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THE COMPACT RADIO SOURCES IN 4C 39.25 AND 3C 345

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ABSTRACT

Long-baseline interferometry of the quasars 4C 39.25 and 3C 345 at 10.65 and 14.77 GHz shows that the centimeter radio source in each object is double, with component separations of 0".0020 (4C 39.25) and 0".0013 (3C 345 at 1974.5). For each source, the separation is the same at both frequencies, as well as similar to the structure observed at 7.85 GHz (and 5.0 GHz for 4C 39.25). The spectra of the individual components are derived, and shown to vary with time approximately as expected for expanding self-absorbed synchrotron sources. The magnetic fields in the components are estimated to be as high as 0.1 gauss, but the structure of the sources appears to be unrelated to the magnetic field orientation derived from low-resolution polarization measurements. The component separation in 4C 39.25 has not changed for several years, whereas 3C 345 shows rapid expansion.

Subject headings: interferometry — quasars — radio sources: variable

I. INTRODUCTION

This paper presents new long-baseline interferometry data, taken at 10.65 and 14.77 GHz, on the compact radio structure in the quasars 4C 39.25 and 3C 345. These data and other observations have been combined to describe the overall nature of the radio sources.

The new observations at 10.65 GHz (2.8 cm) were made at epoch 1974.50 with antennas of the Owens Valley Radio Observatory (OVRO, 40 m), the Harvard Radio Astronomy Station (HRAS, 26 m), the National Radio Astronomy Observatory (NRAO, 43 m), and the Max-Planck-Institut für Radioastronomie (MPIR, 100 m). Other results from these observations have been reported by Pauliny-Toth *et al.* (1976) and Kellermann *et al.* (1977). Earlier, lower-resolution results for 4C 39.25 and 3C 345 were discussed by Shaffer *et al.* (1975). Additional information about the antennas, and a description of the observation, reduction, and calibration procedures, are given by Cohen *et al.* (1975) and Kellermann *et al.* (1977). This experiment has absolute and relative (one baseline with respect to another) uncertainties of at most ~10%.

The new data at 14.77 GHz (2.0 cm) are from two observing sessions of the "Quasar Patrol" in 1974 June and July, using the 64 m Goldstone Tracking Station (GSTN) of the NASA Deep Space Network, NRAO 43 m, and Haystack Observatory (HSTK) 37 m antennas. The observational procedures and data analysis were similar to those at 10.65 GHz, and the absolute and relative uncertainties are about the same: 10%. The internal consistency on a single baseline at 2.0 cm is better ($\lesssim 5\%$) because of better measurements of system temperatures and source antenna temperatures.

For all experiments, coherent integration periods of 15 s to 2 minutes were used. Typically, such integrations were then incoherently averaged for 8 minutes to arrive at one datum. Each such point is plotted in the visibility curves in Figures 1 and 3. In all but a few of the lowest minima, the calibration errors are larger than errors from system noise.

Two-component models with elliptical Gaussian brightness distributions for each component have been fitted to the data from the various experiments, using nonlinear least-squares procedures. Although these models are quite simple, the fits are very good. The parameters given for these models, while accurately describing the data, are only simplified representations

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TABLE 1

MODELS OF 4C 39.25

Epoch	Frequency (GHz)	Stations*	Separation (arcsec)	Position Angle (degrees)	S_A† (fu)	S_B† (fu)
1972.33	10.71	O–H–N	0.00201	100	9.0	2.1
1972.82	10.71	O–H–N	0.00195	97	9.1	2.3
1973.21	10.65	O–H–N	0.00203	99	9.9	2.6
1974.50	10.65	O–H–N–M	0.00196	97	7.7	3.2
1974.5	14.77	G–N–HK	0.00203	97	6.3	3.6
1974.05	5.0	O–H–N–M–OS	0.00202	96	6.9	1.6

* O = OVRO; H = HRAS; N = NRAO; M = MPIR; G = Goldstone; HK = Haystack; OS = Onsala.

† Flux densities of individual components. Components are Gaussians of ~0".0005 FWHM.

of more complex brightness distributions. However, there is no evidence of, or need for, a third component. Nearly all the flux density from both sources comes from two well-separated regions.

II. 4C 39.25

The quasar 4C 39.25 is a 17th-magnitude quasar with time-variable flux density at centimeter wavelengths. Its redshift is 0.698 (Lynds *et al.* 1966). For $H = 55$ km s^{-1} Mpc^{-1} (Sandage and Tammann 1975) and $q_0 = 0.04$ (Gott *et al.* 1974), an angle of 0".001 corresponds to a linear dimension of 28 light years in 4C 39.25, assuming cosmological redshifts.

The results of three earlier experiments at 10.7 GHz have been discussed by Shaffer *et al.* (1975). Table 1 shows the models which describe the earlier data, as well as the new results at 10.65 and 14.77 GHz. Table 1 also gives the results of a 5 GHz experiment at 1974.05 reported by Pauliny-Toth *et al.* (1977). The structure of the source is the same at all these frequencies: two ~0".0005 (FWHM) components separated by 0".0020 in position angle (P.A.) 98°. The variations of separation and position angle in Table 1 are not significant, and are consistent with the errors in determining those parameters. The 7.85 GHz data of Wittels *et al.* (1975) are also consistent with our double model. At least one of the components in the models for the 1974.5 data appears to be somewhat elongated, along the axis of separation. There was no indication of noncircular components in the earlier observations, but the resolution was too low to reveal such effects. Unlike some well-studied compact sources, the components of 4C 39.25 show no measurable change in their separation over an interval of 2 years (see § IV for additional discussion). Indeed, our latest, partially reduced observations of 1976 September (2.8 cm) and 1977 February (2.0 cm) also show no change in separation. So the source size has stayed the same for nearly 5 years.

Figure 1 shows the new data for both frequencies, with calculated visibilities for the models in Table 1. At both frequencies, the models account for the total flux density of the source. On the longest baselines, the model curves show systematic deviations and indicate more compact structure for some fraction of the flux density of the source. Additional data from intercontinental baselines are required to establish the details of this fine structure.

At lower frequencies, because of reduced resolution and the complicating effects of more extended emission, the double structure described above has not been established. At 18 cm (1.67 GHz), the source is elongated in about the same position angle (98°), but the resolution is not sufficient to allow a choice between single and multiple components (Shaffer and Schilizzi 1975). At 13 cm (2.3 GHz), about 86% of the flux density comes from a region smaller than 0".005 (Broderick *et al.* 1972). The limited (u, v)-coverage of these data and the 13 cm data of Kellermann *et al.* (1970) give no indication of the number of components, but the Kellermann *et al.* data do show that the emitting regions are at most ~0".0007 in size, roughly consistent with the sizes found for the components at 2.8 and 2.0 cm.

The data at various wavelengths, taken over a period of several years, may be combined to define the spectra of several components in the source and show their variation with time. The radio spectrum, epoch 1974.5, is shown in Figure 2. The heavy solid line is the total flux density. The straight, light solid line is an extrapolation of low-frequency measurements, and represents a component which accounts for the 15%–25% of the flux that is completely resolved at 13 and 18 cm. Its size is ~1" at 81.5 MHz (Readhead and Hewish 1974). The two curved, light solid lines show the high-frequency compact components (A, B) which dominate the structure at frequencies above a few GHz. The sum of the high-frequency ($\geqslant$20 GHz) spectra of these components is defined by the total flux density values; their ratio was assumed to be the same as determined at 14.77 GHz. The low-frequency behavior of components A and B is not well determined. The components as drawn have a $\nu^{5/2}$ slope below the turnover, as expected for a self-absorbed source. A spectral index of ~1.5 below the turnover would give a better match to the 13 cm results if the same components were being observed. The dotted line is a hypothetical component required to match the total flux density curve. High-resolution observations in the 0.5–1.0 GHz range are required to determine its reality.

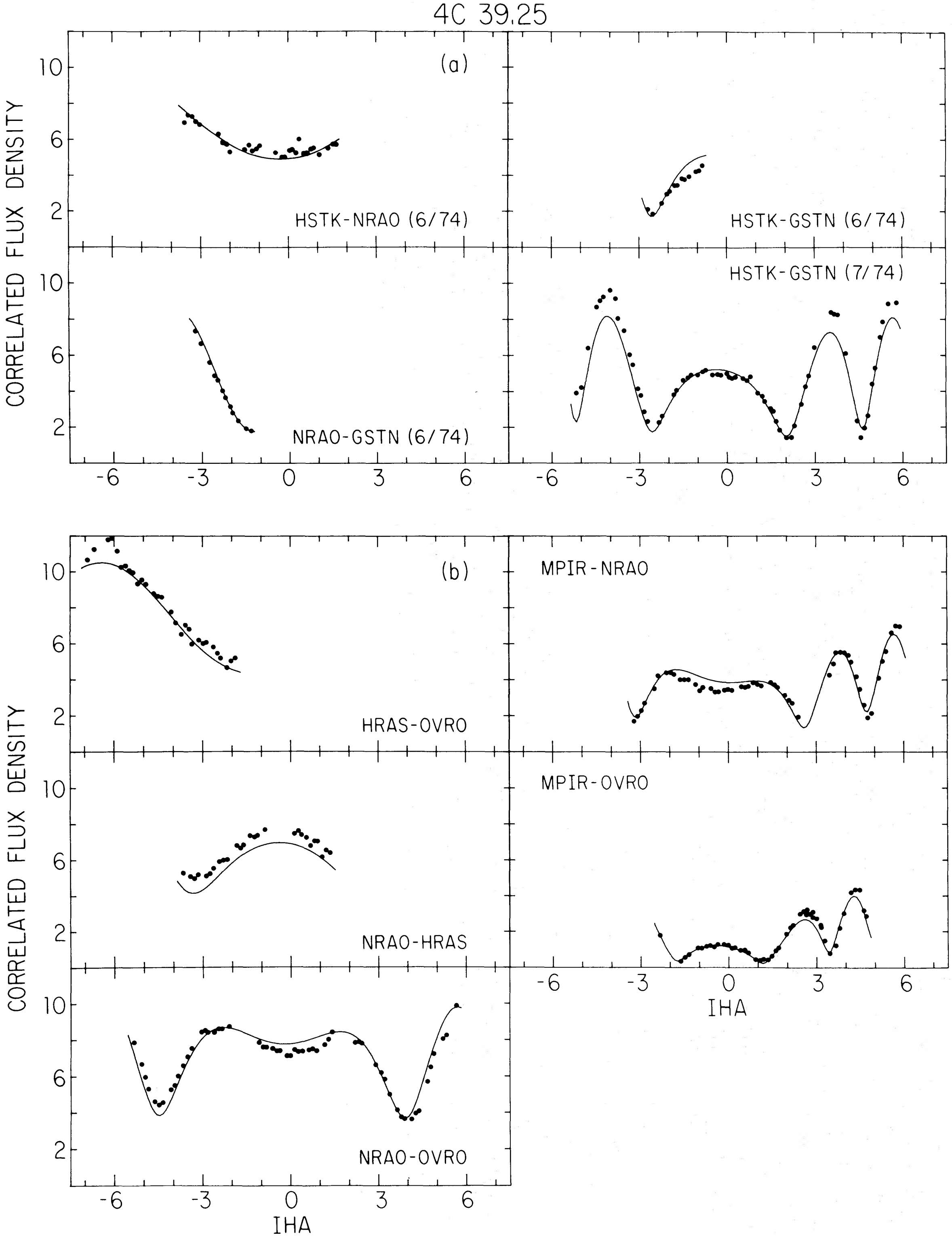

FIG. 1.—The visibility data and model visibilities for 4C 39.25 at (*a*) 2.0 cm, and (*b*) 2.8 cm at epoch 1974.5

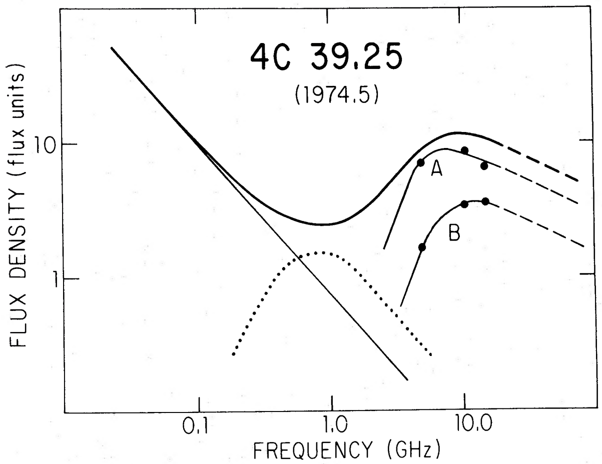

FIG. 2.—Decomposition of the spectrum of 4C 39.25 into several components, as discussed in the text. The flux densities for $\nu > 30$ GHz are uncertain, and shown dashed. The dotted line represents a suggested low-frequency compact source. Large dots at 5, 10.7, and 14.8 GHz show the flux densities for each component at those frequencies, from the models in Table 1.

Components A and B represent the two components of the double models which fit the VLB data between 5 and 14.77 GHz. At four frequencies in this range, the separation, position angle, and component sizes are essentially the same. The intensity ratios between A and B at the several frequencies allow a unique decomposition of the spectrum into the components drawn in Figure 2.

The total flux density of 4C 39.25 at centimeter wavelengths increased slowly from 1967 until ~1974, and has remained nearly constant or decreased slightly since then (Berge and Seielstad 1972; Dent and Kojoian 1972; Medd *et al.* 1972; Dent *et al.* 1974; Dent and Hobbs 1973; and our own measurements). These variations and the changes in the ratio of component intensity at 2.8 cm evident in Table 1 are consistent with expanding self-absorbed synchrotron sources. Such a source has a peaked spectrum, and as the source evolves, the peak frequency decreases (e.g., van der Laan 1966). The flux density at a frequency initially less than the peak frequency will increase with time, reach a maximum, and then decrease. At 1974.5, we observed at a frequency higher than the spectral maximum of component A and less than, or near, the maximum of component B. As expected, and seen in Table 1, the flux density of component A peaked near the beginning of 1973 and had decreased by 1974.5, whereas component B increased continuously from 1972.3 to 1974.5.

Component A is intrinsically more powerful than component B; and since it has a lower peak frequency, it is probably older or has evolved faster than component B. In that case, older data should show only (or mostly) component A. The data available are somewhat sketchy and cannot be interpreted unambiguously. Our 6 cm data taken between 1967 and 1969 (Kellermann *et al.* 1971) are consistent with either a barely resolved (~0″.0003) single component or a very unequal double source (component ratio ~7:1 if forced to fit the same separation and orientation as the models in Table 1). In either case, there were only small structural changes between 1968 and 1974 at 6 cm. There are also high-resolution data at 13 cm (Kellermann *et al.* 1970; Gubbay *et al.* 1977). These observations do indicate structure variations between 1969.4 and 1972.5, but their limited (u, v)-coverage makes it nearly impossible to relate the variations to our models.

III. 3C 345

The quasar 3C 345 is also a 17th-magnitude quasar and has a redshift of 0.595 (Burbidge 1965). For this source, 0″.001 corresponds to 26 lt-yr.

Our early 10.65 GHz results were discussed briefly by Shaffer *et al.* (1975). We now have much more extensive data from our 1974.5 experiment. We also have extensive data at 14.77 GHz at nearly the same epoch. Table 2 gives the results of model fitting for these experiments, and Figure 3 shows the comparison between the models and the new data. Again, simple two-component models fit exceedingly well. The models fit somewhat better with slightly elliptical components, extended approximately along the position angle of separation. The ellipticity of the components is also evident at 7.85 GHz (Wittels *et al.* 1976).

A spectrum of the source for epoch 1974.5 is given in Figure 4, along with a suggested decomposition into several components. The halo, with a spectral index of −0.78, is defined by low-frequency total flux density measurements and the 21 and 11 cm interferometry of Donaldson *et al.* (1969) and Wilkinson (1972). The low-frequency component which peaks near 700 MHz is indicated by interferometry at 448 MHz (Clarke *et al.* 1969) and 607 MHz (Purcell 1973). These latter results also help to define the halo. The two high-frequency components, A and B, are the two components evident in our 10.65 and 14.77 GHz data and the 7.85 GHz models and maps of Wittels *et al.* (1976). The exact shapes of the low-frequency turnovers of A and B are uncertain. Our unpublished data at 2.3 GHz between Goldstone, NRAO, and MPIR for 1973.7 are consistent with Figure 4, although the data indicate that component B may be stronger than shown at 2.3 GHz. Other 2.3 GHz measurements between California and Australia show increasing correlated flux density, from 1969.5 to 1973.8 (Gubbay *et al.* 1977). This trend is consistent with the expected evolution of a self-absorbed synchrotron source for component A, which should contribute most of the flux at 2.3 GHz for observations with 0″.001–0″.002 resolution.

Unlike 4C 39.25, for which we detect no variation in structure, 3C 345 shows rapid changes in its visibility function that are interpreted as rapid expansion of a double source, with an apparent separation velocity greater than c (Cohen *et al.* 1976; Wittels *et al.* 1976). Models with more than two components have been invoked in the past to explain faster-than-light

TABLE 2

Models of 3C 345

Epoch	Frequency (GHz)	Stations*	Separation (arcsec)	Position Angle (degrees)	S_A (fu)	S_B (fu)
1974.15	10.65	O–N	0.00123	105	4.7	4.9
1974.50	10.65	O–H–N–M	0.00130	107	5.5	4.9
1974.5	14.77	G–N–HK	0.00135	107	4.3	5.5

Note.—Component A has diameter $\sim 0\overset{''}{.}0007$, B is $\sim 0\overset{''}{.}0004$ (FWHM).
* As in Table 1.

expansion (Knight *et al.* 1971; Cohen *et al.* 1971; Dent 1972). However, such a model for 3C 345, which has increased in size by considerably more than 50% between 1971 and 1976 (Cohen *et al.* 1976; Wittels *et al.* 1976; Kellermann and Shaffer 1977), requires extreme changes in the strengths of the various components. Moreover, since the total flux density varied only slightly over that interval, any changes in the strength of a component would have required compensating variations in another component. More importantly, the maxima and minima of the visibility function were nearly equally spaced in the transform plane at 1974.5, consistent with a two-component source and requiring no contribution from any hypothetical third component down to a level of a few percent of the total flux. As seen in Figure 3, our two-component models fit all the data extremely well, except on the MPIR–OVRO baseline at 2.8 cm. Those deviations, like the deviations in 4C 39.25, are probably due to structure within the components.

If we naively extrapolate our 2.8 cm results backward to zero component separation, the two components may have been formed ~1968. However, as noted in Cohen *et al.* (1976) and Wittels *et al.* (1976), the apparent rate of separation seems to have increased between 1971 and 1974, and the components may have been created somewhat earlier, perhaps coinciding with a large radio outburst in 1965 (Kellermann and Pauliny-Toth 1968; Kellermann and Shaffer 1977). Following that outburst, the source strength approximately doubled at 2–11 cm wavelengths over a period of several years and has remained at that elevated level ever since, with minor variations superposed on the long-term trends. A comprehensive flux density history does not exist prior to 1965, and it is impossible to tell whether the components were really formed in a single event about 1965. There is evidence of earlier outbursts (Kellermann and Pauliny-Toth 1968, and references therein). The component sizes (10–15 lt-yr) are consistent with ages of 8–10 years, indicating radial expansion velocities somewhat less than c in that case.

IV. DISCUSSION

Both sources appear to be simple doubles at 10.65 and 14.77 GHz, with projected separations of about 55 lt-yr (4C 39.25) and 35 lt-yr (3C 345 at 1974.5). Despite the similarities in appearance, the two sources differ markedly in the behavior of their structure with time. Cohen *et al.* (1976) and Wittels *et al.* (1976) show that the components in 3C 345 seem to be separating at between 0.1 and 0.2 milliarcsec per year, or apparent transverse velocities between 4 and 8 c. For 4C 39.25, any variation in separation is at most ~30 microarcsec over a 5 year interval, and the projected relative motion is at most ~0.2 c. Thus, not all multiple-component compact sources appear to be expanding faster than light.

The separation of the components in 4C 39.25 and their lack of any observed motion indicate at least two possibilities: (1) Both components of the source are more than 200 years old if they resulted from a single outburst which has expanded at a uniform rate. In this case, the recent flux variations have occurred in one or both of the components long after they were created. (2) Alternatively, the two components were created by two separate events which occurred at different locations, and they probably have different ages. Many theories of radio source evolution require a single, nuclear center of activity, which ultimately either grows into an extended source or continuously supplies energy to an extended source. Such theories would require modification if it could be shown that each of the components in a compact source had a separate origin. Since many sources seem to have the same axis of elongation for a large range of sizes (Fomalont and Miley 1975; Kellermann *et al.* 1975; Pauliny-Toth *et al.* 1976), we may be seeing the effect of a well-defined axis along which separate events take place. Yet another alternative is that two stationary blobs of material have been turned on by a signal (blast wave or electromagnetic radiation) from a centrally located object (Blandford, McKee, and Rees 1977).

Assuming the sources contain uniform synchrotron self-absorbed components, we estimate the magnetic field B (in gauss) from

$$B = 2.5 \times 10^{-8} \frac{\nu^5 \theta^4}{S^2(1+z)}, \quad (1)$$

where ν is the frequency (in MHz) of the peak density S (in fu) of a component of diameter θ (in arcsec) for a source with redshift z (Terrell 1966). Table 3 shows the values of B calculated for the high-frequency components in 4C 39.25 and 3C 345, as well as the observed values of ν, θ, and S that were used. The angular size in Table 3 is the diameter of a uniform disk source which has the same flux density and brightness temperature as the flux density and peak

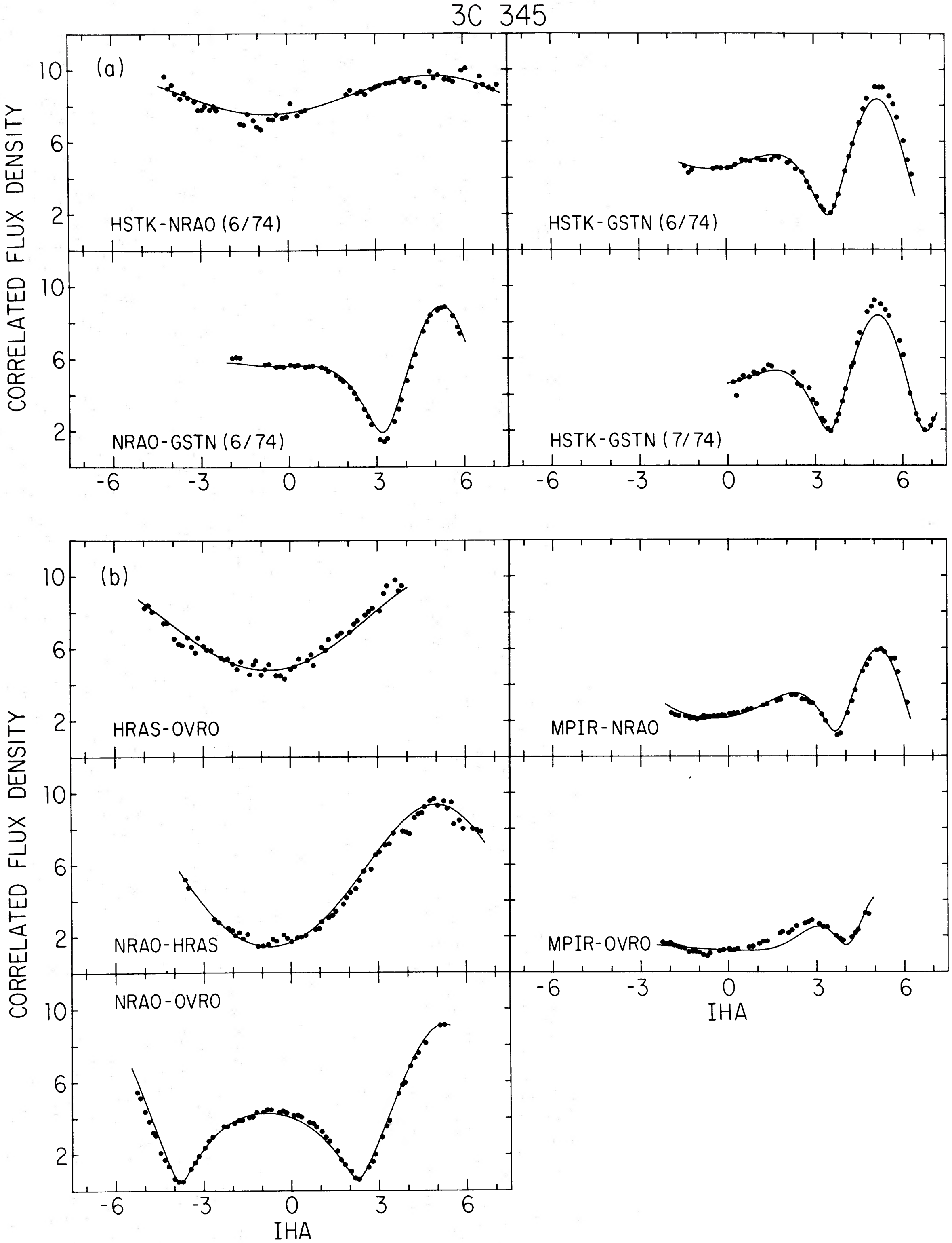

FIG. 3.—Same as Fig. 1, except for 3C 345

TABLE 3

MAGNETIC FIELDS, ASSUMING SYNCHROTRON SELF-ABSORPTION

Source	Component	Component Parameters* ν (GHz)	θ (arcsec)	S (fu)	Magnetic Field (gauss)
4C 39.25	A	8	0.0006	9	8×10^{-4}
	B	15	0.0006	3.5	1×10^{-1}
3C 345	A	4.5	0.00084	7	5×10^{-4}
	B	20	0.0005	6	1×10^{-1}

* As defined in eq. (1).

brightness temperature of the Gaussians given in Tables 1 and 2. The magnetic field strengths in Table 3 are uncertain by about an order of magnitude, because of the strong dependence on the observed quantities ν and θ.

For the two lower-frequency components, the fields found are comparable with those previously determined (Kellermann and Pauliny-Toth 1969). Our new data, at higher resolution and higher frequencies than previous measurements, indicate very strong fields in the high-frequency components, and imply very short lifetimes for the radiating electrons: at most ~ 10 yr for a particle whose spectrum peaks at ~ 15 GHz in a field of 0.1 gauss. Since the components are probably older than 10 years, some generation mechanism for relativistic electrons is probably continuously active, at least in the high-frequency components. Peterson and Dent (1973) have shown that a prolonged injection model is consistent with one of the observed outbursts in 3C 273. They also predict a strong magnetic field for such sources.

The calculated equipartition fields for all the components in Table 3 are of the order of 0.1 gauss. It thus seems likely that particle energy dominates the A components, while the B components may be near equilibrium between particle and magnetic field energy. In the former case, a rapid expansion is expected. For the B components, when they are first created, the magnetic field may be strong enough to contain the particles resulting from prolonged injection for some time, until the particle energy begins to dominate, at which point the component turns into a "normal" expanding source.

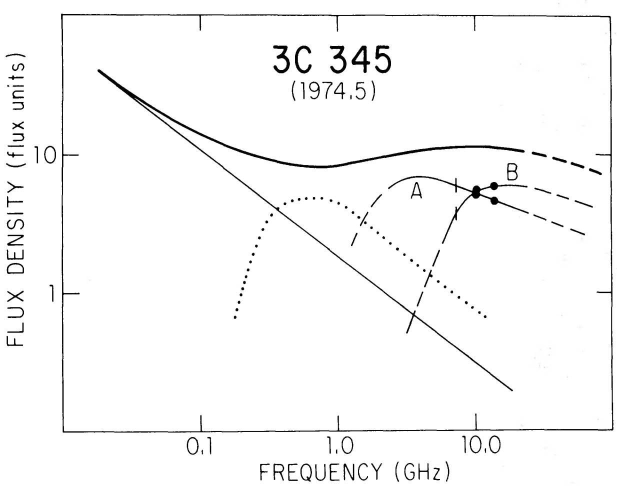

FIG. 4.—Same as Fig. 2, except for 3C 345. In this case, the dotted component is known to exist, but its spectrum for $\nu \gtrsim 1$ GHz is uncertain. Dots at 10.7 and 14.8 GHz as in Fig. 2. The vertical bars at 7.85 GHz cover the range of flux densities in the models of Wittels (1975).

Both sources are polarized at centimeter wavelengths, and show variations in percentage and position angle (Berge and Seielstad 1972; Seielstad and Berge 1975; Altschuler and Wardle 1976). Using observations at wavelengths longer than about 10 cm, Bignell (1973) and Wittels (1975) find an intrinsic position angle of $\sim 47°$ for 3C 345, which is neither parallel nor perpendicular to the axis of separation between the components. Those observations, at longer wavelengths, may well refer to parts of the source completely different from the two compact components considered here. For 4C 39.25, the long-wavelength data are considerably sparser, and there is no well-established intrinsic position angle. For both sources, the position angle of separation between components does not seem to relate to any magnetic field orientation. The polarization variations probably are caused by fluctuations of conditions in the individual components, such as changes in magnetic field orientation, optical depth, or the amount of thermal plasma contained in the components.

V. CONCLUSIONS

We have shown that the structures of 4C 39.25 and 3C 345 at 10.65 and 14.77 GHz are well represented by two elliptical Gaussian components. The structures at 7.85 GHz, and 5 GHz for 4C 39.25, are also very similar. The two discrete components account for nearly all the radio emission at these frequencies.

The structure of 4C 39.25 is stable over a period of several years, whereas the components of 3C 345 appear to be separating at very high speed. It is difficult to decide whether the components resulted from a single outburst or from separate events. By combining structure and total flux density data, we have been able to define the spectra of individual components, and it appears to be possible to follow the evolution of those components. High-resolution data at lower frequencies (1–5 GHz) are required to define the turned-over parts of the spectra. Such observations are in progress.

Very strong magnetic fields probably exist in the highest-frequency components, perhaps strong enough to contain the source. For the lower-frequency components, the pressure of the synchrotron particles should dominate, and the components should expand rapidly, unless constrained by an internal plasma or external material. Polarization, generally assumed to reflect the orientation of the magnetic field, shows little relation to the overall geometry of the most compact structure.

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