sources which we have not looked at have small angular structure containing an appreciable part of the flux. Of the seventy-three known extragalactic sources in the zone of visibility of this interferometer and having 1400-MHz flux densities in excess of 5 f.u., ten (excluding 3C 274, which has only a very small fraction of its flux in a small component) show fringes and are listed in Table 1. Thus, we believe that approximately 15 percent of radio sources strong at decimeter wavelengths exhibit structure of angular size 0″.002 or smaller. From this, we suggest that those sources which contain regions of extremely small size show such structure for at least 15 percent of their lifetimes as strong radio sources.

Considerably more extensive measurements with shorter baselines are needed in order to determine the detailed brightness distributions of the sources with any accuracy. The extensive facilities of the NASA Deep Space Network, with stations widely distributed on the Earth, are well-suited to this type of measurement.

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