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Energy Production in Four Extragalactic Radio Sources

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Four extragalactic radio sources have been mapped at 5 GHz with a resolution of 6.5 × 6.5 cosec δ arc sec. Three of the sources, 3C 47, 249.1 and 263, are associated with quasi-stellar objects and have widely separated radio components, but for the latter two sources radio emission has also been detected from the quasi-stellar objects themselves. Triple structure is also found for the unidentified source 3C 111, which has a compact central component having a relatively flat spectrum. Tables are presented with the basic observational data and physical parameters derived from the observations. The production of energy over long periods of time in these sources is discussed.

INTRODUCTION

Despite the abundant evidence (e.g. Burbidge 1970) for recurrent violent activity in the nuclei of galaxies and in quasi-stellar objects, many more data are required for an understanding of the processes at work. In this paper we describe high-resolution observations of four extended radio sources in which there is evidence of present activity. The three quasi-stellar sources 3C 47, 249.1 and 263 are optically variable (Sandage 1965, Penston and Cannon 1970), and a search for radio emission from the nucleus is therefore important. Mackay (1969) has already found that 3C 111 contains a weak central component, although the source unfortunately lies at $b^{II} = -9°$ in a heavily obscured region, so that no identification has been possible (Wyndham 1966).

OBSERVATIONS

The four sources were previously mapped at 408 MHz and 1.4 GHz with the Cambridge One-Mile telescope (Macdonald *et al.* 1968, Mackay 1969). These new observations at 4.995 GHz have provided maps with a resolution of 6.5 arc sec in right ascension and 6.5 cosec δ arc sec in declination, in which more details of the source structure can be examined, and from which information on the spectral index of individual components can be derived.

The methods of observation and reduction have ...ady been described (Elsmore *et al.* 1966). ...arly polarized feeds were used and they were ...t mutually parallel in position angles 0°, 45°, ...d 90°, selected in turn on a 12-minute cycle. This ...nterval is less than the sampling time required for a complete mapping of the sources, and it therefore allows three independent maps to be derived, comparison of which enables polarized features to be examined. No measurable polarization was in fact found; since the sources themselves are weak this only allows an upper limit of about 10 per cent to be placed on the polarization of any one component.

Maps of the sources are given in Figures 1–4. The declination scales are compressed by a factor sin δ so that the beam apparently has a circular cross section. Owing to the considerable variations in total angular extent the maps could not be reproduced to a uniform scale, but the actual scales are indicated in the figures. It should be noted that the zero level on each map is arbitrary, so that the lowest contour is not a precise indicator of the total extent of the source components.

SOURCE STRUCTURE

Table 1 summarizes the information on the sources which can be derived directly from the observations. The total angular extent is measured between the outer emission peaks. Estimates of the angular size of individual components parallel ($\omega_{\parallel}$) and perpendicular ($\omega_{\perp}$) to the main source axis are also given. The flux density scale is relative to a value of 8.2×10^{-26} W m^{-2} Hz^{-1} for 3C 147 (Kellermann *et al.* 1969). The spectral index, defined in the sense $S(\nu) = k\nu^{-\alpha}$, has been derived from a comparison of the 1.4 GHz and 5 GHz maps.

3C 47: Both components of the source are substantially resolved: the brighter component has dimensions 5 arc sec by 10 arc sec, corresponding to a physical extent of 25 × 50 kpc for $H = 100$ km sec^{-1} Mpc^{-1} (Van den Bergh 1970). The projected component separation is 228 kpc, so that in luminosity and total extent this source is comparable to the most extensive radio galaxies known, such as Hercules A.

TABLE 1

Basic observational data for the four sources observed at 5 GHz. A detailed description of the methods by which the data are derived and the associated errors is not given in this paper, but may be found in Mackay (1969) and Elsmore and Mackay (1969).

Source number	Right ascension 1950.0		Declination 1950.0		Total angular size (arc sec)	Component size (arc sec) $\omega_{\parallel}$	$\omega_{\perp}$	Brightness temperature (K)	Flux density at 5 GHz 10^{-26} Wm^{-2} Hz^{-1}		Spectral index
3C 47	$01^h\ 33^m\ 39.1^s$	$\pm 0.2^s$	20° 41′ 39″	±3″	69	10	5	750	0.75	±0.1	0.9
	01 33 41.7	0.2	20 42 30	3		8	~10	220	0.35	0.1	1.1
optical	01 33 40.3		20 42 16								
3C 111	04 14 54.9	0.2	37 54 31.8	3	184	~16	~8	900	2.7	0.3	0.65
	04 15 00.65	0.1	37 54 20.0	2		<3	<5	>5300	2.0	0.1	0.35
	04 15 09.72	0.2	37 55 17.3	3		~16	~8	1200	3.1	0.3	0.65
3C 249.1	11 00 23.0	0.3	77 15 11.1	2	23.5	4.5	3	2000	0.55	0.05	0.8
	11 00 27.4	0.5	77 15 08.7	2		~4.5	<3	>670	0.18	0.05	0.8
	11 00 30.0	0.5	77 15 07.0	2		~4.5	4	500	0.18	0.05	
optical	11 00 27.32		77 15 08.6								
3C 263	11 37 04.6	0.7	66 04 38	4	46.5	~9	5	170	0.15	0.04	0.8
	11 37 09.0	0.3	66 04 28.0	4		<4	<5	>320	0.13	0.04	0.8
	11 37 11.8	0.2	66 04 21.5	2		<3	<3	>4200	0.75	0.08	
optical	11 37 09.285		66 04 27.04								

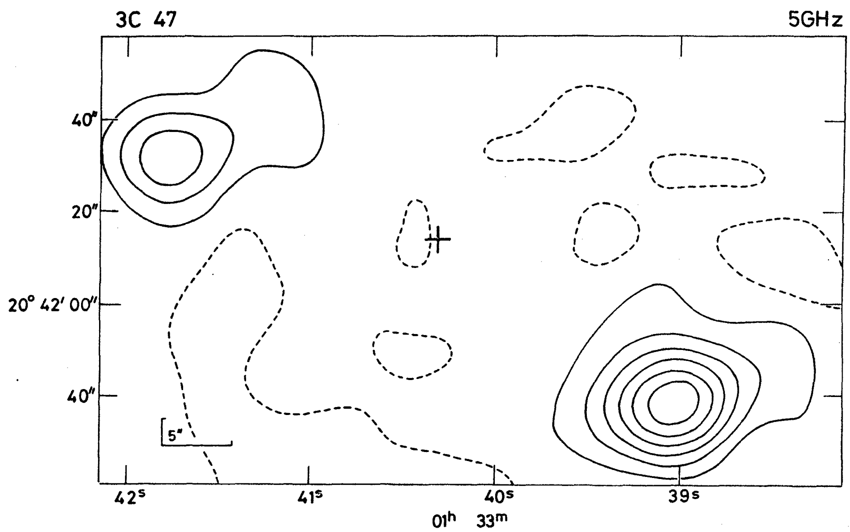

FIG. 1. 3C 47. The radio source is identified (Schmidt and Matthews 1964) with a quasi-stellar object, $V=18.1$ $z=0.425$. Sandage (1965) has shown that it is variable. The position is taken from Sandage *et al.* (1965).

There is no detectable radio emission from the quasistellar object, and an upper limit of 0.10×10^{-26} W m^{-2} Hz^{-1} may be placed on the radio emission from any compact central component. Sandage (1965) has found optical variations of up to 0.20 mag in nine months, so that in this respect the source is similar to 3C 249.1 and 3C 263; however, radio emission comparable to that of the central components of these sources can certainly be ruled out.

It is of interest to compare the present results with those from interferometric observations at other frequencies and also with information derived from interplanetary scintillation studies. Measurements by Bash (1968) at 2.7 GHz with the same resolving power as the present observations showed that 20 per cent of the source was unresolved; the 2.7 GHz observations of Basart *et al.* (1968) with a 100 000 λ interferometer indicated that 15 per cent of the source was unresolved. These results are compatible with a brightness distribution similar to that of Cygnus A, which has a steep gradient of brightness at the outer edge of each component (Mitton and Ryle 1969). Observations of interplanetary scintillation reveal no evidence of fine structure at low frequencies; a similar feature was found for Cygnus A (Hewish *et al.* 1964, Little and Hewish 1968, Harris and Hardebeck 1969).

3C 249.1: Figure 2 shows that the brightness distribution is complex as Hogg (1969) suspected. The Sf component has two distinct emission peaks, one of which is close to the position given by Murray *et al.* (1969) for the quasi-stellar object. This central emission peak accounts for 20 per cent of the 5 GHz flux density and it is unresolved. The optical emission varies on a time scale of a few months (Penston and Cannon 1970).

3C 263: The 5 GHz map of the source (Figure 3) shows a weak third component of flux density 0.13×10^{-26} W m^{-2} Hz^{-1} coincident with the position given by Murray *et al.* for the quasi-stellar object. All components of the source remain substantially unresolved at a baseline of 25 000 λ; the brightest component is less than 3×3 arc sec in size.

3C 111: This map was synthesized with observations made at only eight separate aerial spacings, and because the source has a large angular extent

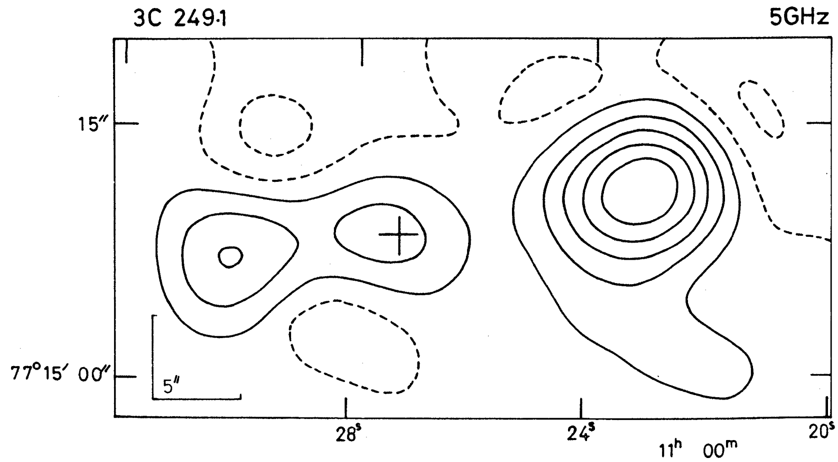

FIG. 2. 3C 249.1. This source was identified by Longair (1965) and it is a $V = 15.7$ quasi-stellar source (Sandage 1965, Sandage *et al.* 1965) for which Schmidt (1966) has obtained $z = 0.3107$. Penston and Cannon (1970) have found that it is variable.

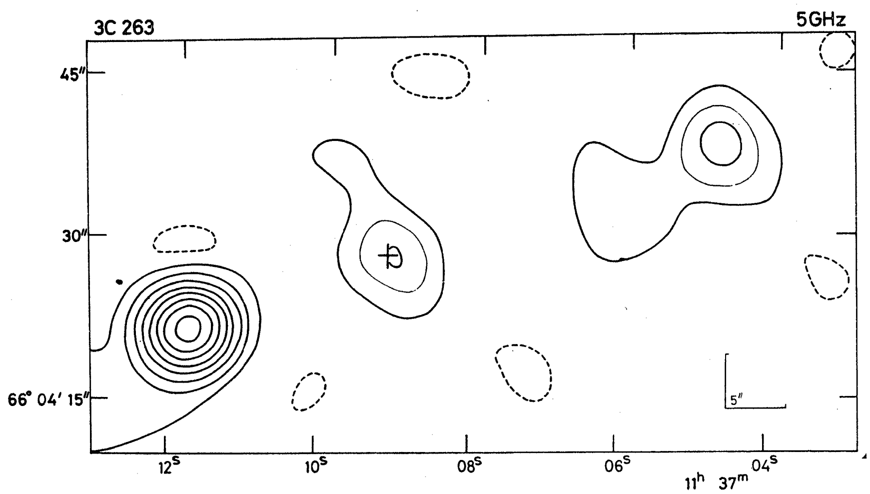

FIG. 3. 3C 263. The cross marks the position (Murray *et al.* 1969) of a $V = 16.3$ quasi-stellar object (Sandage *et al.* 1965) for which Ford and Rubin (1966) have determined a redshift $z = 0.652$. Penston and Cannon (1970) have found that it is variable.

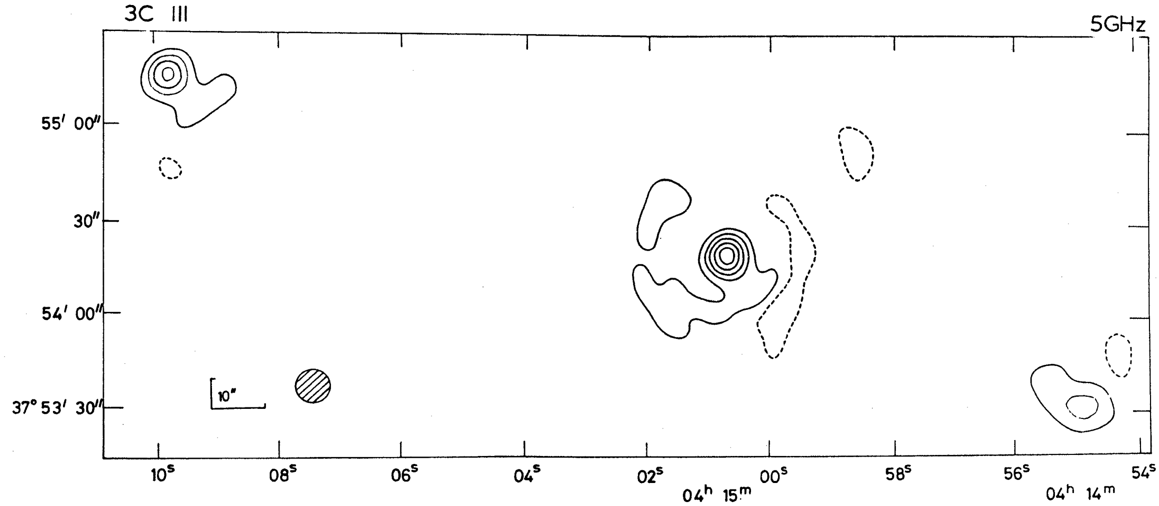

FIG. 4. 3C 111. Structure on a scale exceeding 30 arc sec is absent from this map. Optically the region is obscured (Wyndham 1966).

the primary grating response of the central component intersected the outer components. The map of Figure 4 was obtained by combining a map of the central source with a second map computed using the source removal technique of Neville *et al.* (1969) on the central component. Since the spacing interval used in the synthesis was 3130 λ the map is incomplete for structure exceeding 30 arc sec in scale. A further observation was therefore made at a spacing of 782 λ to determine the flux density from any extended low brightness features. Comparison of the amplitude and phase measured at 782 λ and 3 130 λ showed that 40 per cent of the total 5 GHz flux density is from structure greater than 30 arc sec in size. These measurements are entirely consistent with a distribution of regions of low surface brightness similar to those found by Mackay (1969) at 1.4 GHz.

3C 111 is the only source in the present work for which significant differences in spectral index across the source have been found. The central component has a spectral index 0.35 ± 0.07 over the range 0.4–5 GHz, whereas the outer components taken together have an index of 0.65 ± 0.10. It is therefore clear that the central component has a significantly flatter spectrum than the rest of the source, and for this reason the integrated spectrum of 3C 111 is concave (Kellermann *et al.* 1969) Figure 5 displays the spectrum of the inner and outer components.

The central component is unresolved and an upper limit of 3×5 arc sec may be placed on its size. Interferometric measurements at 2.7 GHz by Basart *et al.* (1968) suggest that this diameter is less than 2 arc sec. Observations of interplanetary scintillation at lower frequencies are more difficult to interpret because of the relatively small flux density of the central component. Measurements made by Harris and Hardebeck (1969) at 408 MHz show that 5 per cent of the total flux density (i.e.

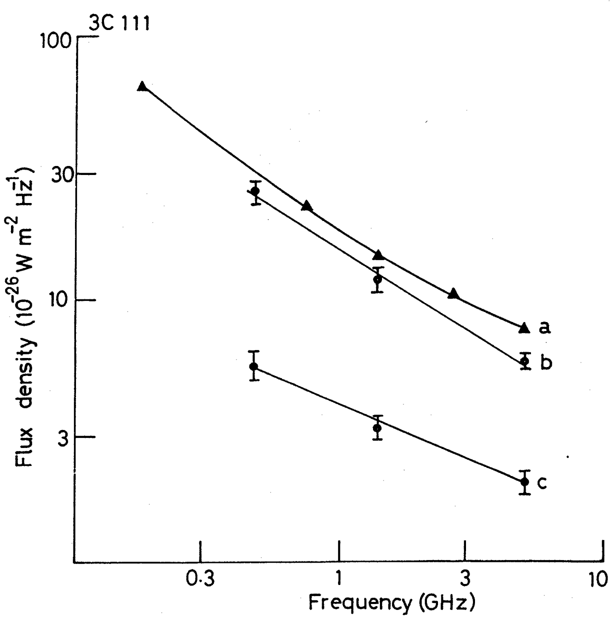

FIG. 5. The spectrum of 3C 111. (*a*) is the integrated spectrum taken from Kellermann *et al.* (1969); (*b*) is the combined spectrum of the outer components, and (*c*) is the spectrum of the compact central component. The 408 MHz and 1.4 GHz points are taken from the work of Mackay (1969) and the 5 GHz points are the result of the present observations.

about one third of that from the central component) originates within structure less than 0.2 arc sec in diameter.

It is unfortunate that obscuration has prevented the identification of the source. A comparison of its angular size and flux density with that of identified sources in the 3C catalogue suggests that it lies at a distance between 100 and 300 Mpc.

SOURCE ENERGIES

Three of the sources have reliable optical identifications and in each case an emission line redshift has been measured. For an Einstein-de Sitter universe with $H = 100$ km sec^{-1} Mpc^{-1} the observed angular structure and flux density may be used to derive various physical parameters which are listed in Table 2.

The minimum energy $U_{\min}$ in the form of relativistic particles and magnetic field is derived on the basis that there is not a large excess of energy in the form of protons. The containment of the plasma clouds by the mechanism described by De Young and Axford (1967) allows an estimate to be made of the minimum kinetic energy which must be present in the clouds (Mitton and Ryle 1969, Mitton 1970). This energy is of the order

$$U_{\min} \times \frac{\text{component separation}}{\text{component diameter}}$$

and it is this quantity which is tabulated in the final column of Table 2.

Before discussing the rates of energy production it is useful to obtain an estimate of the ages of the sources. If the plasma clouds are ejected with a speed close to that of light, the observed angular separations allow lower limits of $1\text{–}3 \times 10^5$ yr to be set. However, velocities greater than $0.7c$ are unlikely since the observed flux densities of the two components would then differ by a large factor, unless the source axis was nearly perpendicular to the line of sight. The containment mechanism of De Young and Axford yields a lower limit to the velocity: it is not likely to be effective for 3C 47, 249.1 and 263 unless the cloud velocity exceeds $0.05c$.

On the assumption that the source is symmetrical in its own frame of reference, Ryle and Longair (1967) indicated how estimates of the velocity of ejection and hence the age of the source could be derived from the measured angular separations of the two components from the optical object. The results for the present sources fall into the range given above, and lead to age estimates ranging from 4×10^5 yr for 3C 249.1 to 2×10^7 yr for 3C 47.

The estimates of $U_{\min}$ and the kinetic energy given in Table 2 show that for those sources in which the outer components are resolved, total energies in the range $5\text{–}50 \times 10^{58}$ erg are necessary. In addition to this the energy radiated as optical and radio emission from the central components of 3C 249.1 and 3C 263 are $10^{52}\text{–}10^{53}$ erg per year. It is unlikely that the central components represent a brief second event, since more than half the quasi-stellar radio sources in the 3C catalogue have

TABLE 2

Physical parameters for the four sources. The data for 3C 111 assume a distance of 150 Mpc

Source	Distance (Mpc)	Total size (kpc)	Volume (10^{66} cm^3)	Luminosity P_{5000} (10^{23} mks)	Minimum energy (10^{57} erg)	Magnetic field (10^{-5} Gauss)	Kinetic energy (10^{57} erg)
47	975	228	210	450	34	4	240
			670	210	36	2.4	250
249.1	760	66	21	140	5	5	30
			<21	45	<2.3	>3.8	—
			37	45	3.3	3.2	20
263	1330	181	<310	180	<19	>2.5	<100
			<140	160	<13	>3	—
			<37	900	<19	>7.5	<100
111	150	180	18	6.4	0.9	1	20
			<1.8	4.5	<0.2	>0.9	—
			18	6.8	1	1	20

extended structure corresponding to ages greater than 10^5 yr. Unless activity in the nuclei is continuous for a comparable period of time we would not expect to observe quasi-stellar objects associated with extended radio sources. We conclude therefore that the additional energy radiated from the centres of 3C 249.1 and 3C 263 is about 10^{58}–10^{59} erg.

The optical variations indicate that the energy release takes place in regions only a few parsec in diameter; the radiation rates must therefore indicate an average rate of energy production within the source, on account of the short expansion lifetime which a small source would have. During the lifetime of the source the energy released at the centre is comparable to the total requirement of the extended source.

CONCLUSION

Radio emission has successfully been detected from the optical objects associated with the extended sources 3C 249.1 and 3C 263, but it is absent in 3C 47. The observations allow certain restrictions to be placed on radio source models: the outer components require total energies $5–50 \times 10^{58}$ erg, 20 per cent of which is in the form of high energy electrons, and a magnetic field of around 10^{-5} Gauss. After these have been ejected from the parent object continuous energy release occurs at the centre, and during the lifetime of the source the energy produced is comparable to that required for the initial violent event.

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