

VARIATIONS IN THE RADIO-FREQUENCY SPECTRA OF 3C 84,
3C 273, 3C 279, AND OTHER RADIO SOURCES

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ABSTRACT

Seventy-eight non-thermal radio sources of small angular size, many of which have been identified with quasi-stellar objects, have been observed at wavelengths of 40 and 22 cm and the results have been compared with similar observations made three years earlier. Nine sources, 3C 120, 273, 279, 345, 418, and 454.3 and NRAO 140, 190, and 530, showed significant changes in their flux density at one or both wavelengths. The variations in 3C 84, 3C 273, and 3C 279 have been studied in detail at 2, 6, 11, 22 and 40 cm.

The observed changes in the radio spectra of these sources suggest the presence of very small components that are optically thick at cm wavelengths and have ages of only about 10 years. The energy requirements for 3C 84 and 3C 279 are discussed, and it is shown that in the case of 3C 279, if the radiation is due to synchrotron emission, the cosmological interpretation of the redshift requires the repeated production of more than 3×10^{68} ergs of relativistic electrons in times of 10 years or less.

I. INTRODUCTION

Between 1962.8 and 1963.9, the flux densities of all sources in the 3C and Revised 3C catalogues were measured at wavelengths of 40 and 22 cm with the NRAO 300-foot transit telescope (Pauliny-Toth, Wade, and Heesch 1966). In February and March, 1966, these observations were repeated for seventy-eight sources which had either been identified with quasi-stellar objects or were known to have small angular diameters, in order to determine what proportion of these radio sources showed variations in their flux densities at these wavelengths. Significant changes were found in nine of these sources.

For the sources 3C 84, 3C 273, and 3C 279, which Dent (1965*a, b*) has reported to be variable at centimeter wavelengths, we have used observations made by us at 11 cm in September, 1965, at 6 cm in August, 1965, and February, 1966, and at 2 cm in October, 1965, and February–March, 1966, to derive the variations in the radio spectra. In addition, we have used the results of earlier observations at the NRAO (Heesch 1961; Baars, Mezger, and Wendker 1965) as well as those of Dent (1965*a, b*), those of Maltby and Moffet (1965), and unpublished observations made at Parkes.

II. THE OBSERVATIONS

a) Results of the Measurements at 40 and 22 Cm

The calibration of the flux-density scales for the present observations was made in the same way as for the earlier measurements (Pauliny-Toth *et al.* 1966). 3C 273 was excluded from the list of standard sources, and allowance was made for a small change in one of the frequencies of observation (1414 MHz instead of 1400 MHz). At each frequency the mean difference in flux density measured at the two epochs was less than 1 per cent and the rms dispersion, σ , was about 4 per cent. For seven sources, 3C 120, 273, 279, 418, NRAO 140, 190, and 530, the differences at 20 cm were more than 3σ . In addition 3C 345 and 454.3 showed changes greater than 2σ . Large variations in the 11-cm flux density of 3C 345 have been found by Bartlett (1965).

At 40 cm, 3C 120 and NRAO 190 changed by more than 3σ . NRAO 140 and 530

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showed smaller but perhaps significant changes at this frequency. No variation was observed at either wavelength in 3C 84.

The observed flux densities for these sources and their changes are given in Table 1, with the exception of 3C 273 and 279, which are dealt with in more detail later. For sources that have been observed on more than one occasion during the earlier period, the percentage change quoted refers to the mean flux density over that period.

b) Variations in the Spectra of 3C 84, 3C 273, and 3C 279

In Figures 1-3 we have plotted the measured flux densities of 3C 84, 3C 273, and 3C 279 against the epoch of observation. For simplicity, we have combined the observations

TABLE 1
FLUX DENSITIES AT VARIOUS EPOCHS OF SOURCES FOR WHICH A SIGNIFICANT DIFFERENCE WAS FOUND BETWEEN FLUX DENSITY MEASURED IN 1966.1 AND THAT MEASURED IN EARLIER PERIOD

SOURCE	EPOCH						CHANGE (Per Cent)
	1962 8	1962 9	1963 2	1963 4	1963 8	1966 1	
Flux Densities at 22 Cm*							
3C 120	5 6±0 3		6 7±0 2		6 0±0 2	3 5±0 2	-38± 5
3C 345					5 4± 3	7 0± 2	+10± 5
3C 418					6 5± 3	6 5± 3	+20± 6
3C 454 3	12 4± 3	11 9±0 2	12 0± 3		12 1± 2	10 8± 2	-11± 2
NRAO 140			3 9±0 2		3 7± 2	3 3± .2	-13± 7
NRAO 190	2 4±0 3					3 7± 3	+54±23
NRAO 530				6 0±0 2	4 9±0 3	-18± 6
Flux Densities at 40 Cm							
3C 120	5 5±0 1		3 9±0 3			4 1±0 2	-25± 4
NRAO 140					4 4±0 3	3 7± 2	-11± 7
NRAO 190	1 4±0 2					1 9± 2	+36±24
NRAO 530					6 7±0 2	6 2±0 3	- 8± 5

* The flux densities quoted are in flux units: 1 flux unit = 10^{-26} W m⁻² Hz⁻¹. At 22 cm they refer to a north-south polarization and at 40 cm to an east-west polarization

of Dent (1965*a, b*) at 1.8 cm with our observations at 2 cm. Since all three sources have spectral indices of nearly zero at this wavelength, this procedure does not introduce any significant errors.

In 3C 84 we have observed an increase of 5 flux units (35 per cent) per year during the past 2 years at 6 cm. No significant changes have occurred at 11 cm during the past 5 years, at 22 cm during the past 4 years, or at 40 cm during the past 3 years. At 3.75 cm, Dent's measurements (Dent 1965*b*) and those of Heeschen (1961) indicate an increase of 2.5 flux units per year over the last 6 years (corresponding to 13 per cent per year in 1964.0). At 1.8 cm Dent (1965*b*) has reported a slower rate of increase of about 1 flux unit per year (4 per cent) over the last 2 years. Our measurements at 2 cm show no change greater than 5 per cent between 1965.8 and 1966.1. Thus, in 3C 84 we observe a large rate of change at 6 cm, with lower rates of change at shorter wavelengths.

The variations in the spectrum of 3C 273 are somewhat more complex. Here, we find

an increase of 1.9 flux units per year at 22 cm over the last 3 years, with a lower rate of increase previously, and an increase of 1.5 flux units per year at 11 cm over the last 4 years. These values are in good agreement with those of Maltby and Moffet (1965). At 40 cm we found no change over the last 4 years, consistent with the absence of any variation reported by these authors at 31 cm. At 3.75 cm and 1.8 cm Dent (1965*b*) reported increases of 3.4 and 8.6 flux units per year, respectively, over the last 2 years. Our measurements at 2 cm in October, 1965, are consistent with the increase found by Dent.

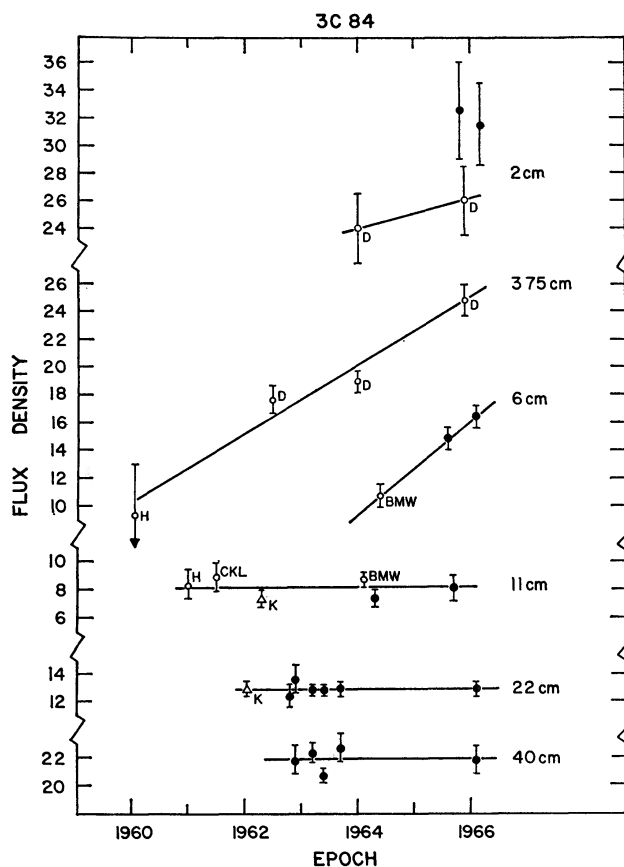


FIG. 1—Measured flux densities for 3C 84 at 40, 22, 11, 6, 3.75, 2, and 1.8 cm. The NRAO observations are shown as solid circles. The letters note other observers as follows: *D*, Dent (1965*a*, *b*); *H*, Heesch (1961); *BMW*, Baars, Mezger, and Wendker (1965); *CKL*, Conway, Kellermann, and Long (1963); *K*, Kellermann (1964).

However, by February 22, 1966, the flux density had increased to 51.8 flux units, compared with 41 flux units measured in October, 1965. The uncertainty in the relative flux densities is only a few per cent while the absolute scale may be in error by about 10 per cent. Between February 22 and March 24, 1966, when the observations ceased, the flux density continued to increase at a rate of 1.7 ± 0.5 flux units per week. A similar rapid increase in the flux density of 3C 273 at 2 cm has been noted by Allen (1966) and Dent (1966).¹ There has been no change in the flux density at 6 cm, although at both longer and shorter wavelengths the flux density has been increasing during this period.

Perhaps the most interesting of the variable sources is 3C 279, for which Dent (1965*b*)

¹ Note added in proof: Further observations made in June and August, 1966, show that at 2 cm the flux density of 3C 273 probably reached a maximum of about 70 flux units in July, 1966.

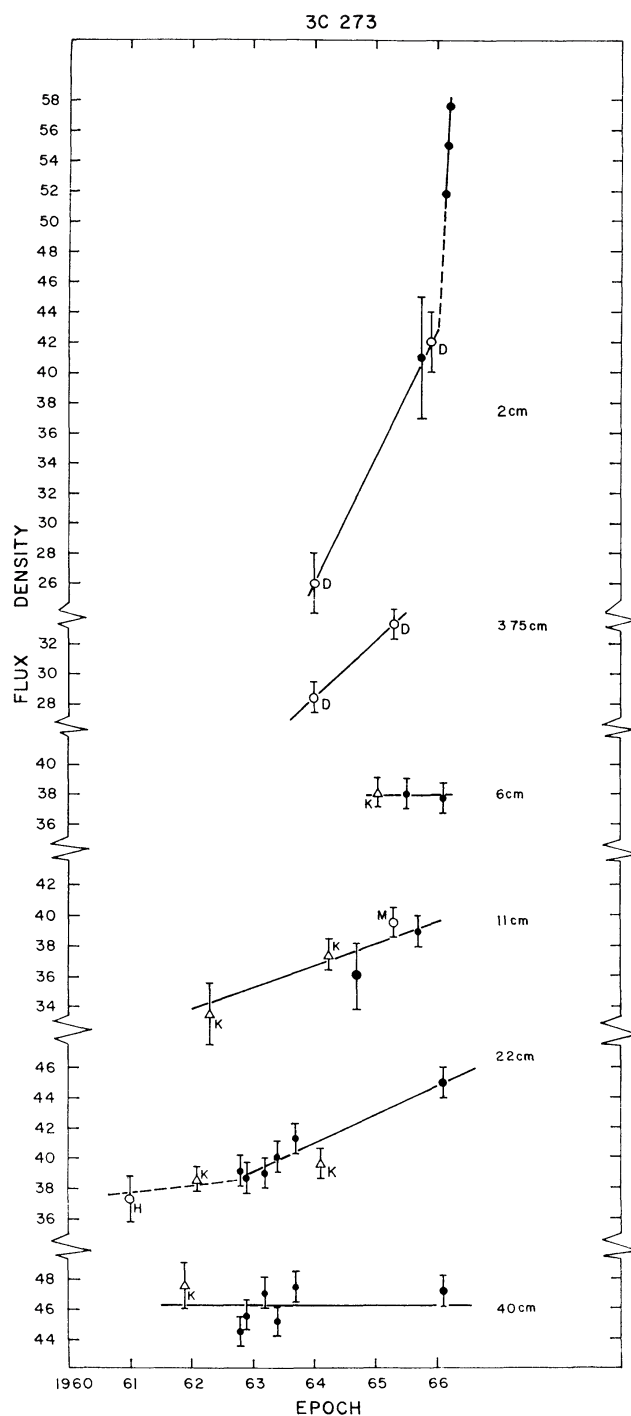


FIG. 2—Measured flux densities for 3C 273 at 40, 22, 11, 6, 3.75, 2, and 1.8 cm. The NRAO observations are shown as solid circles. The letters denote other observations as follows: *D*, Dent (1965*a*, *b*); *H*, Heesch (1961); *K*, Kellermann (1964) or Kellermann, unpublished; *M*, Maltby and Moffet (1965). The error brackets include the uncertainty in the calibration of the flux-density scale. The uncertainty in the relative amplitudes from day to day is considerably less, so that the differences between the three points representing the start, middle, and end of the February–March period are significant.

had reported decreases at 1.8 and 3.75 cm, but for which we have observed an *increase* at 22 cm of 1 flux unit per year over the last 3 years. At 40 cm, we found no change from 1962.8 to 1966.1. At 11 cm the flux density has remained approximately constant during the past 2 years. Before 1964, there is evidence that the intensity was increasing, but there is some uncertainty about the accuracy of these early measurements. At 6 cm we have observed a decrease of 2.9 flux units in 1 year. At 3.75 and 1.8 cm, Dent has reported a decrease from 15.6 and 15.4 flux units, respectively, in 1964.0 (Dent and Haddock 1965) to 11 flux units at both frequencies in November, 1965 (Dent 1965*b*), a rate of decrease of about 2.3 flux units per year. However, a measurement made by the authors in October, 1965, gave a flux density of 8 ± 3 flux units (the error quoted is due to receiver noise and to the uncertainty in the calibration of the gain of the telescope). In February and March, 1966, the observations were repeated with improved equipment and the flux density on February 17 and 22, 1966, was found to be 18 ± 4 flux units, where the error is now largely the systematic error in the calibration of the telescope.

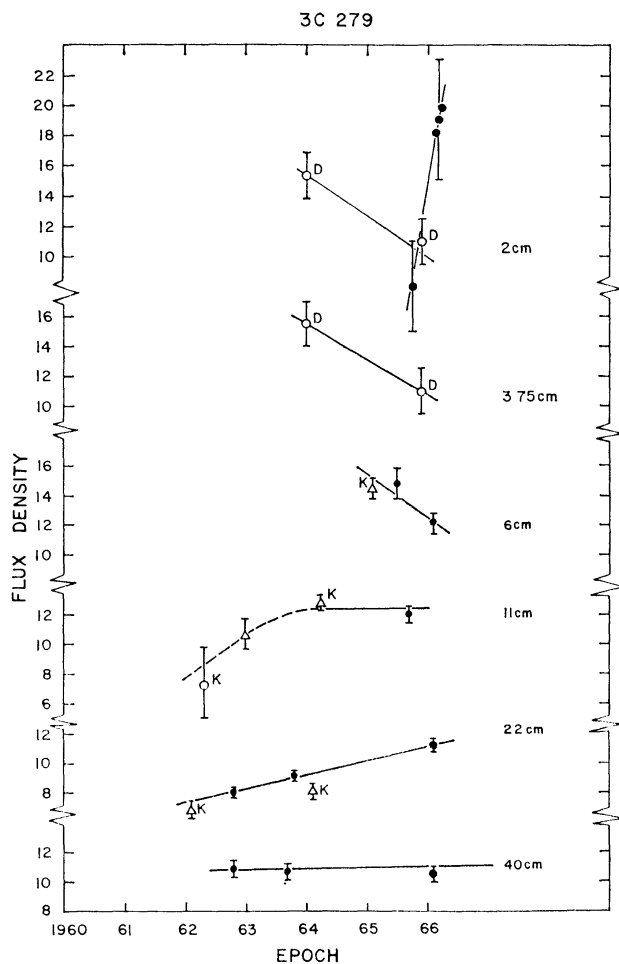


FIG. 3.—Measured flux densities for 3C 279 at 40, 22, 11, 6, 3.75, 2, and 1.8 cm. The NRAO observations are shown as solid circles. The letters denote other observers as follows: *D*, Dent (1965*a*, *b*); *K*, Kellermann (1964) or Kellermann, unpublished. The error brackets include the uncertainty in the calibration of the flux-density scale. The uncertainty in the relative amplitudes from day to day is considerably less, so that the differences between the three points at 2 cm, representing the start, middle, and end of the February–March period, are significant.

There are difficulties in comparing the results of different observers owing to the different instruments and calibration techniques used. Taken at face value, however, the data indicate that the flux density of 3C 279 was decreasing at wavelengths near 2 cm until the end of 1965, and that since that time it has increased by more than a factor of 2.

At 2 cm these three sources, together with Virgo A, were observed frequently throughout the period February 17 to March 24, 1966. Figure 4 shows the individual antenna temperatures measured for each source. The estimated uncertainty in each observation is about 0.1° K. No significant change was found for 3C 84 or Virgo A over the 5-week period. The antenna temperature of 3C 279 increased by $0.20^\circ \pm 0.05^\circ$ K, corresponding to 1.7 ± 0.5 flux units, during this time. For 3C 273 the antenna temperature increased, on the average, by $0.24^\circ \pm 0.05^\circ$ K per week and the flux density by 1.7 ± 0.5 flux units per week during this period. In addition, there were fluctuations in the antenna temperature of 3C 273 with a period of several days and a peak-to-peak amplitude of about 9

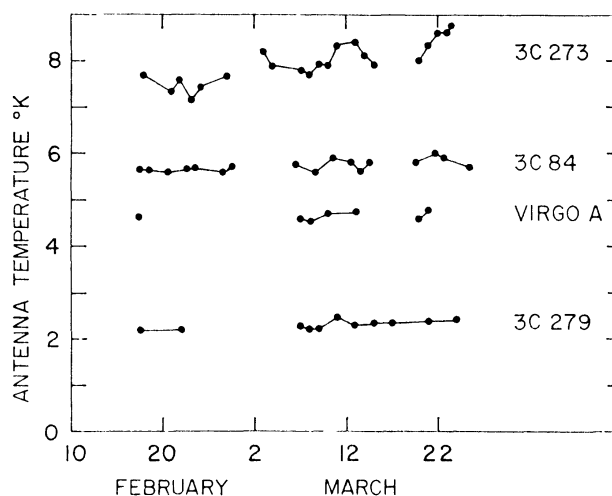


FIG. 4.—Antenna temperatures for 3C 273, 3C 84, Virgo A, and 3C 279, measured during February and March, 1966, at 2 cm.

per cent, which was greater than could be accounted for by experimental errors and also greater than the fluctuations observed for the other sources.

III. DISCUSSION

3C 273, 3C 279, 3C 345, and 3C 454.3 are identified with quasi-stellar objects all of which have shown significant variations in their optical luminosity. All four of these have components which are less than $3''$ at 2650 MHz (Clark and Hogg 1966). 3C 273, 3C 279, and 3C 345 have redshifts of 0.158 (Schmidt 1963), 0.540 (Burbidge and Rosenberg 1965), and 0.595 (Burbidge 1965), respectively. All three contain components with angular sizes of less than $0''.1$ (Barber, Donaldson, Miley, and Smith 1966) at 20 cm. At longer wavelengths, the over-all dimensions of 3C 273 and 3C 279 are about $20''$, comparable with the extent of the jets.

The source 3C 84, on the other hand, is coincident with the 13th magnitude Seyfert galaxy NGC 1275. At 20 cm, 3C 84 also contains a component with an angular size smaller than $0''.1$ as well as a larger source which has a spectrum typical of radio galaxies and which dominates at meter wavelengths. The striking similarity in the radio and optical properties of the quasi-stellar sources and Seyfert galaxies has been emphasized by Shklovsky (1966) and others.

An identification for 3C 120 with a galaxy has been given by Bolton (Day, Shimmins,

Ekers, and Cole 1966). Measurements with the NRAO interferometer at 2650 MHz (Clark, private communication) confirm the identification and show that the radio source is smaller than $3''$. The galaxy appears to have a faint diffuse envelope surrounding a relatively bright nearly stellar nucleus.

All the sources which have shown significant variations have either positive curvature in their radio spectra or positive spectral indices over a limited range of decimeter wavelengths. In at least 3C 84, 3C 279, and NRAO 190, the steep positive indices exclude pure synchrotron emission, which cannot increase faster than $(\text{frequency})^{1/3}$. Such indices suggest the presence of components that are optically thick even at centimeter wavelengths. These components must then be very small and probably quite young and, as Shklovsky (1965) has pointed out, we might expect their flux density to change in a period of a few years.

It has been shown elsewhere that the form of the radio spectra of extragalactic sources can be readily explained if relativistic electrons which have an initial energy distribution $N(E) = KE^{-\gamma}$ (where $\gamma = 1.5$) are injected into a magnetic field in a series of bursts (Kellermann 1966). We consider a symmetrical source of synchrotron radiation, of linear extent l and at a distance R , with $\gamma = 1.5$. At frequencies where the source is optically thick, the flux density follows from the expressions for the emissivity and absorption coefficient given by LeRoux (1961). The flux density is given by

$$S \sim 10^{-3} B^{-1/2} \theta^2 f^2 \text{ flux units,} \quad (1)$$

where

$$\theta = 2.06 \times 10^5 \frac{l}{R} \text{ sec of arc} \quad (2)$$

is the angular diameter, B is the magnetic field in gauss, and f is the frequency in MHz. If we assume that the diameter of the source, l , increases at a constant rate, so that

$$l/l_0 = t/t_0 \quad (3)$$

and if the magnetic flux is conserved during the expansion (Shklovsky 1960) so that

$$\frac{B}{B_0} = \left(\frac{l_0}{l}\right)^2 \quad \text{or} \quad B = B_0 \left(\frac{l_0}{l}\right)^2, \quad (4)$$

then equation (1) may be written

$$S \sim 10^{-3} B_0^{-1/2} \theta_0^2 f^2 \left(\frac{t}{t_0}\right)^3, \quad (5)$$

where the suffix zero denotes the values of the parameters at time t_0 .

Thus, the flux density of an expanding, optically thick source will increase at a rate proportional to the third power of the time. If the rate of change of flux density is dS/dt , then the age, t , is

$$t = 3 \frac{S}{dS/dt}, \quad (6)$$

or we may obtain the age from

$$t = \left(\frac{S}{S_0}\right)^{1/3} t_0, \quad (6a)$$

where S and S_0 are the flux densities at epochs t and t_0 .

At high frequencies, where the source is optically thin, the flux density will decrease according to the relation (Shklovsky 1960)

$$S \propto t^{-2(1-2\alpha)}, \quad (7)$$

where α is the spectral index of the source at these frequencies.

In the optically thick region of the spectrum, equation (1) provides a simple relation between the magnetic field B and the angular diameter θ . An additional relation between B , the density of relativistic electrons n_e , the linear extent of the source l along the line of sight, and the optical depth τ at any frequency f , follows from the expression for the absorption coefficient given by LeRoux (1961). Taking $\gamma = 1.5$ again, we may write

$$\tau \sim 10^{11} B^{7/4} \nu^{-11/4} n_e l, \quad (8)$$

where l is expressed in parsecs and n_e in cm^{-3} . If we assume that the electrons were injected in one burst at the beginning of the expansion, it follows from equation (3), (4), and (8), that the frequency at which the optical depth is unity varies approximately as t^{-2} .

Equations (1) and (8) may now be used to determine the density of relativistic electrons as a function of the magnetic-field strength. The total energy in these particles E_e can be obtained from

$$E_e = 4.7 \times 10^{52} \frac{[1 - (E_1/E_2)^{1/2}]}{[(E_2/E_1)^{1/2} - 1]} E_2 n_e l \text{ ergs}, \quad (9)$$

where E_1 and E_2 are the cutoff energies in the electron energy distribution.

Table 2 gives the values of the angular diameter θ , the linear dimension l , the density of relativistic electrons n_e , their half-life against synchrotron losses $T_{1/2}$ (computed for electrons with a critical frequency of 15 GHz), the energy contained in the relativistic electrons E_e , and that in the magnetic field E_m , for various values of B for 3C 84 and 3C 279.

In 3C 84 there is some uncertainty in the spectral index of the low-frequency component because of the proximity of the source 3C 83.1. Nevertheless, the spectrum of the high-frequency component is consistent with that of a source which becomes optically thick near 8 GHz. For this source, we have taken the distance to be 54 Mpc (Matthews, Morgan, and Schmidt 1964), the cutoff frequencies as 10 MHz and 50 GHz, and γ as 1.5. The optical depth has been taken as unity at 8 GHz and the flux density of the high-frequency component as 5 flux units at 4 GHz.

For 3C 279 we have taken two cases: in the first case, we have assumed the distance to be 15 Mpc and in the second, we have taken the distance indicated by the redshift, of 1500 Mpc. In both cases, the cutoff frequencies and γ were taken to be the same as for 3C 84. The frequency of unit optical depth was taken as 2.5 GHz and the flux of the high-frequency component as 2 flux units at 1 GHz. In both cases, the observed flux density, the corresponding frequency, and the frequency of unit optical depth were increased by the factor $(1+z)$ to correct for the redshift. In the cosmological case, this corresponds to a universe with $q_0 = 1$ where the observed angular size, θ' , is

$$\theta' = \theta(1+z)^2 \quad (10)$$

and where θ is given by equation (2), and R in equation (2) is the luminosity distance (McVittie 1965).

The source with the simplest behavior is 3C 84. Figure 5 shows the radio spectrum at the epochs 1960.0, 1962.0, 1964.0, and 1966.0. From the observed flux densities of the high-frequency component at 4 GHz in 1966.0 and 1964.0 and equation (6a), we estimate the age of this component to be about 7 years. Even if the expansion occurs at the velocity of light, the linear diameter must be less than 5 pc, corresponding to an angular diameter of $0''.02$ at a distance of 54 Mpc. This is less than the observed limit of $0''.1$ (Barber *et al.* 1966). Table 2 shows that, if the half-life of the electrons is to be more than a few months, the diameter must be smaller than 1 pc. A similar conclusion is reached from the consideration that a velocity of expansion of the order of c would obliterate the sharp cutoff in the high-frequency component, since different parts of the source would appear to be optically thick at different frequencies owing to the different

TABLE 2
 CONDITIONS WITHIN THE SOURCES 3C 84 AND 3C 279 FOR
 VARIOUS VALUES OF THE MAGNETIC FIELD

SOURCE	<i>B</i> (gauss)				
	10 ⁻⁶	10 ⁻⁴	10 ⁻²	1	10 ²
3C 84					
<i>T</i> _{1/2} at 15 GHz . . .	2.7 × 10 ⁸ yr	2.7 × 10 ⁵ yr	2.7 × 10 ² yr	99 days	2.4 hr
<i>θ</i> (sec)	7.1 × 10 ⁻⁵	2.2 × 10 ⁻⁴	7.1 × 10 ⁻⁴	2.2 × 10 ⁻³	7.1 × 10 ⁻³
<i>l</i> (pc)	1.8 × 10 ⁻²	5.8 × 10 ⁻²	1.8 × 10 ⁻¹	5.8 × 10 ⁻¹	1.8
<i>n</i> _e (cm ⁻³)	9.1 × 10 ¹¹	9.1 × 10 ⁷	9.1 × 10 ³	9.1 × 10 ⁻¹	9.1 × 10 ⁻⁵
<i>E</i> _e (ergs)	2.1 × 10 ⁶⁰	6.6 × 10 ⁵⁶	2.1 × 10 ⁵³	6.6 × 10 ⁴⁹	2.1 × 10 ⁴⁶
<i>E</i> _m (ergs)	7.2 × 10 ³⁶	2.3 × 10 ⁴²	7.2 × 10 ⁴⁷	2.3 × 10 ⁵³	7.2 × 10 ⁵⁸
3C 279 "Local" (15 Mpc Distant)					
<i>T</i> _{1/2} at 15 GHz . . .	2.7 × 10 ⁸ yr	2.7 × 10 ⁵ yr	2.7 × 10 ² yr	99 days	2.4 hr
<i>θ</i> (sec)	1.9 × 10 ⁻⁴	5.9 × 10 ⁻⁴	1.9 × 10 ⁻³	5.9 × 10 ⁻³	1.9 × 10 ⁻²
<i>l</i> (pc)	1.3 × 10 ⁻²	4.2 × 10 ⁻²	1.3 × 10 ⁻¹	4.2 × 10 ⁻¹	1.3
<i>n</i> _e (cm ⁻³)	1.7 × 10 ¹¹	1.7 × 10 ⁷	1.7 × 10 ³	1.7 × 10 ⁻¹	1.7 × 10 ⁻⁵
<i>E</i> _e (ergs)	1.5 × 10 ⁶⁰	4.7 × 10 ⁵⁶	1.5 × 10 ⁵²	4.7 × 10 ⁴⁸	1.5 × 10 ⁴⁵
<i>E</i> _m (ergs)	2.8 × 10 ³⁶	8.9 × 10 ⁴¹	2.8 × 10 ⁴⁷	8.9 × 10 ⁵²	2.8 × 10 ⁵⁸
3C 279 "Cosmological" (1500 Mpc Distant)					
<i>T</i> _{1/2} at 15 GHz	2.7 × 10 ⁸ yr	2.7 × 10 ⁵ yr	2.7 × 10 ² yr	99 days	2.4 hr
<i>θ</i> (sec)	4.4 × 10 ⁻⁴	1.4 × 10 ⁻³	4.4 × 10 ⁻³	1.4 × 10 ⁻²	4.4 × 10 ⁻²
<i>l</i> (pc)	1.3	4.2	1.3 × 10 ¹	4.2 × 10 ¹	1.3 × 10 ²
<i>n</i> _e (cm ⁻³)	1.7 × 10 ⁹	1.7 × 10 ⁵	1.7 × 10 ¹	1.7 × 10 ⁻³	1.7 × 10 ⁻⁷
<i>E</i> _e (ergs)	1.5 × 10 ⁶³	4.7 × 10 ⁵⁹	1.5 × 10 ⁵⁶	4.7 × 10 ⁵²	1.5 × 10 ⁴⁹
<i>E</i> _m (ergs)	2.8 × 10 ⁴²	8.9 × 10 ⁴⁷	2.8 × 10 ⁵³	8.9 × 10 ⁵⁸	2.8 × 10 ⁶⁴

NOTE: The effect of the redshift corrections applied to 3C 279 for a given value of *B* has been to multiply the source parameters by the factors below:

Parameter	"Local" Case	"Cosmological" Case
<i>θ</i>	0.74	1.7
<i>l</i>	0.74	0.74
<i>n</i> _e	4.5	4.5
<i>E</i> _e	1.7	1.7
<i>E</i> _m	0.38	0.38

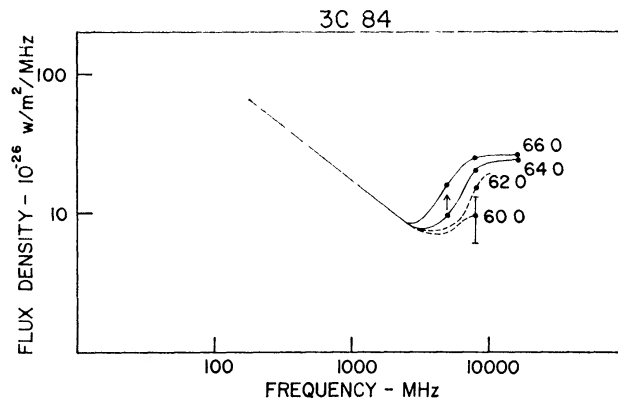


FIG. 5.—Spectrum of 3C 84 at the epochs 1960.0, 1962.0, 1964.0, and 1966.0

Doppler shifts of their radiation. The total energy is a minimum for $B \sim 0.16$ gauss, when $E_e \sim E_m \sim 1.6 \times 10^{51}$ ergs, $l \sim 0.35$ pc, $\theta \sim 10^{-3}$ sec, $n_e \sim 40$ cm $^{-3}$, and the electron lifetime is about 4 years.

In Figure 6 we show the spectrum of 3C 279 at the epochs 1962.0, 1964.0, and 1966.0. The thin dashed lines show the spectrum of the high-frequency component (component II), obtained by subtracting the extrapolated spectrum of the low-frequency component (component I) from the total flux densities observed. It can be seen that, over a limited frequency range, the spectral index of component II is near $+2.5$, which is the value expected if the source is optically thick. The increase in flux density from 1962.0 to 1964.0 is somewhat greater than from 1964.0 to 1966.0, which suggests that the rate of expansion has decreased.

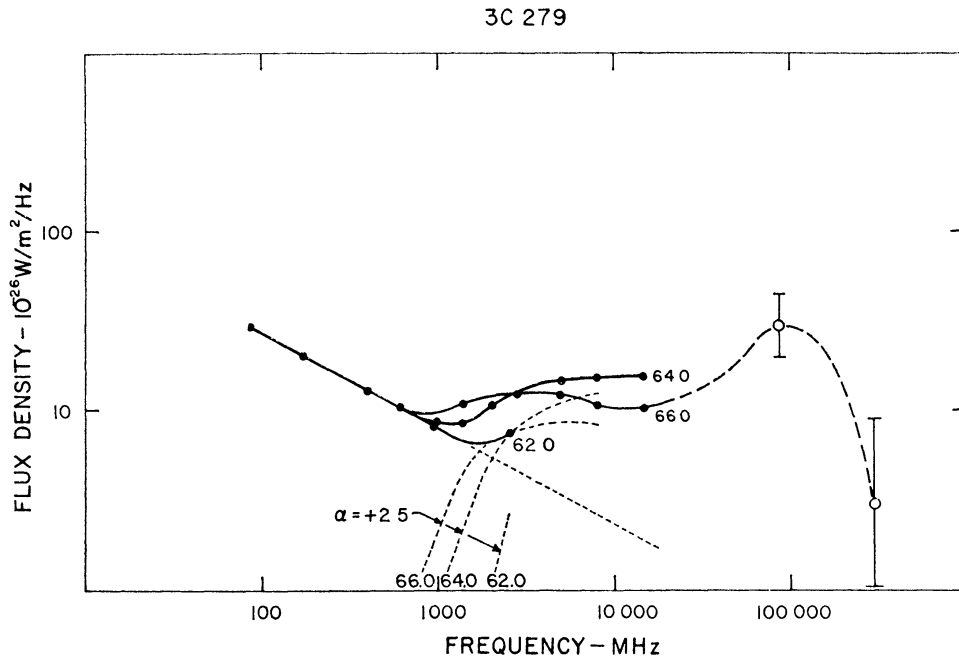


FIG. 6.—Spectrum of 3C 279 for the epochs 1962.0, 1964.0, and 1966.0. The points at 88 GHz and 300 GHz are from Epstein (1965*a*) and Low (1965), respectively. The thin dotted lines show the separation into components I and II.

Above 2.5 GHz, the flattening of the spectrum indicates that component II is becoming optically thin. The flux density should then decrease with time according to equation (7). This is consistent with the decrease at 1.8 and 3.75 cm reported by Dent. However, the increase at 2 cm observed at the present time suggests that there is yet another expanding component (component III) that is still optically thick at 2 cm. The anomalously high flux density at 3.4 mm found by Epstein (1965*a*) in April–May, 1965, and its subsequent decrease (Epstein, private communication), support this suggestion. The observed rate of increase of the 2-cm flux density then indicates an age of about 2 years for this component. If this interpretation is correct, then the continued expansion of component III will cause the flux density at progressively lower frequencies to increase until the dimensions become so large that the optical depth is less than unity. The flux will then decrease according to equation (7). Similarly, as component II continues to expand, the flux density at 22 cm should reach a maximum and then begin to decrease.

The flux densities of component II at 1 GHz in 1964.0 and 1966.0, with equation (6a) give an age of about 10 years for this component, which must therefore have a

diameter smaller than 6.5 pc. If 3C 279 is at the distance of 1500 Mpc, as its redshift indicates, then $\theta < 2 \times 10^{-3}$ sec, $B \lesssim 5 \times 10^{-4}$ gauss, $n_e \gtrsim 6 \times 10^3$ cm $^{-3}$, $E_m \lesssim 6 \times 10^{49}$ ergs, and $E_e \gtrsim 3 \times 10^{58}$ ergs. The cosmological interpretation of the redshift then requires the production of at least 3×10^{58} ergs in relativistic electrons, an energy which corresponds to that released by about 10^8 Type I supernovae, in a period of 10 years or less. Moreover, as was pointed out for 3C 84, the sharp cutoff in component II near 2 GHz indicates an expansion velocity considerably smaller than c . For a velocity of $0.2 c$, for example, the source parameters become: $l \lesssim 1.3$ pc, $\theta \lesssim 4 \times 10^{-4}$ sec, $B \lesssim 10^{-6}$ gauss, $n_e \gtrsim 2 \times 10^9$ cm $^{-3}$, $E_e \gtrsim 10^{63}$ ergs, and $E_m \lesssim 3 \times 10^{42}$ ergs.

On the other hand, if 3C 279 is at a distance of only 15 Mpc, then from equations (1) and (2) the magnetic field may be increased by a factor of 10^3 . The minimum energy

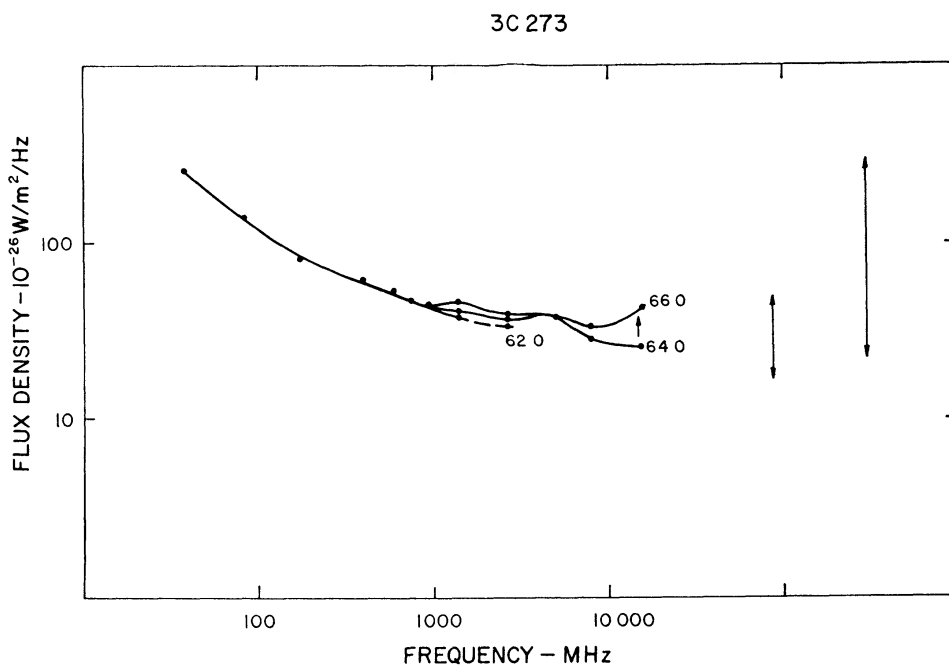


FIG. 7.—Spectrum of 3C 273 for the epochs 1962.0, 1964.0, and 1966.0. The points at 88 GHz and 300 GHz are from Epstein (1965*b*) and Low (1965).

then occurs for $B \sim 0.1$ gauss, with $l \sim 0.2$ pc, $\theta \sim 0.003$ sec, $n_e \sim 13$ cm $^{-3}$, and $E_e \sim E_m \sim 2 \times 10^{50}$ ergs. The expansion velocity in this case is only $0.03 c$. It may be noted that, if 3C 279 is at the same distance as 3C 84, their energy requirements are comparable.

The spectrum of 3C 273, shown in Figure 7, has even more structure than that of 3C 279. Here two peaks are seen, one near 20 cm (1500 MHz), and one near 6 cm (5000 MHz), and a third is appearing at wavelengths near 2 cm (15000 MHz). Since there has been no change in the flux density of 3C 273 at 6 cm over the past year, during which time the flux density has been rising at both longer and shorter wavelengths, we suggest that the increases over the last 2 years below and above 6 cm represent two distinct components in the source. The high flux density of 300 ± 100 flux units observed by Low (1965) at 1 mm in January, 1965, indicates the presence of a third component. An increase in the flux density at 3.4 mm (Epstein 1965*b*) from 17 ± 11 flux units in April, 1965, to 60 ± 10 flux units in July, 1965, occurred while the flux density at 1 mm (Low 1965) decreased to 22 ± 5 flux units in June, 1965. This behavior suggests that during the period January–July, 1965, this third component became optically thin at 1 mm

but remained opaque at 3.4 mm so that the intensity decreased at 1 mm while increasing at 3.4 mm. The expansion of this component has now presumably increased the 2-cm flux density to the level where the rate of increase is easily detectable over a period of a few weeks. Meanwhile Epstein (private communication) has observed a lower flux density at 3.4 mm than in July, 1965, which indicates that the source is now optically thin at this wavelength. The rate of change of flux density at 2 cm suggests an age of less than 2 years for this component. As in the case of 3C 279, continued expansion should cause the flux density to increase at progressively longer wavelengths.

IV. CONCLUSIONS

The complex spectra found in many of the variable sources, particularly 3C 273, suggest continuing activity in these sources that periodically produces an expanding cloud of relativistic particles in time scales ranging from a few days to a few years. Independent arguments based on the distribution of spectral indices also indicate repeated injections of particles in radio galaxies but on much longer time scales (Kellermann 1966). Thus, radio galaxies and quasi-stellar sources may differ only in the frequency of explosions.

However, if synchrotron emission is indeed the radiation mechanism, the cosmological interpretation of the redshift seems to require prohibitively large amounts of energy to be repeatedly created in very short times. On the other hand, if the sources are relatively nearby, the energy requirements are greatly reduced.

Another possibility is that the radio emission is not intrinsically variable and that the observed variations are due to absorption or amplification in the intervening intergalactic, interstellar, or interplanetary medium. It is of interest to note that the 2-cm flux densities of 3C 273 and 3C 279, sources which are only 10° apart in the sky, both began to increase rapidly near the end of 1965. Further observations should decide whether this is merely a coincidence. If a real correlation exists, then the regions that cause the variations in the two sources are not more than a few light-months apart in space, and thus no further than a few light-years away.

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