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MAPS OF THE QUASARS 3C 119, 3C 286, 3C 345, 3C 454.3, AND CTA 102 WITH A RESOLUTION OF 5 MILLI-ARCSECONDS AT 1.67 GHz

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ABSTRACT

The five quasars have been observed with a VLB array of four telescopes; hybrid maps made from the observed visibility amplitudes and closure phases are presented. All the sources show structure on a scale of 0".01, and an asymmetric core-jet morphology is found to be common in compact, flat-spectrum radio sources.

Subject headings: interferometry — quasars — radio sources: variable

I. INTRODUCTION

The five radio sources 3C 119, 3C 286, 3C 345, 3C 454.3, and CTA 102 are typical of the compact sources identified with quasi-stellar objects. In all five most of the flux density originates in a flat-spectrum component smaller than 0".2 and coincident with the quasar (Elsmore and Ryle 1976), although in at least two (3C 345 and 3C 454.3) there is a weaker, steep-spectrum component a few seconds of arc away (Davis, Stannard, and Conway 1977). Four of the sources (all except 3C 119) are known to be variable at frequencies greater than a few gigahertz (e.g., Andrew *et al.* 1978), and two (CTA 102 and 3C 454.3) are also variable at frequencies below 1 GHz (e.g., Sholomitskij 1965, 1966; Hunstead 1972; Condon *et al.* 1979).

Previous studies with very long baseline interferometers (VLBI) (e.g., Wittels *et al.* 1975; Cohen *et al.* 1979; Kellermann *et al.* 1977) have shown that the nuclei of 3C 345, CTA 102, and 3C 454.3 all contain structure on scales less than 10^{-3} arcsec; 3C 454.3, in particular, contains a component which is unresolved on the longest available baselines at 15 GHz. There is some evidence from these studies that the fine-scale structure is frequency-dependent, with larger-scale structure being visible at lower frequencies; but the low-frequency structure has not yet been adequately studied.

The observations reported here were made at 1.67 GHz (wavelength 18 cm) with a maximum resolution of about 0".005 and show the structure of the sources in some detail. Complementary observations of 3C 286, 3C 345, 3C 454.3, and CTA 102 at 0.6 GHz have already been published (Wilkinson *et al.* 1979), and observations of 3C 286 have been made at 0.3 GHz (Simon *et al.* 1980). Taken together, these high-resolution, multifrequency observations provide important constraints on the energy sources and emission mechanisms which may be operating in the sources.

II. THE OBSERVATIONS

The observations were made in 1976 May using four telescopes located at random in the United States (Table 1). The locations of the telescopes and the details of the observing technique have been given by Cohen *et al.* (1975) and will not be repeated here. The journal of observations is given in Table 2, from which the reader can determine the (u, v) coverage; for the high-declination sources (3C 119, 3C 286, and 3C 345) the coverage is fairly uniform and leads to a good synthesized beam shape, and even for the two at low declinations (CTA 102 and 3C 454.3) the coverage is adequate to map the sources. Table 2 also lists the position, flux density, and redshift of each source and the distance at the source corresponding to 1 milli-arcsec. The redshift of 3C 119 has not been measured.

The standard Mark II recording system was used (Clark 1973): the central frequency was 1.671 GHz with a 2 MHz bandwidth, and the received polarization was linear with *E*-vector in position angle 0. The data were cross-correlated using the three-station CIT/JPL Interferometry Processor at the California Institute of Technology in 1978 January–March. The output from the correlator was averaged coherently over intervals of 4 minutes and further processed to obtain the amplitudes of the visibility function on each of the six baselines and the closure phase around each triangle of three telescopes (Rogers *et al.* 1974). The amplitudes were calibrated using the measured system temperatures and sensitivities of the four telescopes (Table 1), the relative calibration of different baselines being determined by inspection of their crossing-points in the (u, v)-plane. The absolute and relative scaling of the various baselines is uncertain by about 5%. The observed amplitudes and closure phases are shown in Figure 1.

Two methods were used to interpret the observations. First, simple models of the sources, consisting of two or three Gaussian components, were derived

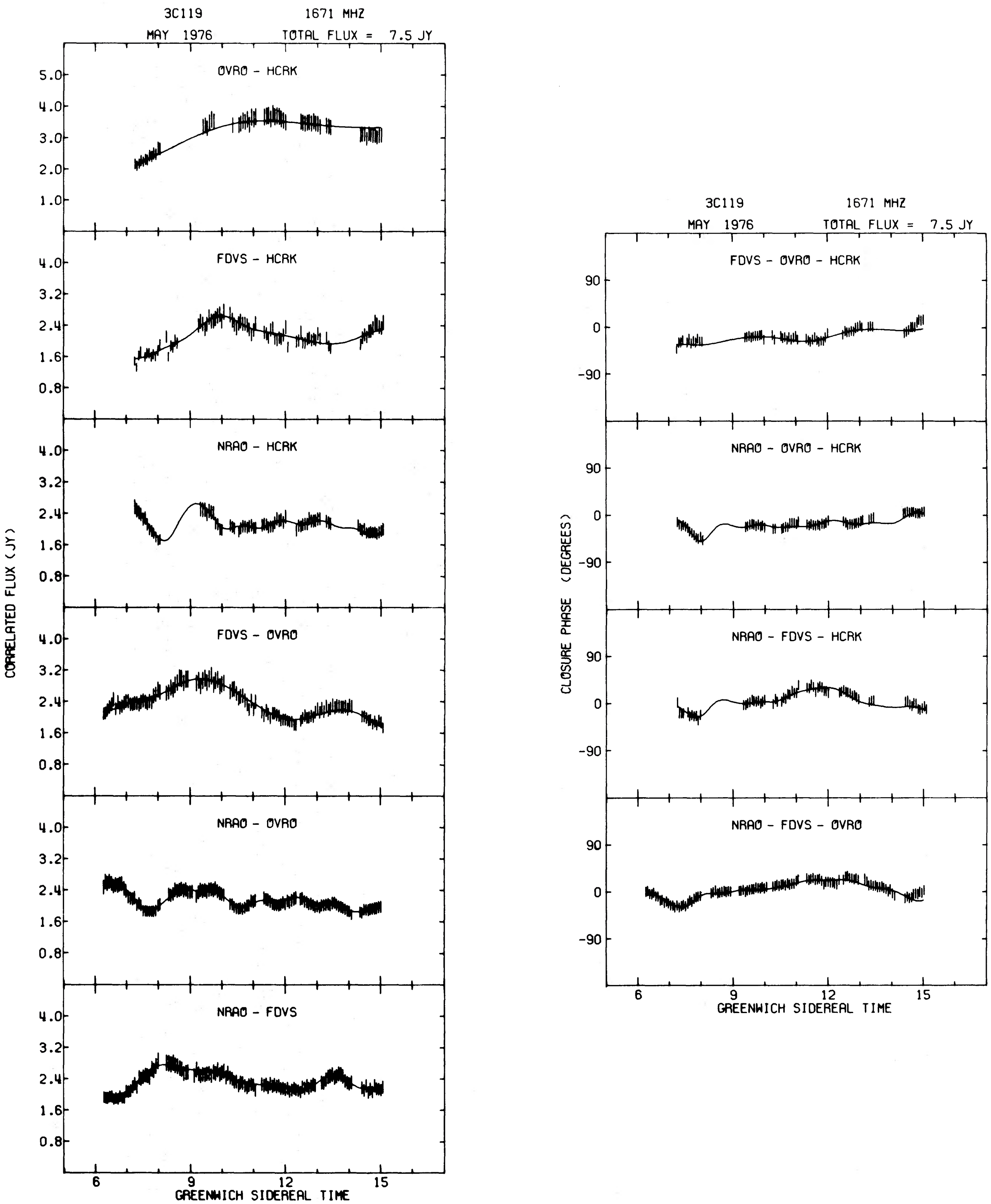

FIG. 1.—Observed visibility amplitudes and closure phases. The solid curves correspond to the brightness temperature distributions of Fig. 2 (prior to convolution with the restoring beam shape); the measurements are represented by 2 σ error bars. The amplitude errors include an estimate of the error in the calibration, which is not independent from point to point. Closure phase is defined as the algebraic sum of the visibility phases around the triangle formed by three telescopes (Rogers *et al.* 1974). The four telescopes are identified by the abbreviations given in Table 1.

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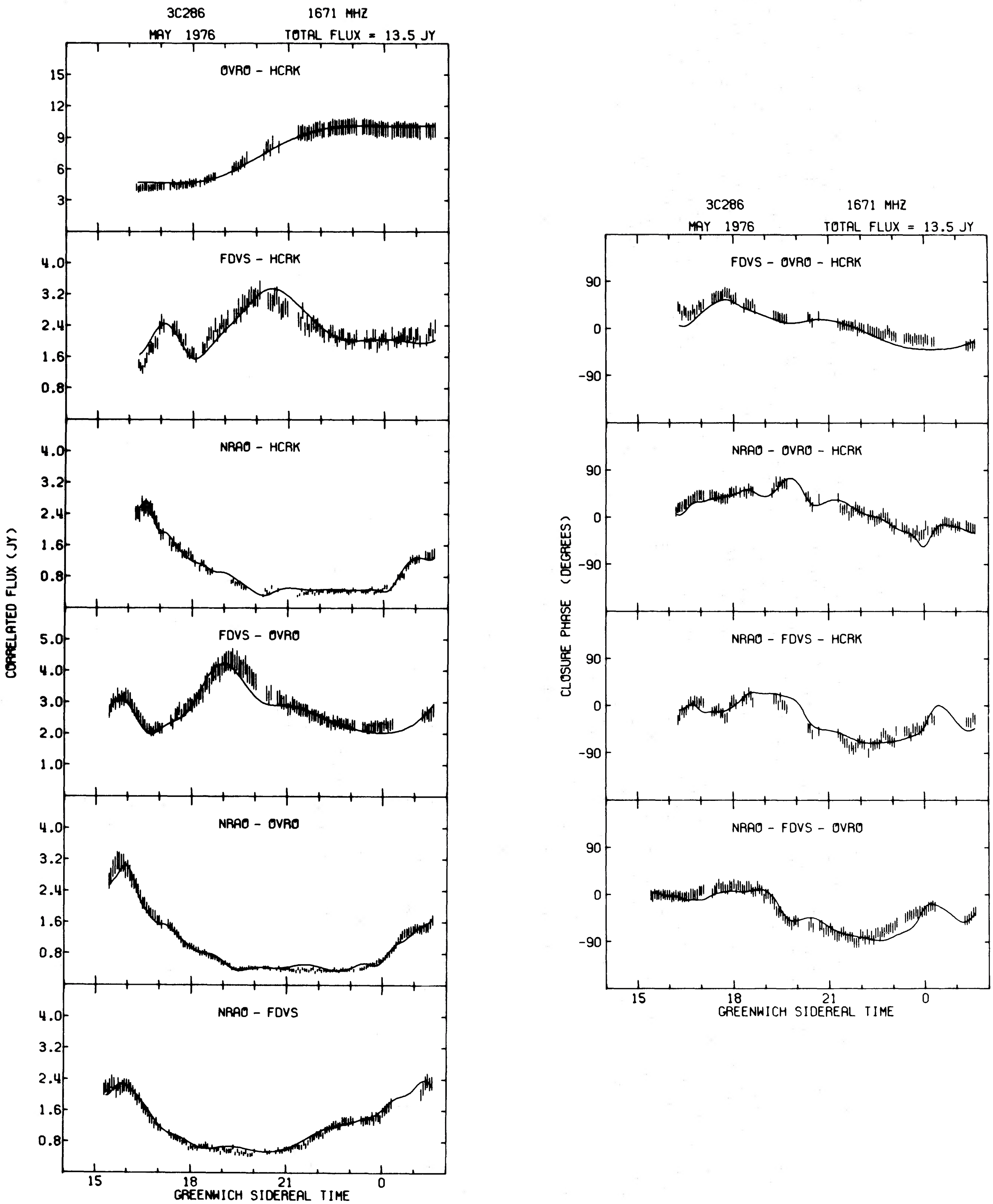


FIG. 1.—*Continued*

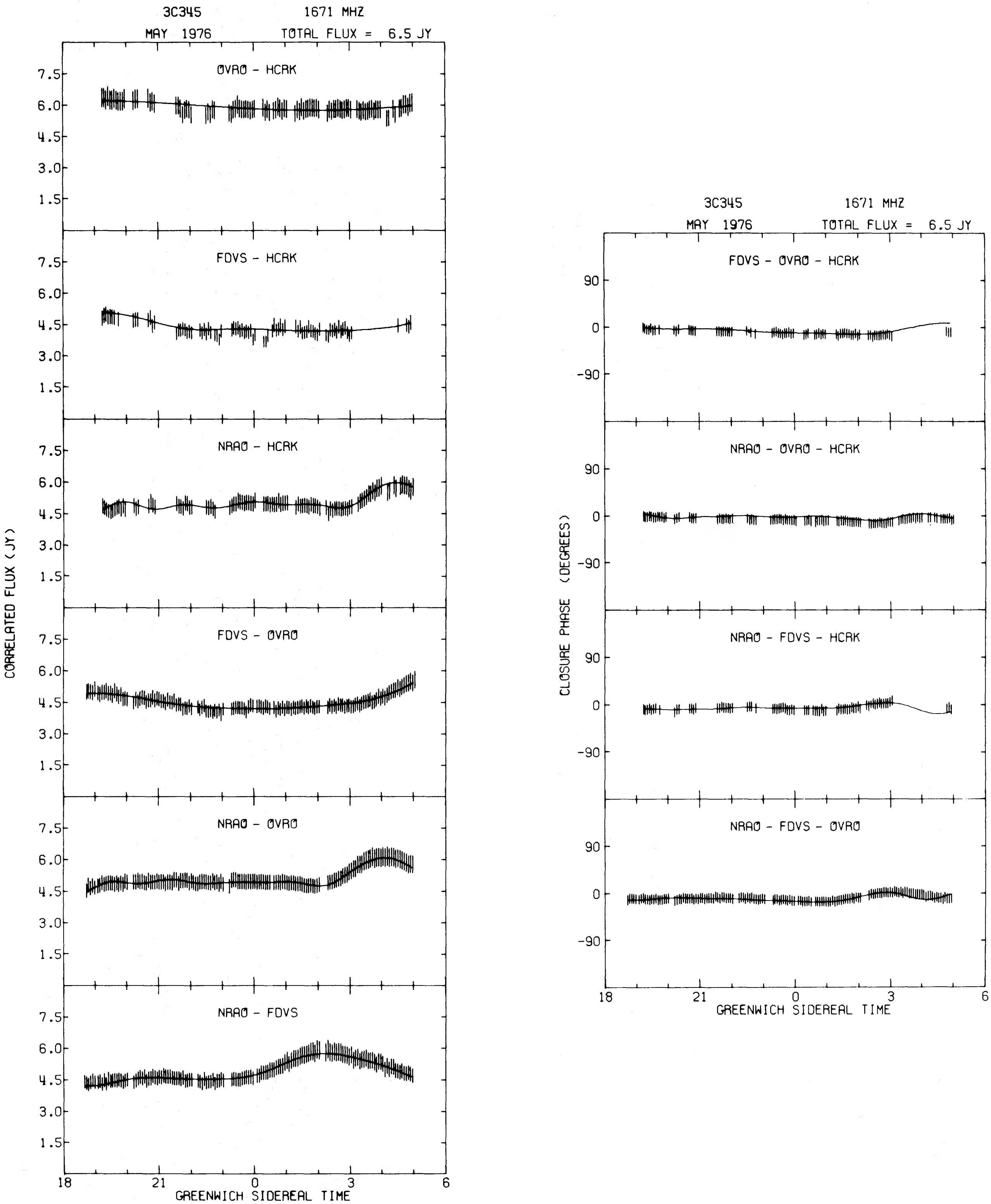
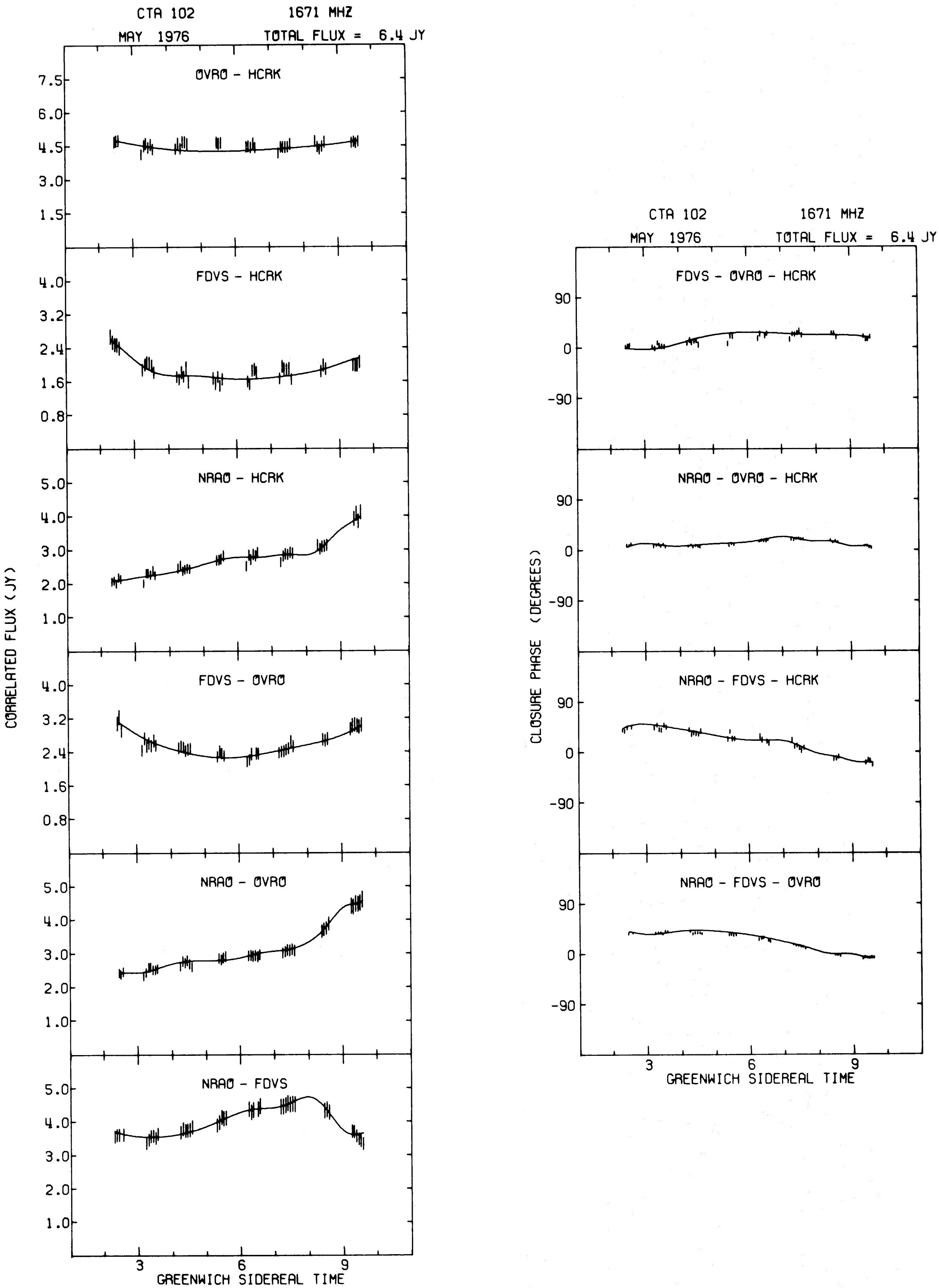


FIG. 1.—*Continued*



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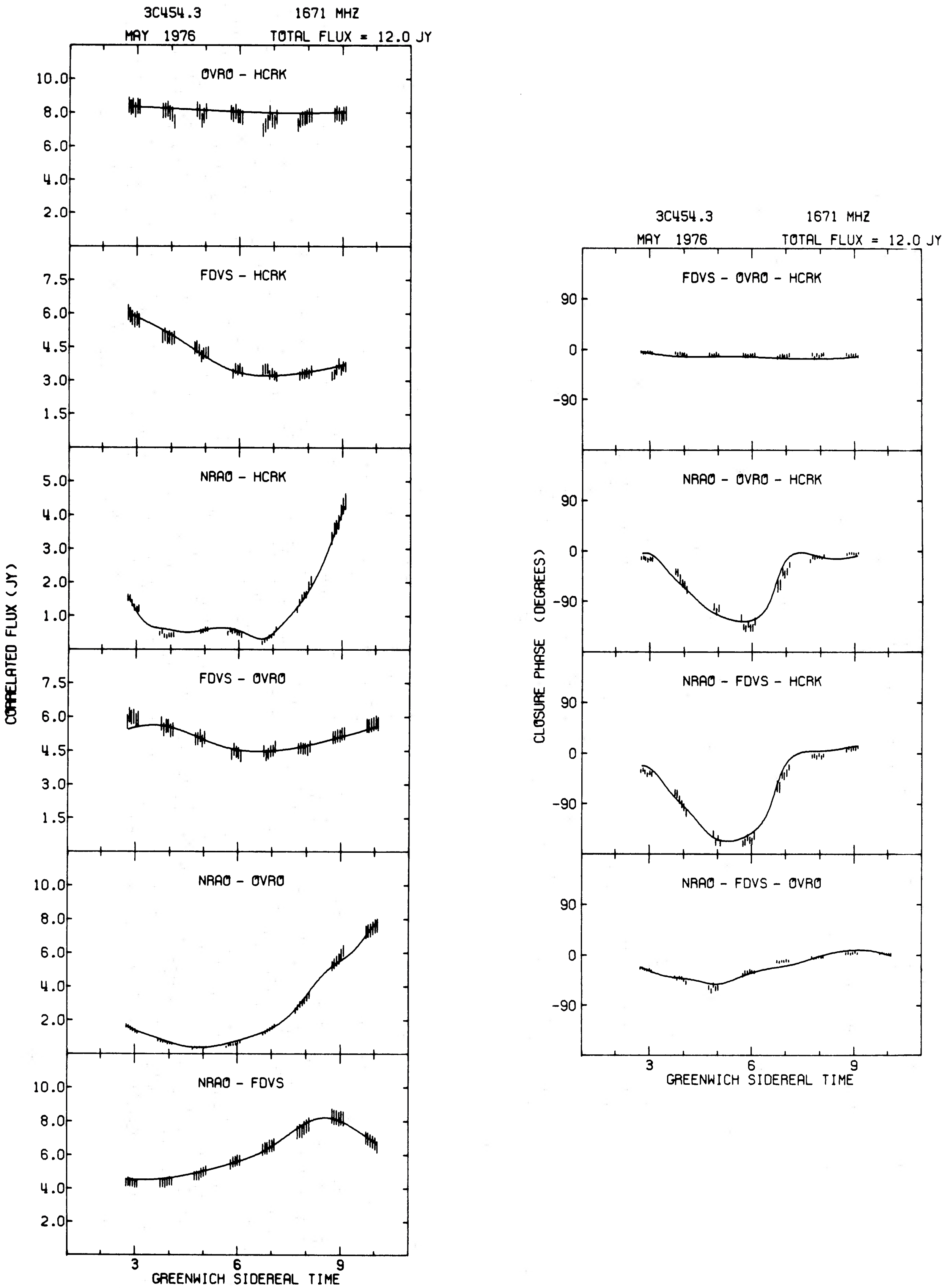

FIG. 1.—*Continued*

TABLE 1

INTERFEROMETER ELEMENTS

Antenna	Location	Diameter (m)	System Temperature (K)	Sensitivity (K/Jy)	Frequency Standard
NRAO.......	National Radio Astronomy Observatory, Green Bank, WV	43	60	0.26	Hydrogen maser
FDVS.......	Harvard Radio Astronomy Station, Fort Davis, TX	26	140	0.10	Rubidium vapor
OVRO.......	Owens Valley Radio Observatory, CA	40	70	0.23	Hydrogen maser
HCRK.......	University of California, Hat Creek Radio Astronomy Station, CA	26	120	0.10	Rubidium vapor

TABLE 2

THE SOURCES

Source Name	R.A. and Decl. (1950.0)[a]	Observing Period (UT): 1976	Redshift	Flux Density (Jy)	Length Subtending 10^{-3} Arcsec (pc)[c]
0429+415 (3C 119)......	04 29 07.90 41 32 08.5	May 23 13:00–23:00	...	7.5	...
1328+307 (3C 286)......	13 28 49.65 30 45 58.7	May 23 23:00–May 24 09:30	0.849	13.5	8.3
1641+399 (3C 345)......	16 41 17.60 39 54 10.8	May 23 02:30–13:00	0.595	6.5	7.6
2230+114 (CTA 102)....	22 30 07.79 11 28 22.4	May 24 10:00–17:30[b]	1.037	6.4	8.5
2251+158 (3C 454.3)....	22 51 29.51 15 52 54.2	May 24 10:30–18:00[b]	0.859	12.0	8.3

[a] From Elsmore and Ryle 1976.

[b] CTA 102 and 3C 454.3 were observed during alternate 30-minute periods.

[c] Assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

by least squares fitting to both the amplitudes and the closure phases. Second, "hybrid" maps were made using the technique introduced by Readhead and Wilkinson (1978). Both methods give very similar results for simple sources, which can be well represented by the simple Gaussian models; and for such sources model-fitting gives greater resolution than hybrid mapping. More complex sources, however, are very difficult to model, and for these the hybrid mapping procedure has great advantages. The accuracy of both the model-fitting and the hybrid mapping is limited by the uncertainty in the calibration and by the (u, v) coverage, which together restrict the dynamic range of the maps, so that components weaker than about 5% of the maximum brightness cannot be detected reliably.

Because the observations were made with linearly polarized feeds at only one position angle, the maps and models represent the distribution of $I + Q$ rather than the total intensity I. In compact sources such as these, the difference is likely to be large: for example, 3C 286 has an integrated linear polarization of 8.7% at 1.67 GHz (Morris and Berge 1964), and individual components may be more strongly polarized.

III. THE STRUCTURE OF THE SOURCES

a) 3C 119

There have been very few previous interferometric studies of 3C 119. Donaldson, Miley, and Palmer (1971), using a baseline of 127 km at 2694 and 1422 MHz, found it to be "probably double, separation $\lesssim$0.08 arcsec in position angle 150°." Clarke *et al.* (1969), using baselines between 0.7 and 3.2 × 10^6 wavelengths at 408 MHz, found two equal components separated either by 0″.29 in position angle 10°, or by 0″.14 in position angle 30° or 140°. The present observations (Fig. 1) show that it is not a simple double source; it was not possible to find a model with two Gaussian components to reproduce the measurements. Mapping the source proved difficult, because it is dominated by an almost unresolved component, so that the closure phases are relatively insensitive to changes in the low-brightness structure. The final hybrid map (Fig. 2) shows the two major features of the source: a bright central source (2.5 Jy) and a weaker component (~0.5 Jy) extended to the NE in position angle 55°. The details of this component are uncertain owing to the limited dynamic range of the map; in particular, the apparent separation from the central component (20 milli-arcsec) is poorly determined. Even on the shortest baseline (OVRO–HCRK) the maximum visibility is only about 0.5, suggesting that there is structure on a larger scale (~0″.1), which would be consistent with the observations of Donaldson *et al.* and of Clarke *et al.* Presumably the structure measured here is to be identified with one of the two components suggested by these authors. It is notable, however, that the position angle found here at the 20 milli-arcsec scale (55°) is very different from that of the larger-scale structure (~150°).

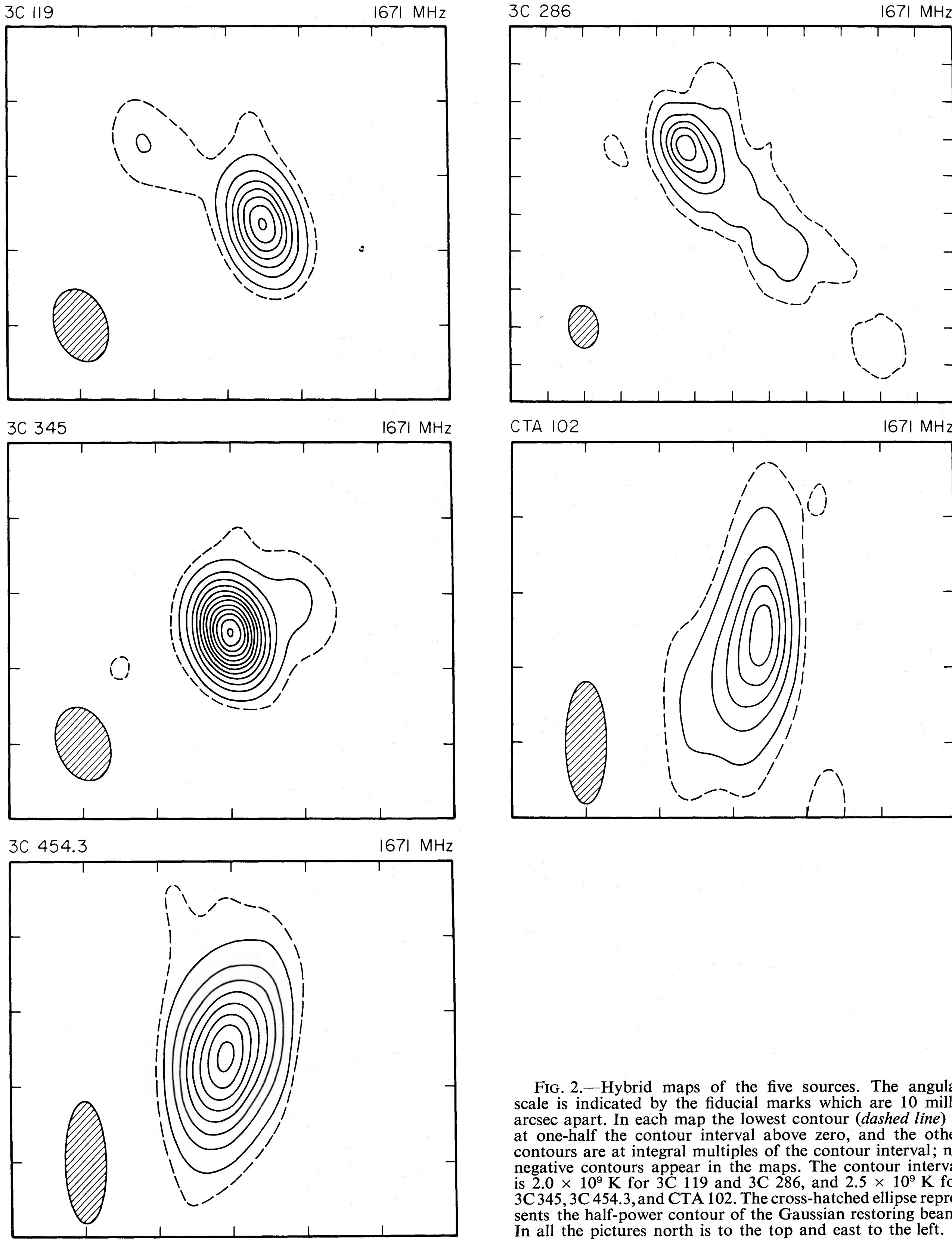

FIG. 2.—Hybrid maps of the five sources. The angular scale is indicated by the fiducial marks which are 10 milli-arcsec apart. In each map the lowest contour (*dashed line*) is at one-half the contour interval above zero, and the other contours are at integral multiples of the contour interval; no negative contours appear in the maps. The contour interval is 2.0×10^9 K for 3C 119 and 3C 286, and 2.5×10^9 K for 3C 345, 3C 454.3, and CTA 102. The cross-hatched ellipse represents the half-power contour of the Gaussian restoring beam. In all the pictures north is to the top and east to the left.

The spectrum of 3C 119 is convex (flatter at low frequencies) suggesting synchrotron self-absorption over a wide frequency range (Scott and Readhead 1977). It is clear that the present observations must be supplemented by observations at lower frequencies and preferably with shorter baselines to determine the complete structure of the source.

b) *3C 286*

The observations of 3C 286 (Fig. 1) indicate that like 3C 119 it has a complex structure that cannot be represented by a few Gaussian components. Starting the hybrid mapping with a three-component model, however, a satisfactory (though imperfect) fit was eventually obtained with the map shown in Figure 2. This shows that the emission region is very asymmetrical—it might be described as a "head-tail" source or as a "core" with a "jet." This 1.67 GHz map is very similar to the 0.6 GHz map of Wilkinson *et al.* (1979).

The direction of major elongation is in position angle $-135°$, and the overall extent in this direction is at least 0"08. This position angle is the same as that seen at 0.6 GHz, but the overall extent is greater by about 0"02. The core contributes about 3 Jy and the more extended regions about 10 Jy; the whole map includes almost all of the total flux density of the source at this frequency (13.5 Jy). The core has a flat spectrum between 0.6 and 1.67 GHz; the extended regions have a steeper spectrum. The paper of Simon *et al.* (1980) discusses the spectrum of 3C 286 in more detail.

c) *3C 345*

The closure phase for 3C 345 (Fig. 1) shows no large departure from zero, suggesting that the source is not very asymmetric; and the amplitudes are closely reproduced by a model consisting of an unresolved core of 4.5 Jy (<2 milli-arcsec in size) and an elongated halo of 1.7 Jy with FWHM 30×3 milli-arcsec in position angle $120° \pm 5°$. The size and location of the halo are very poorly determined. The hybrid map (Fig. 2) shows that the major extension is in position angle $-60°$ rather than $+120°$; this asymmetric structure is similar to that found in 3C 119 and 3C 286. The position angle found on this angular scale (~ 10 milli-arcsec) is intermediate between that seen in the central double source, which has a separation of ~ 2 milli-arcsec in position angle $-75°$ (Readhead *et al.* 1979) and that of the outer "jet" ($-31°$, Davis, Stannard, and Conway 1977). This is discussed further by Davis, Stannard, and Conway (1978) and by Readhead *et al.* (1978).

d) *CTA 102*

The visibility amplitude of CTA 102 varies between 0.25 and 0.70 over the part of the (u, v)-plane sampled. An excellent fit to the observed amplitudes and closure phases was obtained with a two-component model consisting of a 3.0 Jy point source (<2 milli-arcsec) and a 1.8 Jy Gaussian component with FWHM about 7 milli-arcsec. The compact "core" is displaced from the extended component by 10 milli-arcsec in position angle $-34°$. Starting with this model, the hybrid mapping procedure rapidly converged to the solution shown in Figure 2. The lowest contour (dashed line in Fig. 2) is rather uncertain, owing to inadequate (u, v) coverage at short baselines.

The results are consistent with the limited data obtained at the same frequency by Kellermann *et al.* (1971); the model described above, however, does not account for all the flux density of the source, and we cannot rule out the existence of a component with ~ 1.5 Jy on a scale greater than 0"1. The position angle of $-34°$ is similar to the 149° (or $-31°$) found at 0.6 GHz by Wilkinson *et al.* (1979) on the same angular scale. Clarke *et al.* (1969) found a similar structure at 448 MHz.

e) *3C 454.3*

The correlated flux density of 3C 454.3 on the shortest baseline (OVRO–HCRK) is about 8 Jy, or two-thirds of the total flux density; on the longer baselines, the visibility reaches a minimum of 0.02 in some position angles. The minimum can be interpreted most simply as indicating double structure on a scale of ~ 7 milli-arcsec in position angle 120°; the best-fitting two-component model of this type consists of an unresolved component of 2 Jy (<2 milli-arcsec in diameter) and an elliptical Gaussian of 5.7 Jy centered 6.7 milli-arcsec away in position angle 124°, with FWHM 5.9×4.4 milli-arcsec, extended in position angle 120°. Because of the negligible coverage of the (u, v)-plane beyond the minimum, though, it is not possible to discriminate between this and more complicated models. This is reflected in the hybrid map (Fig. 2), which simply shows the emission region elongated in position angle $\sim 130°$. Note that the details of the lowest contour in Figure 2 are uncertain owing to the inadequate short-baseline coverage, and the position angle of the source is distorted by the convolution with the restoring beam shape.

Shaffer and Schilizzi (1975) observed 3C 454.3 at the same frequency on the single baseline NRAO–OVRO and fitted their observations with a single Gaussian component $0''0095 \times 0''001$ in position angle 115°. The greater coverage of the present observations shows clearly that a more complex model is required.

At lower frequencies the structure is essentially the same; the earlier observations at 0.6 GHz (Wilkinson *et al.* 1979) and 0.45 GHz (Clarke *et al.* 1969) have been interpreted in terms of core-halo models in which the core has a long axis $\sim 0''01$ in position angle 120–140°. The position angle of the compact structure is approximately aligned with the overall axis of the source: the line joining the flat-spectrum nucleus (observed here) to the outer steep-spectrum component has position angle 131° (Davis *et al.* 1977). Note that the extended component in the two-component model described above is displaced from the compact "core" toward the outer component; in this respect 3C 454.3

is similar to 3C 345 and 3C 273. Davis *et al.* (1978) suggest that there is a significant difference between the axis of the compact component and the overall axis of the source; the present observations give a misalignment of $7° \pm 4°$.

IV. DISCUSSION

A moderately large number of compact, flat-spectrum radio sources have now been studied by means of VLBI observations with sufficient (u, v) coverage to make reliable maps. It is notable that most of these sources show a one-sided structure and that none has a clearly symmetric structure which could be directly related to the large-scale double structure found in extended, steep-spectrum radio galaxies and quasars.

Of the five sources for which maps are presented here, Davis *et al.* (1977) have shown that in two cases, 3C 345 and 3C 454.3, each has, in addition to the compact component coincident with the quasar, a second, larger component with a steeper spectrum. This places them in class D2 of the classification of Miley (1971). The distinction between D2 quasars and compact sources without an outer steep-spectrum component is not an absolute one, as it requires observations of high resolution and high dynamic range at low frequencies; and it is possible that the other objects discussed here could also belong to class D2. Indeed, there is evidence that both 3C 119 and 3C 286 have steep-spectrum components larger than about $0''.5$ (Scott and Readhead 1977). Only three confirmed D2 quasars have been studied with sufficient resolution to determine the structure of the flat-spectrum component: 3C 273, 3C 345, and 3C 454.3. In all of these, the flat-spectrum component can be resolved into a high-brightness "core" or "nucleus" and a lower-brightness "jet" directed approximately toward the outer steeper-spectrum component (Readhead *et al.* 1979, and the present paper). Davis *et al.* (1978) have shown that the magnetic field in the compact component of each of these three sources is approximately aligned with the "jet"; and the superluminal expansion seen in 3C 273 and 3C 345 (Cohen *et al.* 1979) is also parallel to this direction. Davis *et al.* (1978) and Readhead *et al.* (1978) have shown that there is a significant misalignment between the axis of the compact component and the overall axis of the source in 3C 273 and 3C 345; the present observations suggest a small but less significant misalignment in 3C 454.3.

If the compact, flat-spectrum sources mapped by Readhead *et al.* (1979), Readhead and Wilkinson (1980), and Wilkinson *et al.* (1979) are added to the sample, we have a total of 11 sources. Of these, seven (3C 120, 3C 147, 3C 273, 3C 286, 3C 345, 3C 380, and 3C 454.3) show a clear "core-jet" morphology, which may be defined as a compact component with an extended, steeper-spectrum component on one side. The remaining four sources (CTA 21, 3C 84, 3C 119, and CTA 102) do not show this morphology unambiguously, but in most cases the observations have been made at only one frequency and have insufficient resolution. It is notable that *no* sources are found to have a symmetric or double-sided structure, such as a central component with two steeper-spectrum jets.

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