Mon. Not. R. astr. Soc. (1970) **149**, 101–109.

MAPS OF SIX EXTRA-GALACTIC RADIO SOURCES AT 5 GHz

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(Communicated by J. R. Shakeshaft)

(Received 1970 April 16)

SUMMARY

3C 123, 196, 247, 275·1, 295 and 336 have been mapped with the Cambridge One-Mile telescope at a frequency of 5 GHz, with a resolution of 6·5 arc sec. The maps provide new positional information and physical data for the six sources. 3C 123, 247 and 336 are resolved into double sources, and an identification of 3C 247 with a galaxy is suggested. A comparison of the structural information derived from the 5 GHz work with previous observations using long baseline interferometers, and with observations of interplanetary scintillation, is made. Morphologically the quasi-stellar source 3C 336 is shown to be similar to 3C 47, and this is interpreted as further evidence for continuing or recurring activity in quasi-stellar sources over periods of at least 10^6 years.

1. INTRODUCTION

Since 1968 the Cambridge One-Mile telescope (Elsmore, Kenderdine & Ryle 1966) has been making observations at a frequency of 5 GHz, the maximum baseline being 25 000 wavelengths. The synthesized beam has a half-power width in right ascension of 6·5 arc sec and in declination of 6·5 cosec δ arc sec. With this resolution it is possible to map the structure of extended radio sources in some detail and a number of such maps have already been published (Mitton & Ryle 1969; Mitton 1970; Graham 1970). The purpose of this short communication is to present the observations of a further six sources which are relatively more compact, and in which correspondingly less detail can be seen. The results are nevertheless of interest, particularly when combined with observations of interplanetary scintillation and with data from long baseline interferometers. Three of the sources, 3C 123, 247 and 295 are identified with radio galaxies, and three, 3C 196, 275·1 and 336 with quasi-stellar objects.

The maps are shown in Figs 1–6; in each case the declination scale has been multiplied by sin δ so that the telescope beam is apparently circular, thus facilitating the distinction between resolved and slightly resolved features. The resulting compression is indicated by a scale showing 5 arc sec in each coordinate. The contour interval used is different for each map. The positions of optical objects which may be associated with the sources are marked by crosses. Except for 3C 247, which is discussed separately, the errors are such that the displacement of the optical position from the radio source axis is not significant for any of these objects.

Table I summarizes some of the structural and physical data for each source derived from the present observations. The quoted positions (epoch 1950.0) are

TABLE I

Parameters of the six sources observed at a frequency of 5 GHz. The tabulated quantities, and the method of estimating the source widths are discussed in the text. The values enclosed by brackets are estimates for sources which have no measured redshift

Source number	Right ascension (1950.0) h m s	Declination (1950.0) ° ′ ″	θ ″	p.a.	S_{4995} 10^{-26} W m^{-1} Hz^{-1}	$\omega_{\parallel}$ sec	$\omega_{\perp}$ sec	P_{4995} 10^{25} W Hz^{-1} ster^{-1}	U_{min} 10^{57} erg	H 10^{-5} G
123	04 33 54·59	29 34 30·4	27	150°	8·5	~18	~11	0·7	(3·7)	(4·0)
	04 33 55·22	29 34 30·4								
	04 33 55·78	29 34 12·5			7·5	<4·5	<8	0·6	(<1·4)	(>6·8)
196	08 09 59·53	48 22 07·3	7·5	25°	4·5	7·5	2·5	120	130	13
247	10 56 07·85	43 17 26·9	12·5	70°	0·55	4	<3	1·2	(<5·9)	(>5·2)
	10 56 08·95	43 17 31·5			0·40	5	<3	0·9	(<4·4)	(>5·4)
275·1	12 41 27·58	16 39 17	13	165°	1·0	13	<2·5	8·9	<33	>6·0
295	14 09 33·65	52 26 12·7	8	152°	6·2	8	<2	4·1	48	13
						*1	0·8		7·2	29
336	16 22 32·04	23 51 56·0	21	33°	0·35	<7	<4	8	<48	>5·1
	16 22 32·04	23 52 12·7			0·50	<7	<4	12	<59	>5·7

* Anderson & Donaldson 1967.

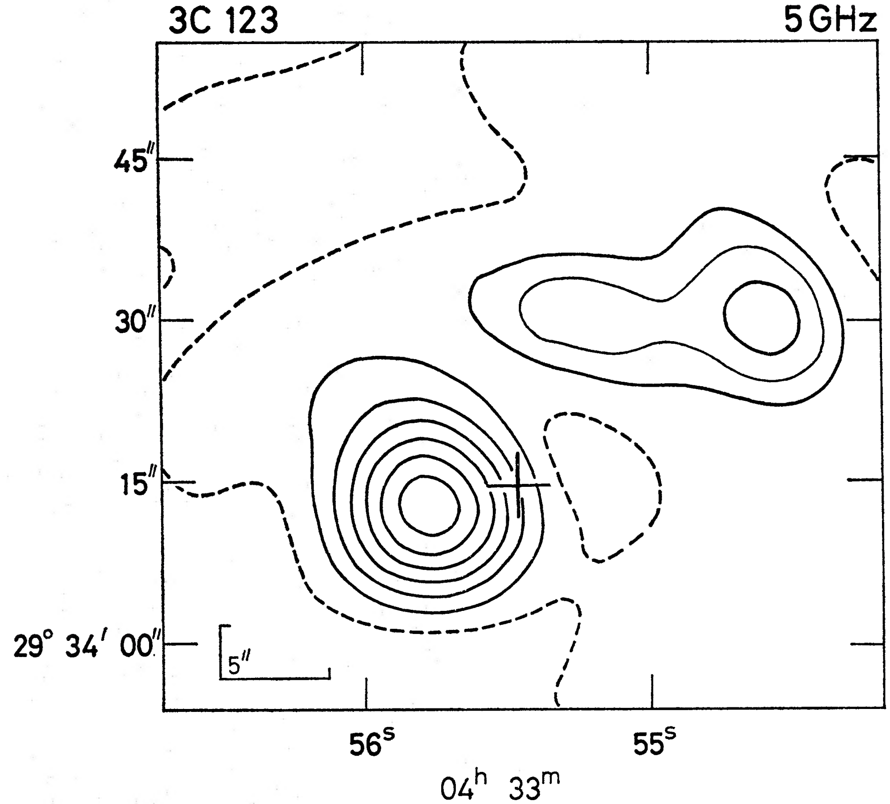

FIG. 1. 3C 123. *The position of the radio galaxy identified by Longair* (1965) *has been measured from the National Geographic Sky Survey prints. An additional contour has been inserted in the Np component to clarify the structure.*

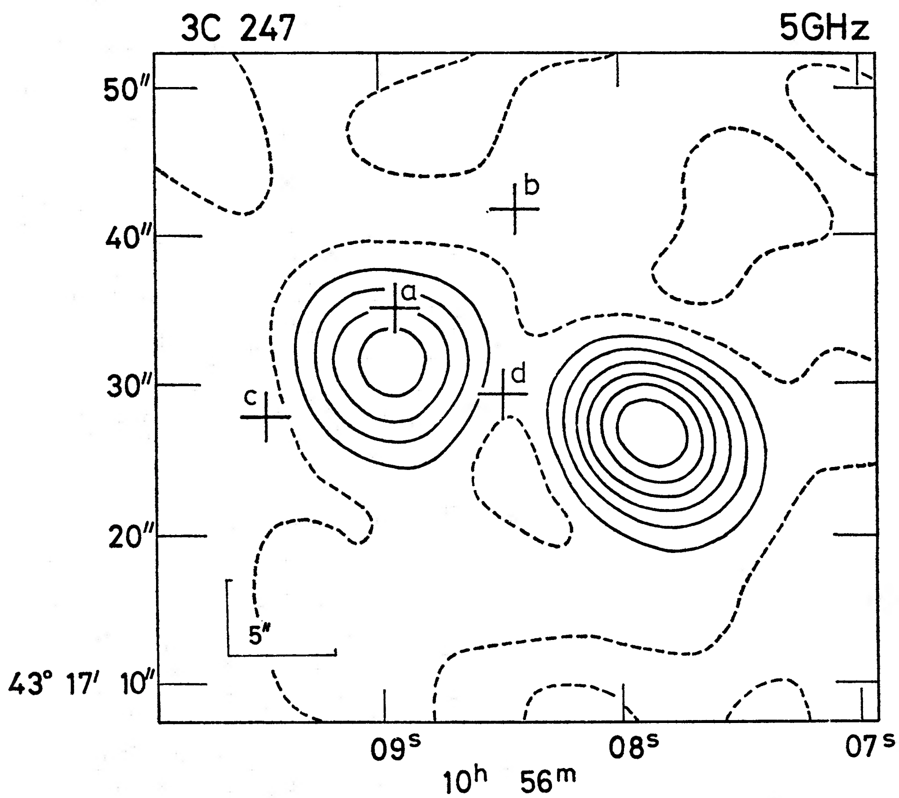

FIG. 2. 3C 247. *The position of the galactic star at* (*a*) *is that of Sandage et al.* (1966). *Also marked are three faint galaxies whose angular distances from* (*a*) *have been measured on the National Geographic Sky Survey prints.*

believed to be correct to within 1·5 arc sec in right ascension and to within 1·5 cosec δ arc sec in declination. The overall angular extent (θ) and position angle (p.a.) along the main radio axis are given. The total flux density of each source was obtained by measuring the maximum fringe amplitude at the smallest interferometer spacing, and for double sources the relative fluxes of each component were measured from the map. All values assume a flux density $S_{4995} = 8{\cdot}2 \times 10^{-26}$ W m^{-2} Hz^{-1} for 3C 147 (Kellermann, Pauliny-Toth & Williams 1969) and are believed to be correct to within 10 per cent. In cases where the components were unresolved on the

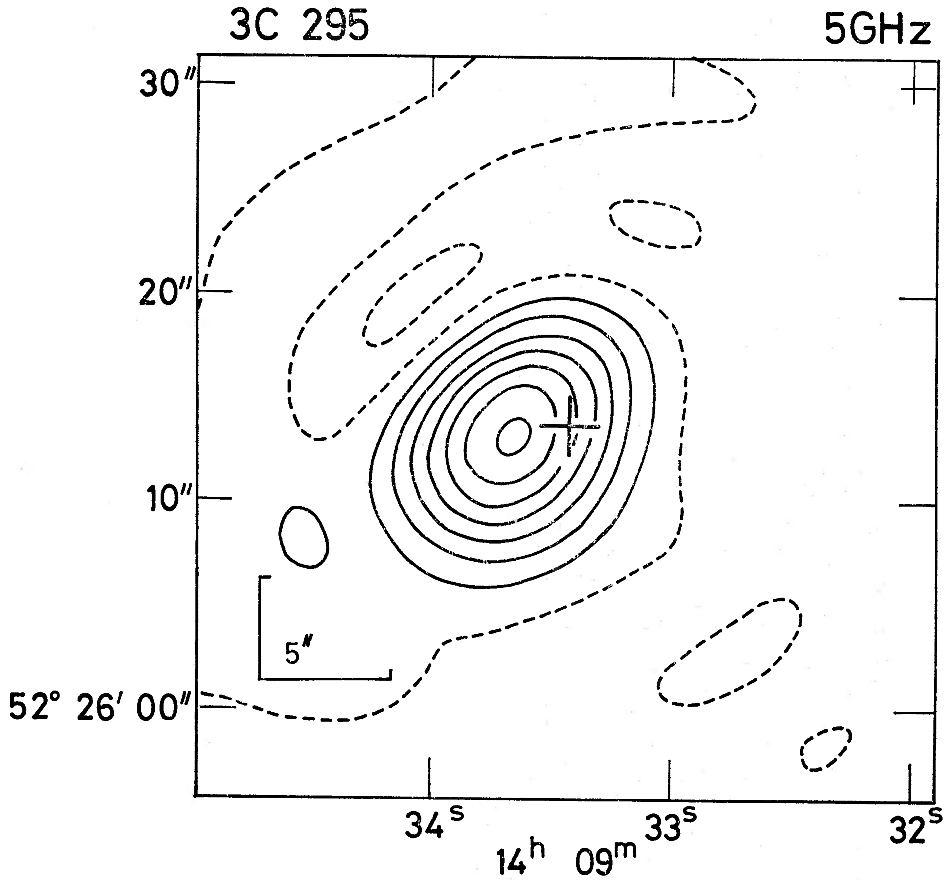

FIG. 3. 3*C* 295. *Griffin* (1963) *has measured the position of the galaxy, which has a redshift* $z = 0{\cdot}461$ (*Minkowski* 1960).

map the angular sizes parallel ($\omega_{\parallel}$) and perpendicular ($\omega_{\perp}$) to the source axis were estimated by assuming a gaussian brightness distribution and comparing the interferometer amplitudes at the largest and smallest spacings.

Optical redshifts are known for the four objects associated with 3C 196, 275·1, 295 and 336. By taking a value $H = 100$ km s^{-1} Mpc^{-1} for Hubble's constant (van den Bergh 1970) and assuming an Einstein–de Sitter universe, the intrinsic luminosity (P_{4995}), minimum energy ($U_{\min}$) and equipartition magnetic field (H) in these four objects were derived and the values are listed in Table I. Values, shown in brackets, were also derived for the other two sources on the basis of less accurate distance estimates discussed below. Equipartition between relativistic electrons and the magnetic field was assumed for these calculations and the radio spectra were taken as extending from 10 MHz to 10 GHz.

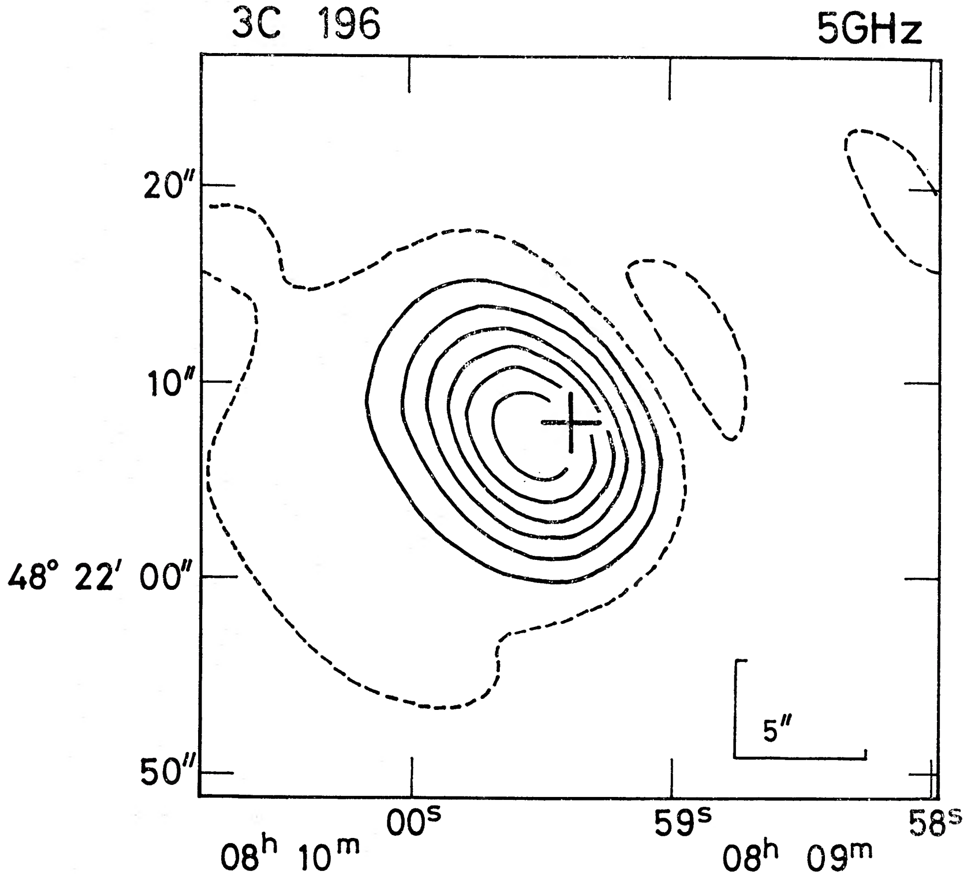

FIG. 4. 3*C* 196. *The cross marks a quasi-stellar object* (*Matthews & Sandage* 1963), $z = 0{\cdot}871$ (*Lynds, Heere, Hill & Stockton* 1966), $V = 17{\cdot}6$ (*Sandage* 1965), *whose position has been given by Murray, Tucker & Clements* (1969).

2. NOTES ON INDIVIDUAL SOURCES

2.1 *The radio galaxies* 3*C* 123, 3*C* 247 *and* 3*C* 295

The *Np* component of the source 3C 123 is 18 arc sec in length, but the *Sf* component is less than $4{\cdot}5 \times 8$ arc sec in size. Measurements of interplanetary scintillation (Harris & Hardebeck 1969) indicate that only 5 per cent of the flux density at 408 MHz originates in structure less than 1 arc sec in size. Longair (1965) identified the source with a faint red galaxy, which Matthews (1966) described as type D, approximately at the same distance as Cygnus A, in a heavily obscured region of the sky. An inspection of the National Geographic Sky Survey prints shows that the galaxy is only visible on the red print; it has an apparent diameter of 7 arc sec, and is extended along position angle $155° \pm 20°$. The position has also been measured from the red print and has an estimated error of 3 arc sec in each coordinate. The radio source components are less than 15 arc sec from the nucleus of the galaxy, and may therefore have only recently emerged from the envelope of the parent galaxy. If this radio source is at a similar distance to Cygnus A, it has one-fifth the overall extent and one-tenth the power of Cygnus A.

Both components of 3C 247 are less than 5×3 arc sec in size and the separation is $12{\cdot}5$ arc sec; these values are in agreement with the source models suggested by Bash (1968) and Hogg (1969). Observations of interplanetary scintillation (Bell

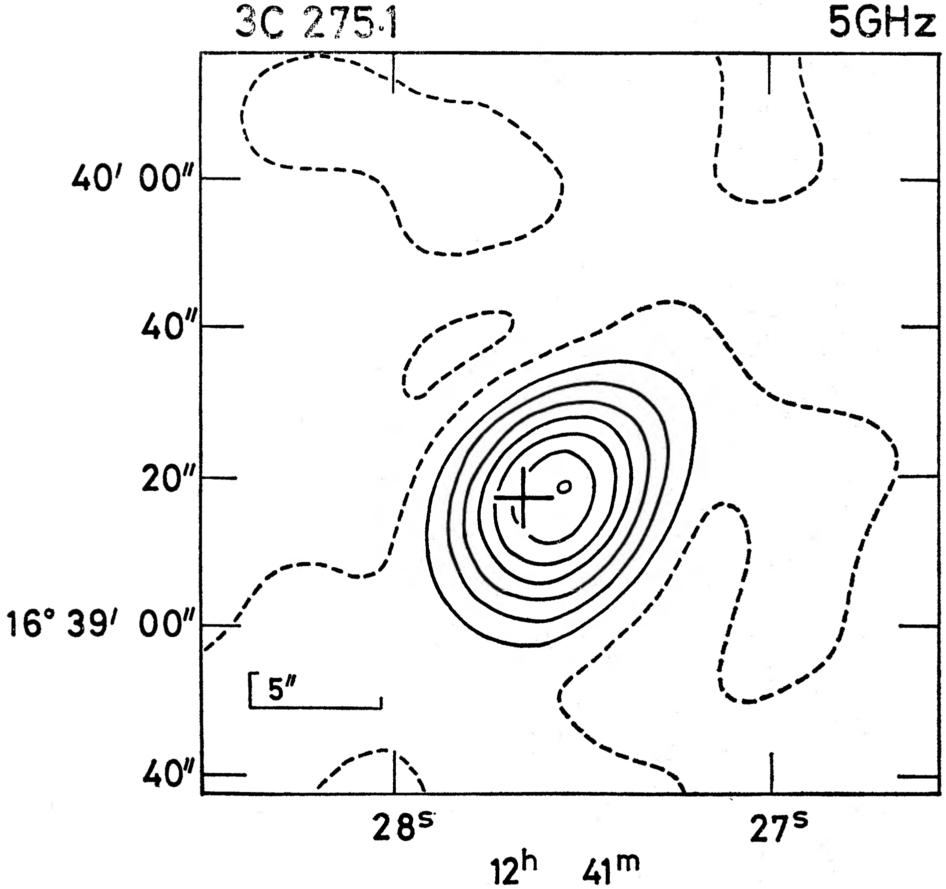

Fig. 5. 3*C* 275·1. *The cross marks a quasi-stellar object,* $z = 0{\cdot}557$ (*Lynds et al.* 1966), $V = 19{\cdot}00$ (*Sandage* 1965). *The position is from Sandage et al.* (1966).

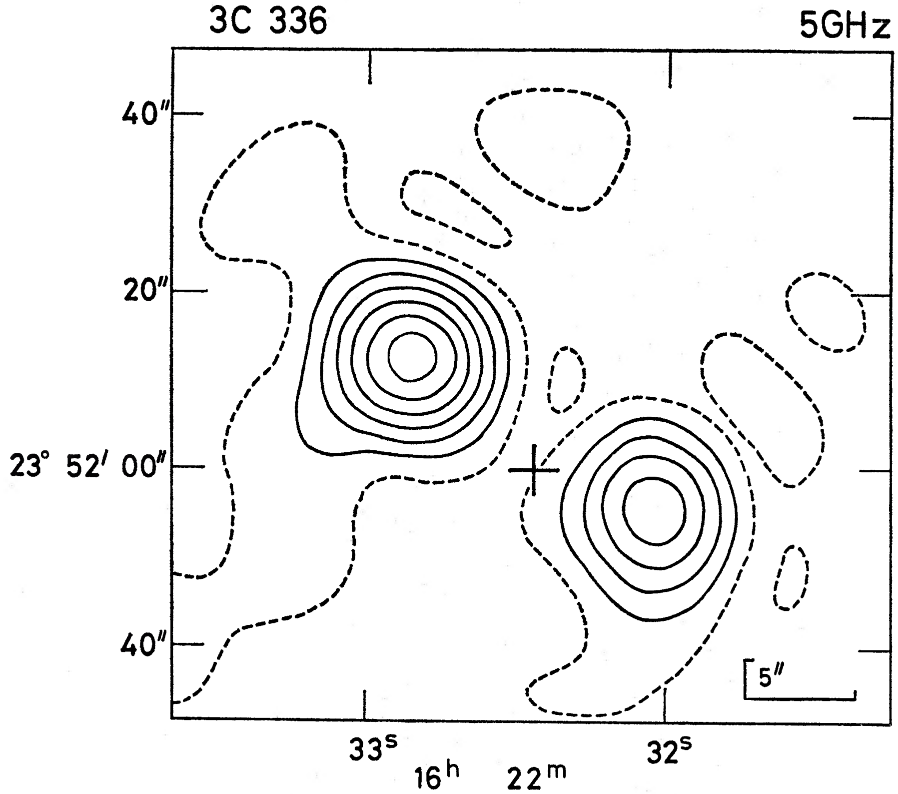

Fig. 6. 3C 336. *The cross marks a quasi-stellar object,* $z = 0{\cdot}927$ (*Lynds et al.* 1966), $V = 17{\cdot}47$ (*Sandage* 1965), *whose position has been given by Sandage et al.* (1966).

1968) show that 30 per cent of the flux density at 81·5 MHz originates within a component whose size is about 0·1 arc sec. The present observations suggest that the identifications previously made for this source may not be correct. Four objects in the field are marked by crosses: (a) is an $18^{m}\cdot 8$ sub-dwarf galactic star (Schmidt, quoted by Sandage 1966). It was shown by Mackay (1967) that the density of galactic star images is sufficient for the association of (a) with the radio source suggested by Wlerick & Véron (1967) to be accounted for as a random coincidence. Also marked are two faint $19^{m}\cdot 5$ galaxies described by Wyndham (1966): (b) is red and (c) is blue. Mackay (1969) noted a further faint galaxy (d) which is only visible on the red prints of the National Geographic Sky Survey. Sandage, Véron & Wyndham (1965) have given an accurate position for (a); (b), (c) and (d) were measured relative to this position, and the displacements from (a) shown on the map are correct to 1 arc sec. The positions of (b) and (c) with respect to the source components do not suggest a convincing identification with either galaxy, but the diffuse galaxy at (d) lies on the radio axis. If (d) is the source identification and it has an absolute magnitude of $M_v = -21\cdot 5$, then the source is at a distance of 1000 Mpc, and it has a physical extent half that of Cygnus A, and about one-tenth the power.

3C 295 is of interest because it is a galaxy with a very high radio luminosity. The source, which is identified (Minkowski 1960) with the most distant galaxy known ($z = 0\cdot 461$), is slightly resolved in the present observations. Our results are consistent with those of Anderson & Donaldson (1967) who used a 180 000 wavelength interferometer at a frequency of 410 MHz, and Anderson, Palmer & Rowson (1962) who used a 61 000 wavelength interferometer at 158·6 MHz. From these observations a double source with a separation of 4·5 arc sec was inferred, the two components having equal flux densities and an angular size $1\cdot 0 \times 0\cdot 8$ arc sec. The agreement of the present results with this model indicates that the two components have similar spectral indices over the frequency range 158 MHz to 5 GHz. Owing to the high ecliptic latitude (60°) of the source it is not possible to derive further information on structure from interplanetary scintillation studies.

The spectrum of 3C 295 reaches a maximum at 100 MHz, so that part of the source has become opaque at this frequency (Kellermann & Pauliny-Toth 1969). The positional information available at low frequencies is not sufficiently precise in itself to determine whether one or both components become optically thick. However, since the flux density at 38 MHz is only 20 per cent of that expected by extrapolating the spectrum from higher frequencies, it is clear that both components are involved. If the cut-off is attributed to synchrotron self-absorption within the source and the component sizes of Anderson and his co-workers are used, then a magnetic field of $3-30 \times 10^{-4}$ G is indicated, which agrees with a figure of 3×10^{-4} G obtained by using the same sizes and an equipartition argument.

2.2 *The quasi-stellar sources* 3*C* 196, 3*C* 275·1 *and* 3*C* 336

These three radio sources are identified with quasi-stellar objects; data on their redshifts z, and photoelectric magnitudes V, are given in the captions to the figures.

The maps of 3C 196 and 275·1 show that they are extended sources; 3C 196 is just resolved perpendicular to the axis and has a width of 2·5 arc sec. There are, unfortunately, no extensive interferometric observations at longer baselines to confirm whether or not these might be double sources, as suggested by Hogg (1969) with studies at 2·7 GHz, using less resolving power than the present observations. In the case of 3C 196 the map is consistent with the model proposed which has components 2×2 arc sec separated by 5 arc sec, the flux ratio at 2·7 GHz being 11 : 8. However, there is known to be finer structure from the observations of interplanetary scintillation made by Little & Hewish (1968), who deduced that some 15 per cent of the flux density at 178 MHz originates in a component less than 0·7 arc sec in diameter.

For 3C 275·1 Hogg (1969) suggested a double source model in which the component separation is $13{\cdot}2 \pm 1{\cdot}8$ arc sec. Our observations agree with these estimates, although the separation given by Hogg appears to be about 3 arc sec too large. Interplanetary scintillation results for 3C 275·1 show that 30 per cent of the flux density at 81·5 MHz is contained in a compact source whose angular diameter is 0·15 arc sec or less (Bell 1968), while at 408 MHz a comparable value of 20 per cent from a component less than 0·2 arc sec in diameter was obtained by Harris & Hardebeck (1969). Presumably this small-scale structure is also present at 5 GHz.

3C 336 is shown to be a double source, with each component less than 7×4 arc sec in size, separated by 21 arc sec; this confirms the models derived by Bash (1968) and Hogg (1969). The absence of interplanetary scintillation at 81·5 MHz (Readhead, private communication) suggests that neither component has structure as small as 1 arc sec at lower frequencies. The previous observations made at 1·4 GHz with the One-Mile telescope by Mackay (1969) had insufficient resolution to separate the components properly, but a comparison of the 1·4 GHz map with the 5 GHz map, modified by a convolution technique so that the beam shape is the same as at 1·4 GHz, shows that both components have similar spectral indices ($0{\cdot}9 \pm 0{\cdot}1$) over this frequency range.

The double structure of this quasi-stellar radio source reveals it to be morphologically similar to 3C 47. The physical separation of the components (85 kpc) and the radio luminosity ($P_{4995} = 2 \times 10^{26}$ W Hz^{-1} ster^{-1}) are comparable to those of 3C 47 (230 kpc and $0{\cdot}6 \times 10^{26}$ W Hz^{-1} ster^{-1}) and again suggest that the mechanism responsible for the energy production in quasi-stellar objects can continue, or recur, over periods of about 10^6 years, as inferred for 3C 47 by Ryle, Elsmore & Neville (1965).

3. CONCLUSIONS

Previous observations made at Cambridge at a frequency of 1·4 GHz with a 23 arc sec beam showed that roughly half the extra-galactic sources in the 3C catalogue possess complex or double structure, and the remainder were not properly resolved (Macdonald, Kenderdine & Neville 1968; Mackay 1969; Elsmore & Mackay 1969). The present study with higher resolution of six sources which were previously not properly resolved has confirmed that in the case of three of them the characteristic double structure persists to smaller angular scales. Several authors (e.g. Ryle 1967; Burbidge 1967) have remarked that, on the basis of radio properties alone, extended sources associated with quasi-stellar objects cannot be distinguished from powerful radio galaxies. The present observations again support this suggestion, since the physical dimensions of 3C 336, like 3C 47, are similar to those of extended radio galaxies. The optical emission from both 3C 47 and 3C 336 indicates a source of energy which produces some 5×10^{44} erg s^{-1}; this value is similar to that required to account for the line radiation from the radio galaxy Cygnus A (Baade & Minkowski 1954, with a correction for the presently accepted value of Hubble's constant). In all cases it thus appears that a continuing source of energy production persists for around 10^6 years; it is interesting that the total energy associated with the central optical source is comparable with the total energy in the form of relativistic electrons and magnetic field required to account for the radio emission.

ACKNOWLEDGMENTS

It is a pleasure to thank Dr N. J. B. A. Branson for supervising the observations, and Professor Sir Martin Ryle, Dr J. R. Shakeshaft and Dr C. D. Mackay for valuable discussions and suggestions relating to this work. I am grateful to Mr A. C. Readhead for permission to use interplanetary scintillation data prior to publication. During the course of this work the author was supported by a research studentship from the Science Research Council.

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