VARIABLE RADIO SOURCES[1]

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INTRODUCTION

Time variations in the observed flux density of discrete radio sources may arise either from intrinsic variations within the radiating region or from absorption, amplification, reflection, or refraction between the source and the observer.

Variations with time scales of the order of tens of seconds caused by ionospheric irregularities have been observed at meter wavelengths since the discovery of discrete sources, and it was in fact through these variations that the discrete nature of the sources was first realized (1). More recently, very short-term fluctuations with time scales of 1 sec and less have been observed in sources with angular sizes smaller than 1 sec of arc; these are due to scattering in the interplanetary medium (e.g. 2). It had been suggested earlier that irregularities in the interplanetary medium might affect the strong sporadic emission observed from the planet Jupiter at decimetric wavelengths (3). Variable radio emission has of course also been observed from the Sun, both in the form of the so-called "slowly varying component" and as intense bursts or storms at meter and centimeter wavelengths (e.g. 4).

Until 1965, however, the only observed radio variability believed to arise from outside the solar system was from the intense supernova remnant Cassiopeia A. In this case the possibility of a secular variation in the flux density had been predicted by Shklovskii (5) before the experimental verification by Högbom & Shakeshaft (6). Fluctuations have also been noted in the intensity of the very narrow-band line emission from compact OH-emission regions (7, 8). These variations occur on time scales of days or less and it has been suggested that the effect arises in the interstellar medium rather than within the sources themselves (8). The possibility that the rapidly fluctuating OH emissions are due to artificial transmissions from an extraterrestrial civilization has also been considered (e.g. 9). *Note added April 28, 1968:* The discovery of an entirely new and unexpected class of variable radio source, announced in February 1968 (126), has produced an unprecedented flurry of activity and publications. These objects, four of which are now known, emit a pulsed radiation with repetition rates ranging from 0.253 to 1.337 sec (127). In any individual source the rate is extraordinarily constant to an accuracy up to 1 part in 10^7 (126–128). The intensity of the emission from each source is, however, highly erratic with bursts of pulses lasting about a minute (126) and with periods of activity recurring on time scales of

[1] The survey of literature for this review was concluded in December 1967.

about an hour (128). The duration of each pulse is independent of frequency (129, 130) and ranges from 5 to 40 msec for the four sources (127). Each pulse may be composed of two or more components each of which has a high degree of linear polarization that is in a different position angle for each component (131). The individual pulses are characterized by a rapid rise time of the order of a millisecond (129) and somewhat longer decay times. The pulses, which occur over a wide range of frequencies, are generally much weaker at the shorter wavelengths (129, 130), and in at least one case there is evidence for frequency structure on a scale less than 1 MHz (132). The time of arrival of an individual pulse drifts with frequency in the manner expected if the dispersion is due to a delay in the interstellar medium (128, 129). The distances deduced in this way range from about 10 to 100 pc and the diameters estimated from the pulse width are several thousand kilometers. Interpretations of these unusual objects have been suggested in terms of oscillating or rotating neutron stars or white dwarfs (126, 133), binary neutron stars (134), and collapsing supernovae (135). Tentative identifications of two pulsing sources have been made with stellar objects (136, 137).

Until recently, it had been generally felt that, apart from occasional supernova explosions or fluctuations of variable stars detected in relatively nearby galaxies, no significant changes either in the radio or in the optical luminosity of extragalactic objects could take place on a time scale shorter than the lifetime of a human observer. In the case of possible optical variations, this was a natural consequence of the then prevailing ideas on the formation and evolution of galaxies. The large linear dimensions and high luminosities of the extragalactic radio sources (e.g. 10) likewise seemed to preclude radio variations on short time scales. Specifically, in the case of the synchrotron hypothesis, it seemed unlikely that the time required for the acceleration of particles to ultrarelativistic energies, or the subsequent decay by synchrotron radiation loss or by inverse Compton collisions could be much less than about 10^6 years.

The unexpected discovery of remarkably intense fluctuations in the radio and optical luminosities of a number of quasi-stellar radio sources (QSS) seems to imply the generation of enormous amounts of energy in extremely small volumes of space and has therefore caused some to doubt whether the QSS are in fact at cosmological distances. However, the similar variations that have since been observed in some galaxies both at radio and at optical wavelengths have greatly weakened such arguments for a local origin of the QSS. The now obvious similarity between certain types of variable galaxies and QSS (e.g. 11) suggests that previous conceptions of the processes involved in the generation of strong extragalactic radio sources or in the origin of the galaxies themselves were unjustified.

In this review we have concentrated on the radio and to a lesser extent the optical variations from extragalactic radio sources, that is, radio galaxies and QSS. The radio variations in galactic supernova remnants and the optical variations in the apparently radio-quiet quasi-stellar galaxies (QSG) and

Seyfert-type galaxies are included to the extent that they may give some insight into the phenomena involved in the radio galaxies and QSS. Variable emission from objects in the solar system, such as the Sun and Jupiter, and variability caused by the influence of the interplanetary medium on the radiation from extragalactic sources and from galactic OH regions are not discussed.

OBSERVED RADIO VARIATIONS

In view of the relatively large changes that are now observed both in the radio and in the optical flux, it is natural to wonder why these effects had not been detected earlier. In the case of the optical variations the answer seems to be simply that no one thought of looking for time variations in extragalactic objects. This was true to some extent at radio wavelengths also, although it has only been in the last few years that sensitive radiometers have been available for use at centimeter wavelengths where the variations are apparently most rapid and most intense. Nevertheless, it is probably fair to say that before 1965 there were very few serious attempts to detect variations in any radio sources other than galactic supernova remnants.

In 1951, before the extragalactic nature of most discrete sources was realized, Ryle & Elsmore (12) measured the intensity of about 100 radio "stars" at 85 MHz every day for more than 18 months. They found no significant changes in the flux densities during this period and placed an upper limit on any variations of 10 per cent for the weaker sources and 5 per cent for the stronger sources.

Between 1960 and 1962 Heeschen (13) observed the intensity of seven sources, Cassiopeia A, Cygnus A, Virgo A, Taurus A, 3C 48, Hydra A, and 3C 295 every day for 28 months using a 40-foot transit telescope at 20 and 40 cm wavelengths. No significant changes were found in any source other than Cas A over this period, although the low signal-to-noise ratio for most sources prevented any small changes from being detected.

Following the identification of 3C 48 in 1960 as a quasi-stellar object which showed optical fluctuations from day to day, special observations were made at the Owens Valley Observatory of the California Institute of Technology (Caltech) to search for similar variations at radio wavelengths (14). No variations as great as 3 per cent over a 10-day period or 5 per cent over a 4-month period were found, the limits being set by the uncertainty in the measurements.

On the other hand, there have been two well-documented and convincing reports of time variations that have remained unconfirmed. Slee (15), observing for about 200 days spaced over a little more than 1 year, found significant variations in the flux density of Hydra A at 85 and at 110 MHz. Observations of the intense sources Taurus A, Virgo A, Centaurus A, and Fornax A made for comparison did not show this effect. A particularly large decrease, of more than 50 per cent, was observed in December 1955 at both frequencies, while nearly simultaneous interferometer measurements by Carter

(16) showed apparent changes in the angular size of the source. It is not possible to explain these results by ionospheric effects. On the other hand, attempts by many workers to confirm the reported variations in Hydra A have been unsuccessful. In particular, Heeschen (13) found no variations greater than 1 or 2 per cent at 21 cm over a 4-month period. It must be remarked, however, that the work of Slee and Carter was done at a wavelength of about 3 m while all of the apparently contradictory evidence comes from observations made at wavelengths shorter than 75 cm.

Perhaps even more difficult to explain are the unconfirmed periodic variations reported by Sholomitskii (17, 18) in the 32-cm radiation from the quasi-stellar source CTA 102. From observations of the relative intensity of CTA 102 and 3C 48 made on 9 days during the period August 1964 to February 1965, Sholomitskii found an apparently periodic variation in the intensity of CTA 102 with a peak-to-peak amplitude of 30 per cent and a period of 102 days. Further observations by Sholomitskii (19) through November 1965 covering nearly six cycles of the variation appeared to confirm his earlier result and led to the speculation that CTA 102 was a source of radiation from an extraterrestrial civilization (20).

The implications of Sholomitskii's discovery were clearly very great. However, a number of other workers have observed CTA 102 over extended periods of time and have found no evidence for any time variations. In particular, Maltby & Moffet (21) re-examined older observations made at the nearby frequency of 960 MHz at Caltech during the period 1959 to 1961 and concluded that the flux density of CTA 102 was constant to within ±4 per cent of the mean value. Nevertheless, their data were not closely spaced in time and in fact do not entirely exclude variations of the approximate amplitude and period reported by Sholomitskii. Other observations at 611 MHz (22), 1175 MHz (23), and 2295 MHz (24), which all overlapped the Soviet observations to some extent, likewise found the flux of CTA 102 to be constant. Later Sholomitskii pointed out that his observations were made using an antenna feed sensitive to circular polarization, and he suggested that the apparent disagreement between his data and those of other workers could be resolved if CTA 102 had a high degree of variable circular polarization and if the total intensity remained constant (19). The observations made by Nicholson at 2295 MHz (24), which were also sensitive to circular polarization, showed no variations greater than 5 per cent during the period September to November 1965, though during this period there is also little evidence of intensity variations in Sholomitskii's data at 920 MHz. Other attempts have been made to detect circular polarization in CTA 102 and other sources at 610 MHz (25) and 820 MHz (26) with no positive results.

Thus, although there are no other observations made with the same polarization at precisely the same frequency, and covering exactly the period when Sholomitskii found large intensity variations, a very implausible model would be required to explain all the available data, including the numerous negative results. Since little is known about the antenna or radiometer system used by Sholomitskii, his results have generally not been accepted.

Both for Hydra A and for CTA 102, and particularly for the latter, it is difficult to find a specific reason for the apparent discrepancy among the various observers. The measurement of the absolute flux densities has always been a difficult problem, largely owing to the uncertainty in determining the gain of large radio telescopes. Therefore it is usually the practice to measure the relative intensity with respect to several standard calibration sources as was, in fact, done by Slee and by Sholomitskii in their measurements of intensity variations. Nevertheless there are several systematic effects that can cause an apparent change in the relative intensity of different sources over a period of time, particularly when the observations are made near the short-wavelength limit of the instrument. Perhaps the most serious problem is the effect of a rapidly changing ambient temperature causing distortions of the parabolic surface and consequent changes in the gain of the telescope.

Thermal distortions of the telescope surface or feed support legs may also cause a displacement of the antenna feed from the true electrical focus. This may result in a substantial loss of gain unless the feed is accurately repositioned before each observation. In principle these gain changes can be monitored by observing several standard nonvariable sources throughout the observing period. Nevertheless, care is required in the selection of standard sources, since in general the degradation of the antenna temperature resulting from thermal distortions of the surface or changes in the focal length is greater for a "point" source than for an extended source, with an angular size comparable to the width of the antenna pattern. All of the known variable radio sources are of extremely small angular size ($\ll 1''$) so that extended sources do not make satisfactory calibrators. Unfortunately, at short centimeter wavelengths where the observed intensity variations are most intense and most rapid, there are few strong nonvariable point sources suitable as calibrators.

Galactic Sources

The first clear evidence for intensity variations at radio frequencies in a source outside the solar system which have subsequently been confirmed by other observers was presented by Högbom & Shakeshaft (6) in 1961. The relatively young age of the galactic supernova remnant Cas A prompted Högbom & Shakeshaft to repeat in 1956 and 1960 their earlier measurement of intensity made in 1948 at a frequency of 81.5 MHz. By using the same antenna for each observation, they eliminated a number of possible sources of systematic error and deduced a secular decrease of 1.06 ± 0.14 per cent per year. Independent evidence for a decrease in the flux density at 1400 MHz and 9400 MHz consistent with that found at 81.5 MHz has been given by Heeschen & Meredith (27) and Lastochkin & Stankevich (28). Findlay, Hvatum & Waltman (29) have reported a decrease of 1.75 ± 0.52 per cent per year between 1960 and 1964 at 1440 MHz; and Mayer, McCullough, Sloanaker & Haddock (30), working at 3200 MHz, found a decrease of 1.14 ± 0.26 per cent per year between 1954 and 1963.

A secular decrease in the intensity of Cas A of about this amount had in fact been predicted by Shklovskii (31) in 1960. This was based on the age of 256 ± 14 years as derived by Minkowski (32) from the projected radial velocity of a number of filaments of the nebulosity associated with the radio source. Shklovskii assumed that the observed radio emission was due to synchrotron radiation from a cloud of relativistic electrons moving in a magnetic field which was expanding at a constant rate. [A complete review of the synchrotron process has been given by Ginzburg & Syrovatskii (33).]

If the electron energy distribution is a power law of the form

$$N(E)dE = KE^{-\gamma}dE \qquad 1.$$

then the observed synchrotron radiation at a frequency ν from a source which is optically thin at this frequency and which subtends an angle θ is

$$S(\nu) \propto KB^{(\gamma+1)/2}\theta^3\nu^\alpha \qquad 2.$$

where the spectral index $\alpha = (1-\gamma)/2$. If the magnetic field is fixed in the expanding cloud, then the magnetic flux is conserved and

$$B_2 = B_1(r_1/r_2)^2 \qquad 3.$$

where B_1 and B_2 are the magnetic-field strengths when the radius is r_1 and r_2. Each electron loses energy at a rate proportional to its energy so that the form of the energy distribution is unchanged, thus for each particle

$$E_2 = E_1(r_1/r_2) \qquad 4.$$

and if no additional particles enter or leave the region

$$K_2 = K_1\left(\frac{r_1}{r_2}\right)^{\gamma+2} \qquad 5.$$

Then from Equations 2, 3, and 5

$$S_2 = S_1(r_2/r_1)^{-2\gamma} \qquad 6.$$

Equation 6 diverges for small values of r (or t) so that it clearly cannot be extrapolated indefinitely back in time. This is because at an early epoch, when the density of relativistic electrons is large, the source is no longer completely transparent to its own radiation. This in fact is the case in some of the extragalactic variable sources where large optical depths are found for several months to several years after an outburst of relativistic particles. Since it seems that the time variations in both the galactic supernovae remnants and in the extragalactic sources can be explained on this model of an expanding cloud of relativistic electrons, it is of some interest to compare the predictions of the model with the secular decrease of intensity observed in Cas A.

If the rate of expansion has been constant for t years, Equation 6 gives

$$\frac{\Delta S}{S} = -2\gamma\frac{\Delta t}{t} \qquad 7.$$

For Cas A, $\alpha = -0.76 \pm 0.02$ (34) so $\gamma = 2.56$. In 1959 $t = 256$ years (32) so that the expected rate of decrease is 2.0 per cent per year.

The uncertainty in the spectral index and the expansion rate is negligible, so that this value is significantly greater than the measured values. However, there are several modifications to the model that can affect the rate of decrease of flux:

(*a*) The expansion may have been slowed down by the interstellar medium so that the true age is smaller than 256 years and the expected rate of decrease is even greater than 2 per cent per year. The small observed rate could be explained if the expansion has accelerated, but this seems unlikely.

(*b*) The relativistic particles may still be accelerating, perhaps from the interaction of the expanding supernova shock front; or particles may still be injected. Both of these effects would increase the number of relativistic electrons of any given energy and would thus lessen the observed rate of decrease of the intensity. If particles escape, then of course the flux decreases at an even greater rate than that given by Equation 7.

(*c*) The magnetic flux may not be conserved during the expansion if the relativistic electrons gyrate freely in a field fixed in space. In this case Equation 7 becomes

$$\frac{\Delta S}{S} = -(2+\gamma)\frac{\Delta t}{t} \qquad 8.$$

For Cas A the expected rate of decrease becomes 1.8 per cent per year when the field remains constant.

(*d*) High-resolution interferometric observations made with the Cambridge 1-mile radio telescope show that the Cas A radio source is a shell whose thickness is about 0.25 of the radius (35), so that Shklovskii's assumption of a filled spherical volume is not correct. The dynamics of expanding shell sources have been discussed by van der Laan (36, 37) and by Lequeux (38). Clearly several modes of expansion are possible; the shell may expand in thickness as well as radius, or its thickness may remain constant if the expansion takes place in a vacuum and is not influenced by an external magnetic field. Although the latter case may hold for extragalactic sources, in the case of supernova remnants it seems likely that the interstellar medium will influence the expansion. Lequeux (38) has discussed the case where the shell grows with the Alfvén velocity. Equation 7 for a shell of thickness s and radius r at time t then becomes

$$\frac{\Delta S}{S} = -\frac{5}{4}(\gamma+1) + \frac{2}{3}\,\frac{s}{r}\,\frac{\gamma-3}{2}\,\frac{\Delta t}{t} \qquad 9.$$

which for Cas A gives an expected decrease of 1.7 per cent per year with the same parameters used above.

Even the shell model is probably an oversimplification since the Cambridge observations show that the shell itself is composed of a number of smaller condensations which may or may not individually expand with time.

Since no data are available on the form of the brightness distribution over extended periods of time, it is not possible now to specifiy a unique model. Finally, all the models assume that γ has remained constant throughout the expansion, and this assumption may be incorrect.

Extragalactic Sources

The first clear evidence for radio variability in extragalactic sources came from observations made by Dent at the University of Michigan at 3.75 cm which showed a 40 per cent increase in the flux density of the quasi-stellar source 3C 273 over a 1000-day period between 1962 and 1965 (39). Smaller and less certain changes were also found in the quasi-stellar sources 3C 279 and 3C 345. Further observations at many wavelengths made at Michigan (2, 3.75 cm) (40, 41); Caltech (11, 21, 30 cm) (42–44); Massachusetts Institute of Technology (MIT) (2, 3.75 cm) (45); the National Radio Astronomy Observatory (NRAO) (2, 6, 11, 21, 40 cm) (46–48); Aerospace Corporation (3 mm) (49–51); Parkes (6, 11, 21 cm) (52); Fort Davis (6 cm) (53); the Algonquin Radio Observatory (2.8 cm) (54); Pulkova (6.4 cm) (55); and Serpukhov (56), all have confirmed the variations in 3C 273, 3C 279, and 3C 345 and have clearly established the radio variability of about 25 presumably extragalactic sources.

All of the sources known or suspected of being radio variables are listed in Table I together with their optical identification and the wavelengths at which the variations have been observed. For most of these sources only a few measurements are available at one or two frequencies. However, six (3C 84, 3C 120, 3C 273, 3C 279, 3C 345, and 3C 454.3) are relatively intense and have been very active during the past two years. These have been observed often by many observers over a range of wavelengths. In Figures 1 through 6 the available flux-density measurements at a number of wavelengths, including some made before the discovery of the intensity variations, have been plotted as a function of time for each of these six sources. In order to minimize errors caused by differences in the calibration of the flux-density scale by different observers, all of the observations at a given wavelength have been put on a uniform scale, either by referring to standard nonvariable sources, or by comparing the observations of the variable sources made by the different observers during the same period of time. Nevertheless, the scatter among measurements of the flux density of a given source made by different observers may for a variety of reasons be expected to be greater than that obtained by a single observer using one instrument. The error bars have been omitted when the data are closely spaced in time, but their magnitudes may be estimated from the scatter of individual observations.

Not enough time has passed since the initial discovery in 1965 of time variations in extragalactic sources to establish whether or not there is any systematic pattern to the observed radio fluctuations at any one wavelength. There is no evidence in any source of periodic variations of the type claimed

TABLE I[a]

VARIABLE SOURCES

Source	Identification	α	Wavelength (cm)
0106+01	QSS	+1.16	6
0202–17	QSS	+0.11	21
CTA 26	QSS	+0.12	6–40
3C 84	SEY	+1.03	2–11
NRAO 140	QSS	−0.12	6–40
3C 120	SEY	+0.09	2–40
NRAO 150		+0.89	6–11
0420–01	QSS?	+0.64	11–21
NRAO 190		+0.2	6–40
0607–15		−0.42	11
0735+17		−0.03	21
0736+01	QSS	−0.42	11–21
1055+01	QSS	+0.06	6–21
1148–00	QSS	−0.50	21
3C 273	QSS	+0.08	0.3–20
3C 279	QSS	+0.40	0.3–20
1510–08	QSS	+0.71	6–21
NRAO 512		+0.15	11, 2
3C 345	QSS	−0.10	2–20
NRAO 530		+0.01	6–40
3C 371	N galaxy	−0.24	21
3C 380	QSS	−0.52	6(11?)
3C 446	QSS	−0.08	2–11
3C 454.3	QSS	+0.99	2–40
2345–16		+0.05	11–21

[a] The table lists sources known to be or suspected of being variable at radio wavelengths. The identification is given, as is the spectral index between 6 and 11 cm and the wavelengths at which variations have been detected. The spectral index refers to approximately 1967.0; it is, of course, itself variable.

by Sholomitskii. A common pattern seems to be one of a large outburst of energy on a time scale as short as a few months and in some cases followed by another burst within 1 year. In general, a given event appears first as a rapid and intense increase at short centimeter or at millimeter wavelengths followed by a more gradual decline or by a broad maximum lasting 6 months or more. The same sequence is repeated later at longer wavelengths with smaller amplitudes. The time scale for the propagation of a given event from short centimeter wavelengths to long centimeter wavelengths is typically several months. At wavelengths longer than 30 or 40 cm, the change in the flux density becomes negligible.

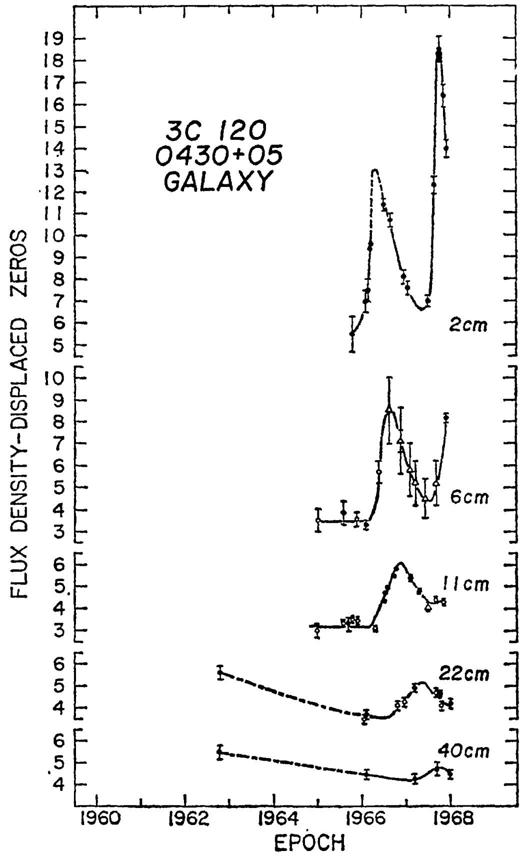

FIG. 1. Radio variations of 3C 120.

● NRAO measurements at all wavelengths (46–47).
6 cm: ○ Parkes measurements, Kellermann (57) for 1965.1, otherwise Harris (52).
△ Maxwell (53).
11 cm: ○ Kellermann (58) for 1965.0, otherwise Harris (52).
△ Moffet (44, 59).
22 cm: ○ Harris (52), ■ Altenhoff (60).

VARIATIONS OF RADIO POLARIZATION

Most of the variable radio sources are polarized, at least at longer radio wavelengths, and in general the degree of polarization decreases towards the short wavelengths. Since the variable components are usually strongest at the short wavelengths, it might be concluded that they are unpolarized and that the observed polarization comes from the quiescent component (45).

However, the variations in the polarized flux density of 3C 273, 3C 279, and 3C 345 that have been reported by Aller & Haddock (61) at 3.75 cm show that in these sources the largest changes both in the position angle and in the polarized flux density occurred when the total flux was changing. This implies that the variable component is polarized and suggests that an ordered magnetic field is present in the variable source. For 3C 345 they derive a value of 20 per cent for the degree of polarization of the variable component. The

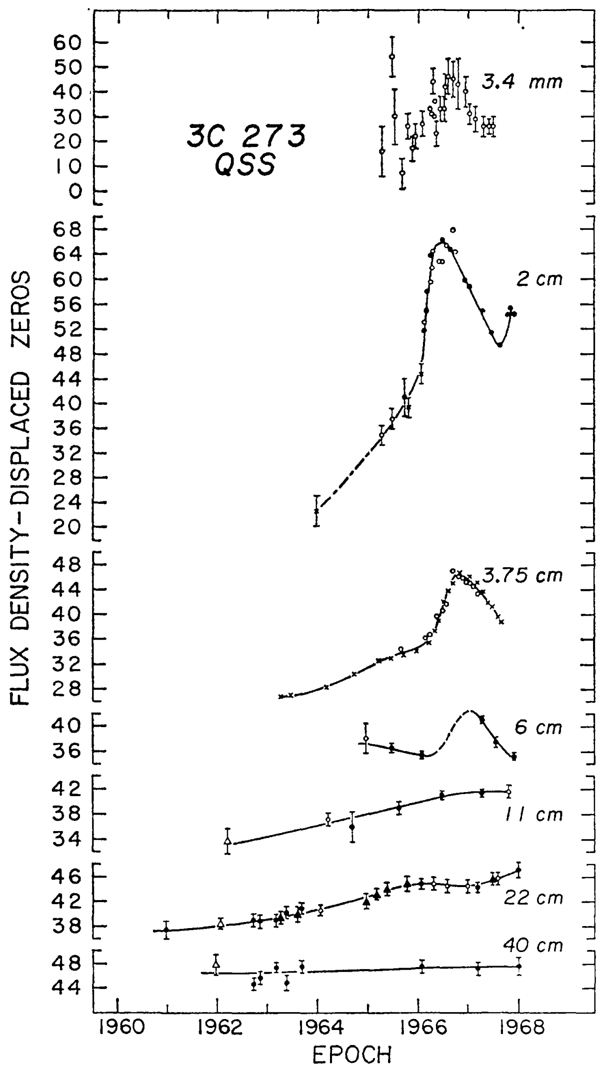

FIG. 2. Radio variations of 3C 273.

● at all wavelengths (46–48).
3.4 mm: ○ (51).
2 cm: × Dent, quoted in (45), ○ (45).
3.75 cm: × Dent (41) and quoted in (61), ○ (45).
6 cm: ○ (57).
11 cm: △ (62), ○ (58) for 1964.3, otherwise (52).
22 cm: △ (62), ▲ (42, 59), ○ (58) for 1964.1, otherwise (52).
40 cm: △ (62).

observed variations are, however, less than a few per cent of the total flux density. Both 3C 273 and 3C 279 showed remarkably similar changes in the polarized flux and a rapid rotation of the plane of polarization which occurred in both sources in mid-1966, when their flux densities were approaching their maxima.

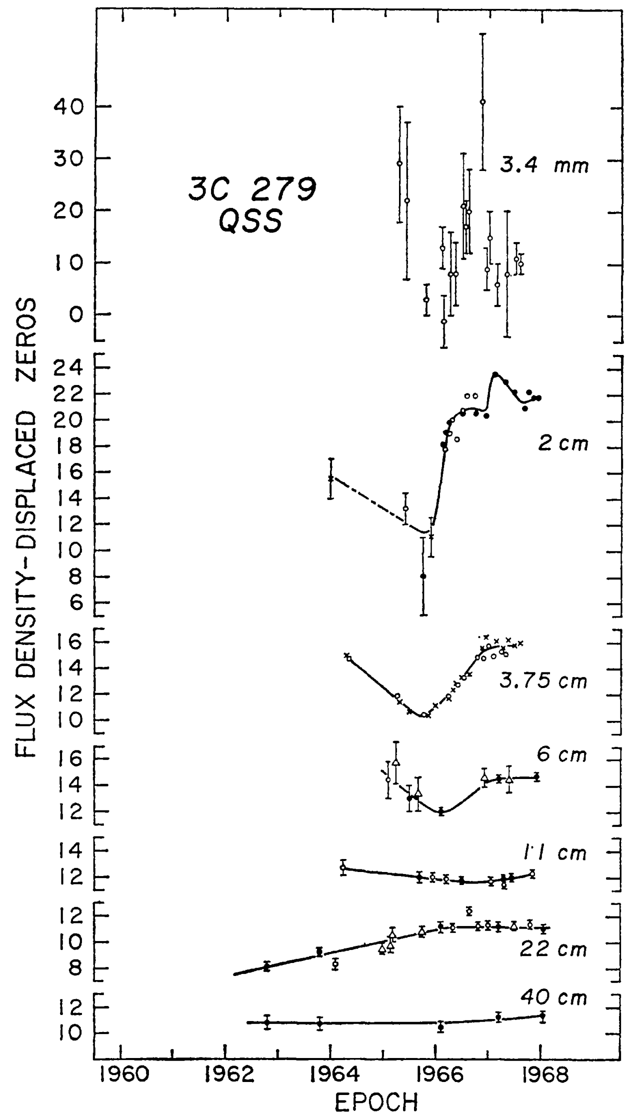

FIG. 3. Radio variations of 3C 279. The symbols are the same as for 3C 273, with the addition of △ (53) at 6 cm.

OPTICAL VARIATIONS

Three of the variable radio sources, 3C 84 (NGC 1275), 3C 120 (PKS 0430+05), and 3C 371, are identified with radio galaxies; 14 others are quasi-stellar objects. A variety of photographic and photoelectric observations show that at least half of the QSS vary optically on time scales as short as months or weeks, and in several cases there is evidence for significant daily variations (67–69). The strongly variable radio sources, 3C 279, 3C 345, and 3C 454.3, all show large variations at optical wavelengths. Other QSS which are not radio variables, several radioquiet QSG (68, 70), and a compact, radio-quiet galaxy (71) also show light variations.

At least one of the variable radio galaxies, 3C 371 (72, 73) and two non-

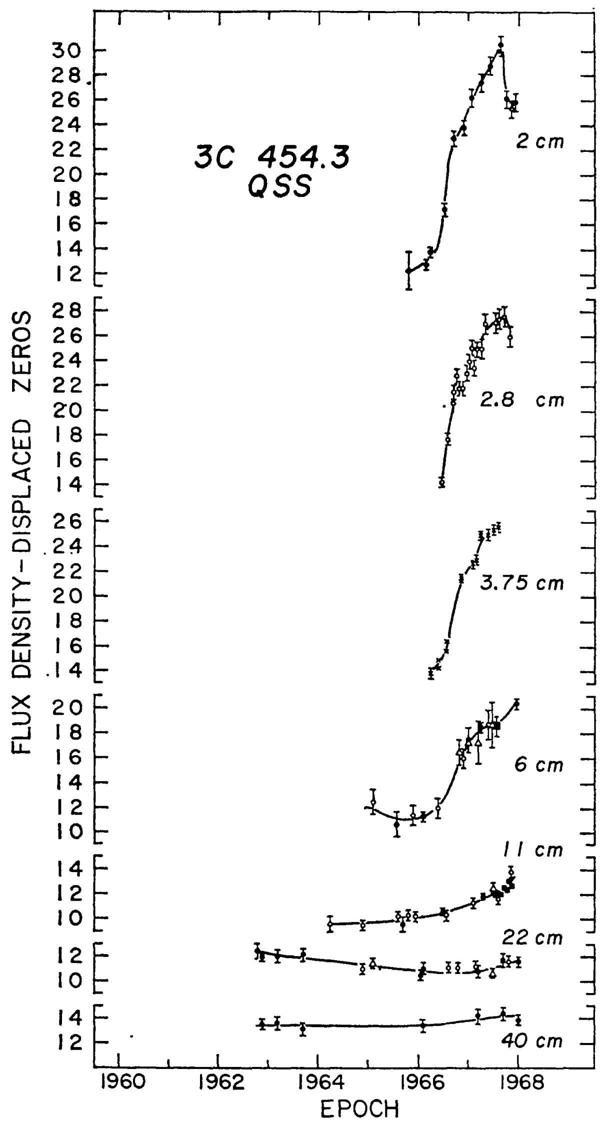

FIG. 4. Radio variations of 3C 454.3.

● at all wavelengths (46–48).
2.8 cm: ○ (54).
3.75 cm: × (41).
6 cm: ○ (57) for 1965.1, otherwise (52), ■ (60).
11 cm: ○ (58) for 1964.3, otherwise (52), △ (59), ■ (63).
22 cm: ○ (52), △ (64) and (59), ■ (60).

variable radio galaxies, 3C 390.3 (68, 74) and 3C 109 (74), are variable at optical wavelengths; the Seyfert galaxy NGC 4151, which is a weak radio source (75), is variable at optical and infrared wavelengths (76).

Only in the case of a few sources such as 3C 446 and 3C 345 are there extensive measurements of optical variations. Prediscovery plates of 3C 273 have provided a wealth of information (77–80). Otherwise, except for a few

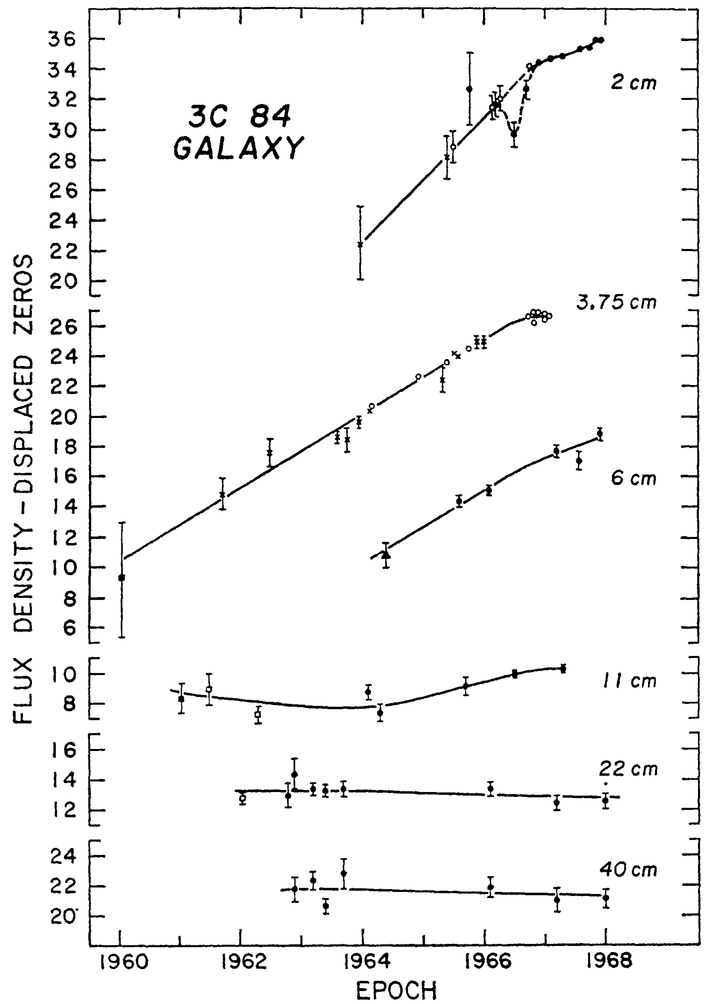

FIG. 5. Radio variations of 3C 84.

● at all wavelengths (46–48).
2 cm: × Dent, quoted in (45), ○ (45).
3.75 cm: × (40), ○ (45), ■ (65).
11 cm: ■ (65), □ (62).
22 cm: □ (62).

special observations made by Sandage (67), Kinman et al. (81, 82), Cannon & Penston (68), and Oke (69), only a few scattered observations have been made in order to obtain an identification or to measure a redshift. The available data up to the end of 1966 have been collected in a previous review (83) and here we only summarize the results and bring them up to date.

There is no clear general pattern to the optical time variations, although in 3C 273 and 3C 345 there is some indication of periodic changes. From over 2000 plates taken from the Harvard Observatory plate collection and dating back to about the year 1890, Smith & Hoffleit (77, 78) found evidence in 3C 273 for a quasi-periodic variation after 1929 with an average period of 13

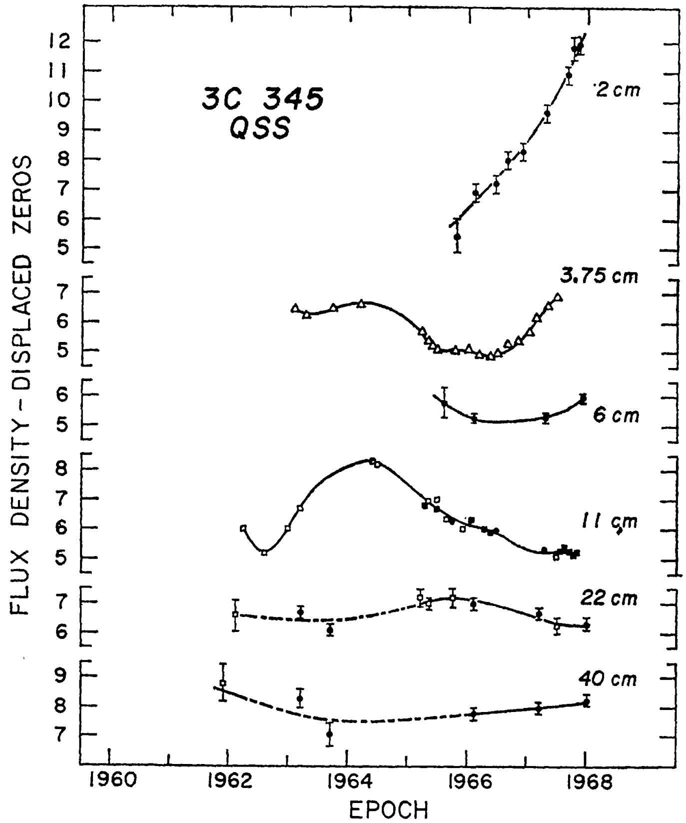

FIG. 6. Radio variations of 3C 345.

● at all wavelengths (46–48).
3.75 cm: △ Dent, quoted in (61), and (41).
11 cm: □ Bartlett, quoted in (44), ■ in 1966 (66), in 1967 (63).
22 cm: □ in 1964 (62), otherwise (44).
40 cm: □ (62).

years or one that decreased from 15 to 11 years. The mean amplitude is about 0.5 mag but there is some evidence that this, too, has decreased since 1929. Superimposed on this is a short-term fluctuation of 0.2 to 0.5 mag in a period of months. In 1929 a "flash" of 0.7 mag occurred in a 10-day period. Sharov & Efremov (79, 80) have independently found similar results. Curiously, since 1963 when accurate photoelectric measurements began, no variations greater than 0.4 mag have been reported, while during this time there have been large fluctuations at radio frequencies.

Ozernoi & Chertoprud (84) have smoothed the observations over 2-year intervals and have derived a period of 9.0 ± 1.2 years. On the other hand, Manwell & Simon (85), using the same data, found that the light curve does not differ significantly from the superposition of random events and concluded that there is no evidence for any long-term periodicity.

Extensive observations of 3C 345 (81) indicate that in addition to a constant component, there is (*a*) a component that slowly varies with an amplitude of about 0.5 mag with a time scale of a few months and (*b*) a component that shows outbursts of over 0.5 mag with a period of about 80 days; the pattern of these outbursts repeats every 321.5 days. Large fluctuations of as much as 3 mag have also been detected in 3C 446 (67, 69, 86–90). Since the large increase in brightness was noted by Sandage (86) in June 1966, the intensity has been fluctuating with changes of more than 1 mag occurring on time scales of the order of 1 month. During this time the radio flux density at 2 cm has slowly increased by about 50 per cent.

One of the most striking results of the optical measurements is the strong correlation found between high optical polarization and variability (81, 82). The sources 3C 279, PKS 1510–08, 3C 345, 3C 446, 3C 454.3 which all have a high degree of polarization and optical variability are also all strongly variable at radio frequencies. In 3C 446 (87) and 3C 345 (82) large changes in the total brightness have been accompanied by a rotation of the plane of polarization. It has been suggested, therefore, that the variable components are highly polarized (81).

There have also been reports of possible variations in the structure of the Mg II doublet in the spectrum of 3C 345 (91–93). These can be attributed to motions within the source with velocities of several thousand km/sec (91), and Shklovskii has suggested that spectral variations may be a common property of QSS (94). However, the spectral variations have not been observed by other workers and there is some doubt as to their reality (95, 96).

In 3C 446 bright emission lines are visible when the object is faint, but disappear when the continuum brightness increases, so that apparently the line strength remains constant (69, 97).

INTERPRETATION OF THE RADIO VARIATIONS

The angular dimensions of the variable radio components are always small with upper limits of less than a few hundredths of a second of arc on most sources (98, 99). As shown in Figure 7, in every variable radio source the radio-frequency spectrum is unusually flat (39, 46). The spectrum, however, is not a simple power law, but shows positive curvature, or even several maxima and minima. Owing to the large bandwidth of the emission from a single electron radiating by the synchrotron mechanism, such sharp features in the radio spectra cannot be due to a pure emission process. The large positive spectral indices observed in some sources, and the very small angular dimensions suggest the presence of one or more components which are optically thick at short wavelengths. In general, the spectra indicate that the variable components are optically thick at wavelengths where the flux density is increasing and optically thin at wavelengths where it is decreasing.

This is just the behavior expected from an expanding cloud of relativistic electrons which is initially optically thick at some wavelength. As a result of the expansion, the magnetic field and the electron energy decrease and the cloud becomes optically thin at progressively longer wavelengths. At any frequency where the expanding component is optically thick, the flux density

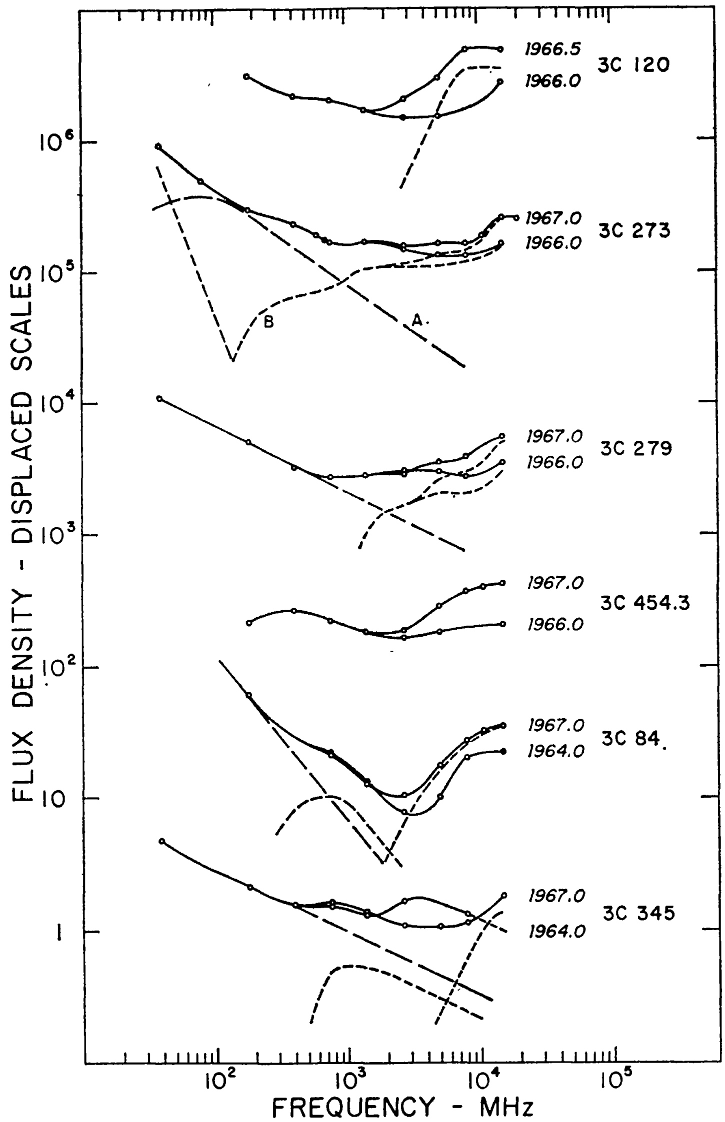

FIG. 7. The radio spectra of six variable sources. The spectra are shown at two epochs. In some cases, a possible separation into components is shown, based on interferometer data or on the variations themselves. Errors are not shown, but are usually 2–3 per cent in the measurement of a change of flux density and 5–10 per cent in the scale of flux density.

will be observed to increase when an appreciable fraction of the total flux is contributed by the expanding component. In the optically thin region of the spectrum, the flux density will decrease with time in the manner described by Shklovskii (5) for expanding supernova remnants. (See section Galactic Sources.)

Even before the discovery of time variations in extragalactic sources, Shklovskii pointed out that sources such as PKS 1934–63 (100, 101), which showed maxima in their radio spectra and were thus presumably optically thick even at decimeter wavelengths, must be very young and might therefore change in intensity over a relatively short period of time (102). Although no variations have in fact been seen in PKS 1934–63 (101), it was soon noted (44, 46, 103) that the variations in the radio spectra of other sources followed the pattern expected from an expanding source that was optically thick over part of the radio spectrum. From the observed variations, it was established that the characteristic age was 1 to 2 years when the intensity reached a maximum at short centimeter wavelengths, and it was possible to predict the future time dependence at longer wavelengths (46, 47). A more detailed mathematical treatment has been given by van der Laan (104).

Continued observations (45, 47, 48) are in good agreement with this model which closely specifies the relation between the observed rates of increase and decrease at any frequency, and between the maximum flux density and the time when it occurs at any one frequency. The expressions describing the variations in the synchrotron emission from an expanding, optically thick cloud of relativistic electrons are derived below. These are then applied to the observed radio variations, and some physical parameters of the variable components are deduced.

Given the observed spectrum $S(\nu, t)$ and the angular size $\theta(t)$ at any time t, the spectrum at any other time is determined only by the instantaneous value of θ. In general the angular sizes of variable sources are too small to be measured directly, so for simplicity it is convenient to assume a constant expansion rate and to present the results in terms of the time t, which is a directly observable parameter. It is further assumed that the velocity of expansion is nonrelativistic. In the expressions that follow, the magnetic field B is expressed in gauss, the frequency ν in MHz, the linear size in pc, and the particle density n_e in cm^{-3}.

For an optically thick source of radiation, the brightness temperature depends only on the value of the magnetic field, and the flux density is given by

$$S(\nu, t) \propto B^{-1/2}(t)\nu^{5/2}\theta^2(t) \qquad 10.$$

If the magnetic flux is conserved during the expansion, Equation 3 gives

$$B(t_2) = B(t_1)(t_1/t_2)^2 \qquad 11.$$

so

$$S(t_2) = S(t_1)(t_2/t_1)^3 \qquad 12.$$

If the particles expand in a magnetic field of constant strength, then the intensity depends only on the projected solid angle and varies as $(t_2/t_1)^2$. In either case the rate of change of flux density is independent of the electron energy distribution, since as long as the source is optically thick the observed radiation comes from only a fraction of the total number of electrons.

From Equation 6 the flux density in the optically thin region of the spectrum decreases as

$$S(\nu, t_2) = S(\nu, t_1)\left(\frac{t_2}{t_1}\right)^{-2\gamma} \qquad 13.$$

The frequency ν_m at the which flux density is a maximum may be computed from the formulae given by Le Roux (105) for the absorption coefficient and emissivity or from the simple numerical expressions derived by Terrell (106). In terms of the flux density $S(\nu')$ at a frequency ν' where the source is optically thin

$$\nu_m^{(4+\gamma)/2} = f(\gamma)B^{1/2}\theta^{-2}S(\nu')\nu'^{(\gamma-1)/2} \qquad \text{14a.}$$

or in terms of $S(\nu_m)$, the flux density at ν_m

$$\nu_m^5 = g(\gamma)B\theta^{-4}S^2(\nu_m) \qquad \text{14b.}$$

where $f(1.5) = 6.4\times10^3$, $g(1.5) = 4.9\times10^7$, $f(2.5) = 4.6\times10^3$, $g(2.5) = 3.5\times10^7$. If S_{m1} is the maximum flux density reached at frequency ν_{m1} at a time t_1, then from Equations 13 and 14 the frequency of maximum flux at time t_2 is given by

$$\nu_{m2}/\nu_{m1} = (t_2/t_1)^{-(4\gamma+6)/(\gamma+4)} \qquad \text{15.}$$

and the maximum flux S_{m2} at frequency ν_2 and time t_2 is

$$(S_{m2}/S_{m1}) = (t_2/t_1)^{-(7\gamma+3)/(\gamma+4)} \qquad \text{16.}$$

or

$$(S_{m2}/S_{m1}) = (\nu_{m2}/\nu_{m1})^{(7\gamma+3)/(4\gamma+6)} \qquad \text{17.}$$

The complete expression for the flux density as a function of ν and time is given by van der Laan (104)

$$S(\nu, t_2)/S_{m1} = (\nu/\nu_{m1})^{5/2}(t_2/t_1)^3 \left\{\frac{1 - \exp\left[-\tau_m(\nu/\nu_{m1})^{-(\gamma+4)/2}(t_2/t_1)^{-(2\gamma+3)}\right]}{1 - \exp(-\tau_m)}\right\} \qquad \text{17a.}$$

where τ_m, the optical depth at the frequency at which the flux density is a maximum, is given by the solution of

$$e^{\tau_m} - \left(\frac{\gamma+4}{5}\right)\tau_m - 1 = 0 \qquad \text{18.}$$

which is

$$\tau \simeq \tfrac{1}{2}\{[9 - 4.8(1-\gamma)]^{1/2} - 3\} \qquad \text{19.}$$

to within 1 per cent for $\gamma < 3$. There is no solution for $\gamma \leq 1$ ($\alpha \geq 0$); for $\gamma = 1.5$, $\tau = .19$ and for $\gamma = 2.5$ $\tau = .51$.

The maximum flux density *at a given frequency* as a function of time occurs at a different optical depth τ_m' which is given by the solution of

$$l^{\tau'_m} - \frac{2\gamma+3}{3}\tau'_m - 1 = 0 \qquad \text{19a.}$$

This equation has a formal solution for any $\gamma > 0$; approximate solutions are $\tau'_m = 0.95$ for $\gamma = 1.0$, $\tau'_m = 1.25$ for $\gamma = 1.5$ and $\tau'_m = 1.73$ for $\gamma = 2.5$. The flux density as a function of frequency and time can be obtained in terms of the maximum flux density observed at a given frequency by substituting τ'_m for τ_m in Equation 17a.

In terms of the density of relativistic particles n_e and the depth l of the source along the line of sight, the optical depth may be determined from the expression for the absorption coefficient (105) and is

$$\tau = h(\gamma)B^{(\gamma+2)/2}\nu^{-(\gamma+4)/2}n_e l \quad 20.$$

where $h(1.5) = 1.0 \times 10^{11}$ and $h(2.5) = 6.7 \times 10^{11}$.

It may also be shown that the polarization of a source should change as it becomes optically thin. The expressions for the emissivity and absorption coefficients (105) give $I_\perp/I_\parallel = (3\gamma+5)/(3\gamma+8)$ for an optically thick source and $I_\perp/I_\parallel = (3\gamma+5)/2$ for an optically thin source where $I_\parallel$ and $I_\perp$ are the intensities in planes of polarization parallel and perpendicular to the projection of the magnetic field on the sky. Thus a rotation of the plane of polarization by 90° and an increase in the degree of polarization are expected as the source becomes optically thin.

Each of the expressions 12, 13, 15, 16, or 17 provides an *independent* estimate of the characteristic age of the source at any time t. Clearly these do not hold for very small times since it is not realistic to suppose that the production of relativistic particles occurs instantaneously or in an infinitesimal volume of space.

In principle a measure of the radio spectrum at any time and its time rate of change may be used to predict the future behavior of the spectrum at all frequencies. In practice this is difficult since several variable sources have already shown more than one outburst in the short period during which observations have been made; and from the complex nature of the spectra of variable sources, it appears that outbursts of relativistic particles repeated at intervals as short as 1 year are not uncommon in variable QSS and radio galaxies. Since the typical time scale at centimeter wavelengths over which a particular event is observed is somewhat greater than 1 year, individual events overlap both in frequency and time. Nevertheless, analysis of the flux curves at different wavelengths and the form of the radio spectrum do allow an approximate separation and some quantitative statements can be made about the age and size of several variable sources.

Individual Sources

3C 120 (Figure 1).—This galaxy, in which there have been two recent outbursts, provides a good example of the evolution of a young source. In the first of the outbursts, it can clearly be seen that the maximum intensity decreased with increasing wavelength and the maximum occurred at progressively later times. After a baseline level of between 3 and 4 flux units is subtracted from each of the light curves at 2, 6, 11, and 21 cm, the flux at each wavelength is found to increase as $(t-t_0)^3$ in the region where the source is optically thick and to decrease approximately as t^2 where it is optically thin. The time of origin $t_0 = 1965.95 \pm 0.10$. The epoch $(t-t_0)$ at which the flux reaches a maximum at any wavelength, and the maximum flux at that wavelength are shown as a function of wavelength on a logarithmic scale in Figures 8 and 9. As expected from Equations 15 and 17, both these plots can be

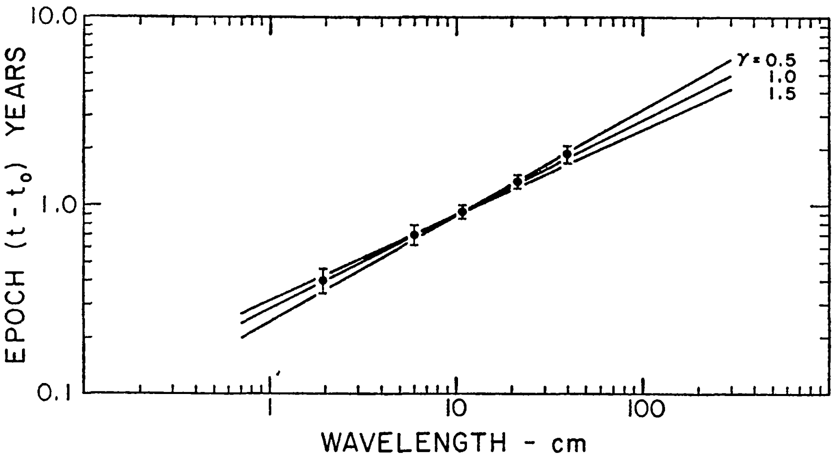

FIG. 8. The epoch, counted from the time of origin 1965.95, at which the flux density reached a maximum at any wavelength as a function of wavelength for the first outburst in 3C 120 (see Fig. 1).

fitted reasonably well with straight lines, the slopes of which correspond to $\gamma \sim 1$. The maximum flux observed at 2 cm is somewhat below the value predicted from the long-wavelength data, but inspection of Figure 1 shows that a much higher maximum, possibly equal to that of the 1967 event, is consistent with the observations. Unfortunately, there were no observations at the time of the expected maximum. If the development of the second out-

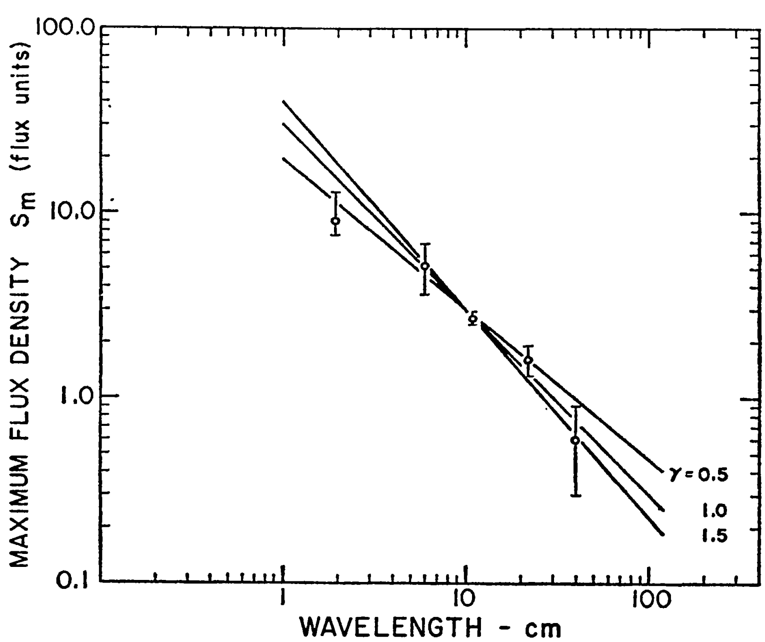

FIG. 9. The maximum flux density reached at any wavelength as a function of wavelength for the first outburst in 3C 120 (see Fig. 1).

burst, which reached a maximum in 1967.75 at 2 cm, is similar to that of the earlier outburst, then t_0 for this event is 1967.4.

3C 273 (Figure 2).—For this source an analysis of the variations at 2 and 3.75 cm has been made by Allen et al. (45) and Dent (41). They distinguish between the slow variation which began in 1963 and the sudden burst of 1966. For the recent outburst, t_0 is about 1965.7; from Equation 17 the decrease in the maximum flux with increasing wavelength gives γ in the range 1.0 to 1.5 which is consistent with the value obtained directly from the spectral index in the optically thin region of the spectrum. The slow variations at 22 and 11 cm are probably not due to the same component as those at 2 and 3.75 cm, since at 6 cm, no such increase is seen. The slow variations at these longer wavelengths correspond to a characteristic age of about 7 years. At 3.4 mm, the maximum in 1966.5 corresponds roughly to that at 2 cm, so that there is apparently no time delay between the two events. On the other hand, the peak at 3.4 mm in 1965.5 does not correspond to any observed feature at 2 cm. A large flux density was observed by Low at 1 mm in January 1965 (107), and may correspond to the 1965.5 event at 3.4 mm; the expected time delay for this ratio of frequencies and $\gamma \sim 1$ is about 0.5 years.

3C 279 (Figure 3).—This source also shows the propagation of an outburst to long wavelengths. The decrease at 2, 3.75, and 6 cm from 1964 to 1966 and the increase at 22 cm have been attributed to one component with $t_0 \sim 1956.0$ (46). The sharp increase in 1966 at 2 cm is a younger event, with $t_0 \sim 1965.0$; its changes are consistent with $\gamma \sim 1$. At 3.4 mm, the decrease in 1965 and the maximum at 1966.8 correspond roughly with the variations at 2 cm. The 3.4-mm variations were, however, much more rapid, and the peak was reached almost a year after the increase at 2 cm began.

3C 454.3 (Figure 4).—3C 454.3 has only been observed for 1-1/2 years at high frequencies, so that no quantitative results can be obtained. A "shoulder" in the curve at 2 cm at 1966.75, however, is also seen at 2.8 cm (54), and at 6 cm with a time delay of about 6 months. For this event t_0 is 1965.8.

3C 84 (*NGC 1275*) (Figure 5).—From the work of Dent (40) between 1962 and 1966 and the early measurement of Heeschen (65) in 1960, it may be concluded that 3C 84 has been increasing in flux density more or less linearly at 3.75 cm for at least 7 years, and at 6 and 2 cm for at least 3 years (48); at 11 cm, a smaller increase has occurred and at 22 and 40 cm, the changes are barely significant. The nature of the source in NGC 1275, however, appears to be considerably more complex (108) than was initially assumed by Dent (40). The spectrum clearly shows that one component is optically thick below 2 cm. This component should contribute less than 10 per cent of the flux density at 20 cm, yet a large part of the flux at this wavelength originates in a region smaller than 0".1 (98), so that a second small component is present. The form of the spectrum indicates that this component becomes optically thick below 40 cm. In addition, there is a component with an angular size of a few minutes of arc and a normal power-law spectrum (64, 108) as well as a larger halo (109). The interpretation of the variations is not clear since the flux is increasing in both the optically thick and optically thin regions of the spectrum. The increase in the optically thin region could be explained by the continued injection of particles, and the linear increase by an expansion in only one dimension. The value of t_0 for this component is about 1956.0; the second optically thick component must be at least four times older and its variations proportionately smaller.

3C 345 (Figure 6).—In this source the pattern of the variations is more complex. The increase and decrease seen at 11 cm (44) were also observed at 3.75 cm (41, 61) but the variation was less intense. At 6 cm, only part of the decrease is seen. The changes at 22 and 40 cm, if real, appear different in form. At 2 cm, a linear increase has occurred over about 2 years and has begun to appear at 3.75 cm (41) and 6 cm. It is possible that in this source the conditions in the 1964 outburst were such that the source was always optically thin above 11 cm so that the intensity reached at 3.75 cm was not as high as at 11 cm. Alternatively, the time delay in this source between events at 3.75 and 11 cm could be such that the maximum at 3.75 cm occurred before 1963, when observations began. This interpretation is consistent with the rather long delay of about 1 year between the beginning of the present increase at 2 cm and that at 3.75 cm, and also with the delay between the maximum at 11 cm and that at 22 cm.

DISCUSSION

In general, then, the model of a uniformly expanding source accounts for most of the observed variations. It also appears that particles are injected with $\gamma \geq 1$ which corresponds to a radio spectral index near zero. The relation of the events observed at millimeter wavelengths to those at centimeter wavelengths is not yet clear. The data suggest that the high flux densities predicted by the model are not reached at millimeter wavelengths and that there may be no time delay from millimeter to short centimeter wavelengths. This in turn would imply that the particles are injected in such a way that the source remains optically thin at millimeter and shorter wavelengths.

Typically, the apparent age of a variable component is only of the order of 1 year when the maximum flux is reached at short centimeter wavelengths, so that the maximum dimensions of the source must certainly be less than 1 pc. Even in the absence of a specific model, it is generally accepted that significant variations cannot occur in a time much shorter than the light travel time across the region. The observations then seem to require not only a very high level of radio emission from a small volume of space, but the creation of a large flux of relativistic particles in extremely short times (46). Several authors (e.g. 18, 39, 106, 110) have therefore argued that either the QSS are not at cosmological distances or the synchrotron mechanism, at least in its conventional form, must be abandoned. For the most part these arguments have been based either on unconfirmed and possibly incorrect data, or on an oversimplified interpretation of the data or the theoretical models.

For example, from the apparent 100-day periodicity in the intensity of CTA 102 Sholomitskii (18) and later Terrell (106) deduced that the linear dimensions of the source could not greatly exceed 100 light days. Using an angular size of $\simeq 0\overset{''}{.}01$ obtained from the self-absorption cutoff in the radio spectrum near 800 MHz, Sholomitskii then concluded that CTA 102 was not more than 2 Mpc distant. The measured redshift of CTA 102 is 1.037 so that on the cosmological interpretation its distance is about 3000 Mpc. It now seems that the flux of CTA 102 is in fact constant (21–24) at least over time scales of a few years so that there is no real evidence against the cosmological interpretation of its redshift.

A similar argument was used by Dent following his discovery of the variation in the 3.75-cm flux of 3C 273 (39). From the observed time scale of about 13 years, Dent determined that the maximum dimensions of the source could not be greater than 4 pc. At the distance of 470 Mpc indicated by the redshift of 0.158, the angular size would be only $0\overset{''}{.}002$. From the apparent absence of a self-absorption cutoff above 400 MHz, Dent then found that the true angular size must be greater than $0\overset{''}{.}1$. Dent (39) and also Terrell (106) therefore concluded that either 3C 273 was not at the cosmological distance or the radio emission was not due to synchrotron radiation. The conclusion is incorrect for two reasons. First, as Field (111) pointed out, there was a numerical error in Dent's calculations; second, the flat spectrum observed for 3C 273B is not a result of a flat electron energy distribution as was assumed by Dent and Terrell, but is due to the fact that the source contains several distinct components which become optically thick at different wavelengths. The component which Dent found to vary at centimeter wavelengths actually becomes optically thick near 15,000 MHz, and so from Equation 14b the angular size is less than $0\overset{''}{.}001$, well within the limits imposed by the light travel time. Direct interferometer measurements place an upper limit of $0\overset{''}{.}005$ on a small-diameter component (112).

A second objection to the cosmological interpretation of the redshifts of variable sources has been based on the inverse Compton effect. In an intense radiation field, the relativistic electrons may be elastically scattered by the radio photons. The electrons lose energy to the photons, by a factor $(E/mc^2)^2$. For a typical electron of energy E, radiating at 1000 MHz, $(E/mc^2) \sim 10^3$ so that the scattered radiation is increased in frequency from about 10^9 cps (radio) to about 10^{15} cps (optical). For an isotropic and homogeneous source, the ratio of energy loss by the inverse Compton effect to that by synchrotron radiation is equal to the ratio of the energy density of the radiation field $U_{\rm rad} = 3L/4\pi r^2 c$ to that of the magnetic field, $U_H = H^2/8\pi$, so

$$\frac{U_{\rm rad}}{U_H} = 6 \frac{L}{r^2 H^2 c} \qquad 21.$$

where L is the radio luminosity due to synchrotron radiation, r the radius, and c the velocity of light in cgs units.

If the maximum dimension of a variable component is limited to the distance traveled by light during the characteristic time of the variations, e.g. $\sim$1 pc, then there is a restriction on the maximum value of the magnetic field through Equation 14. As Hoyle, Burbidge & Sargent (110) have pointed out, if the variable QSS are at cosmological distances, then owing to their very small dimensions and high luminosity, $U_{rad}/U_H \gg 1$. This in turn implies that the radiation density at optical wavelengths due to the inverse Compton effect is greater than that due to synchrotron radiation at radio frequencies. This, they argued, raises two problems: first, the resulting optical luminosity cannot exceed the observed value; and second, successive inverse Compton interactions will result in a catastrophic loss of energy by the relativistic electrons. However, as Moffet (44) and others have pointed out, the cross section from Compton scattering decreases when the photon energy is comparable with the electron rest energy, so that the process does not in fact become self destructive. Nevertheless, the optical radiation produced in the first stage of scattering from the radio photons must be kept below the observed optical fluxes. This is not necessarily a severe condition, since the Compton scattered radiation is spread over a much wider bandwidth than the synchrotron emission. Woltjer (113) has pointed out that if the relativistic electrons move in the magnetic field with small pitch angles ($\sim$10°), the radio photons generated move in essentially the same direction, so that the inverse Compton scattering is greatly reduced and a local hypothesis for the sources is not required. Such a configuration would probably occur if the electrons are moving away from a central source in a radially symmetrical magnetic field.

It should be noted that it is possible for $U_{rad}/U_H \gg 1$ as long as the optical flux limit is not exceeded and as long as the particle lifetime is not much shorter than the time scale of the variations, i.e., one to several years. Thus the statement sometimes made (e.g. 110) that if $U_{rad}/U_H > 1$ the synchrotron mechanism is not operating or the source is not at a cosmological distance is incorrect.

In view of the great difficulties encountered in interpreting the variable radio sources in terms of the conventional synchrotron mechanism, several other modifications have been suggested in an attempt to overcome the seemingly impossible requirements. There is, of course, at the time of this writing no clear-cut "proof" that the variable sources are in fact located at great distances (e.g. 83) or that the variations are intrinsic to the sources and not the effect of some intervening medium.

With regard to the second possibility, it is interesting that two of the most intense outbursts that have been observed occurred in the spring of 1966, when both 3C 273 and 3C 279 showed a large and nearly simultaneous increase in their flux density at 2 cm (45, 46, 114). Since these two sources are separated by only 10 degrees in the sky, it was speculated that the two sources might be physically coupled or that the effect was caused by a local disturbance in the line of sight to a distant source of constant intensity (46). Since the observed increases in the two sources were not separated in time by more than 1 or 2 months, this interpretation required that the "disturbed" region of space was not more than a few light months in extent and therefore not more than a few light years away.

Subsequent observations at 9 mm (115), 2 cm (47, 48, 114), and 2.8 cm (54) have shown that while the flux of 3C 273 reached a rather sharp maximum in the summer of 1966, the intensity of 3C 279 has remained more or less constant. This does not support the argument that the intensity changes are coupled, although no definite conclusions can be reached without further data since a detailed correlation might not in fact be expected.

A similar curious situation exists in the two sources 3C 345 and NRAO 512 which are only about half a degree apart in the sky, have similar radio spectra, and are both variable (48). 3C 345 is a well known quasi-stellar object and NRAO 512 has been tentatively identified as a quasi-stellar object although no confirming spectra are yet available.

If the cosmological interpretation is accepted, then the required energy densities are very high. Equation 20 may be used to determine the density n_e of relativistic particles. For a homogeneous and isotropic model, the total energy contained in the particles is (46)

$$E_e = \begin{cases} 4.7 \times 10^{52} \dfrac{[1 - (E_1/E_2)^{1/2}]}{[(E_2/E_1)^{1/2} - 1]} l^3 n_e E_2 \text{ ergs} & \text{for } \gamma = 1.5 \\ 8.8 \times 10^{55} \dfrac{[1 - (E_2/E_1)^{1/2}]}{[1 - (E_2/E_1)^{3/2}]} l^3 n_e E_2 \text{ ergs} & \text{for } \gamma = 2.5 \end{cases} \qquad 22.$$

where l is in pc, n_e in cm^{-3}, and E_2 and E_1 the upper and lower cutoff energies of the electron distribution in GeV. In a strong outburst such as those that have occurred in 3C 273 or 3C 454.3, the required energy in relativistic particles must be about 10^{58} ergs, which is equivalent to the energy released in 10^8 type II supernovae. From the time scale of the observed changes of flux density, it appears that this must be created during a period of a few months or less.

The release of this amount of energy in such a short time in a volume of space less than a cubic parsec is difficult to understand. Even if such energies could be liberated, for example by gravitational collapse, it is not at all clear how the energy is transformed into relativistic particles, or why these particles always seem initially to have the characteristic power-law spectrum with an exponent of 1 to 1.5. Moreover, any process releasing such a vast amount of energy would probably be catastrophic. The repeated outbursts observed in several sources suggest either that this is not the case, or that each new component is created in a volume of space separated from the earlier sources. It is important to note that the observed variations in the nuclei of the Seyfert galaxies and in the QSS are very similar, although in the former, the energy requirements are greatly reduced.

Rees (116, 116a) has shown that if the optically thick source is expanding with a relativistic velocity v, the apparent rate of increase in angular size and flux density is increased by the factor $\beta=(1-v^2/c^2)^{-1/2}$. Thus a source with an apparent age of 1 year and $\beta=5$ would have an actual diameter of 10 light years and not 2 light years. The larger size of the source, the large blueshift of the radio emission, and the beaming effect of the motion all combine to reduce the energy requirements.

Although very large expansion velocities might occur in the QSS, if the expansion occurs in intergalactic space, it seems unlikely that relativistic expansion velocities could also be maintained for any length of time in the dense nuclear region of the Seyfert galaxies.

Even with a nonrelativistic expansion and if we accept the short time scales and the implied small dimensions, the energy problem can be greatly reduced if the sources do not radiate isotropically. It has already been pointed out that by dropping the assumption of an isotropic and homogeneous source, the inverse Compton catastrophe can be avoided. If a significant fraction of the radiation is beamed toward the Earth in a solid angle Ω, the energy requirements are reduced by the factor $\Omega/4\pi$. This, of course, would require that the actual number of variable QSS and radio galaxies be greater than the observed value by the reciprocal of the beaming factor.

If in fact the radiation is beamed, then variations might be observed even if the power output remained at a constant level as the rotation of the source periodically swept the beam in the direction of the observer (117). In this case one would expect to see periodicities in the observed emissions. It might be thought that the delay in the event at longer wavelengths could then be explained by dispersion in an ionized gas. A time delay between optical and radio events was predicted by Haddock & Sciama (118). It can, however, be shown that if a time delay of 1 year at a wavelength of 20 cm is produced over a pathlength of 10^9 pc, an electron density of ~ 10 cm^{-3} is required. Such a medium would give rise to a high sky brightness at meter wavelengths unless the kinetic temperature of the medium is greater than 10^{10} ° K, and a systematic relation between the delay and the redshift would be observed. If the dispersive medium exists only in a region of size l pc around the source, the required density is about $10^{10}/l$ cm^{-3} and the temperature greater than $10^{12}\, l^{2/3}$ ° K. The physical conditions in either case seem improbable.

Beaming would occur if the electrons were radiating coherently rather than incoherently as is usually assumed. Sometime ago Twiss (119) discussed the possibility of negative absorption or stimulated emission which might produce coherent radiation in optically thick sources of synchrotron radiation. Although he concluded that this might be possible under certain conditions where the gradient in the electron energy distribution is positive, Wild, Smerd & Weiss (4) later reached the opposite conclusion—that stimulated emission was not possible. More recently, however, several authors have pointed out that negative absorption may in fact occur when the relativistic electrons are moving in a dispersive medium where the index of refraction is less than unity (120–123).

SUMMARY

In an isotropic model, it is clear that large changes in radiated power occur over very short intervals of time. If the quasi-stellar sources are at the cosmological distance indicated by their redshifts, then the absolute monochromatic power radiated near the wavelength of 2 cm increases by at least 10^{27} W $(Hz)^{-1}$ for several sources. The *change* in total radiated power is undetermined since the radio spectrum is uncertain at short wavelengths but it is certainly greater than 10^{44} ergs/sec for 3C 454.3. This value is equivalent to the total radio luminosity of the most powerful radio galaxies such as Cygnus A or 3C 295. If the emission is not isotropic, then these values are reduced by the beaming factor. The variations in the optical luminosity are even larger and correspond to changes greater than the total light output of an entire galaxy in a time of a few weeks or less.

It is by no means clear what relationship there is, if any, between the variations observed at radio and at optical wavelengths. Two coupling mechanisms are immediately suggested:

An obvious possibility is a simple extension of the model described earlier where the bursts appear first at optical wavelengths and then propagate to longer wavelengths. The expected amplitude of the optical bursts extrapolated from the radio observations is, however, very much greater than that actually observed. Moreover, the large variations which would then be expected at the intermediate infrared wavelengths are not detected (124).

A second possibility is that the variable optical emission is due to Compton-scattered radio photons. In this case we would expect a one-to-one correlation between the radio and optical luminosity fluctuations, whereas the observed optical fluctuations are generally more intense, more rapid, and more frequent than the radio variations. We cannot, however, rule out the possibility that the Compton-scattered optical emission originates at radio wavelengths short of 1 cm where there have been relatively few radio observations. The limited data available certainly suggest that variations at millimeter wavelengths are indeed more rapid than at the longer wavelengths.

Another unsolved question is the relationship between the phenomena observed in the nuclear regions of galaxies and in the quasi-stellar objects which are very similar in the time scale and in the pattern of their radio variations. An even more basic problem is the unknown role of the optical quasi-stellar objects or the dense nuclei of Seyfert and N-type galaxies. It is tempting to assume, as is usually done, that the relativistic particles are produced in the quasi-stellar objects or in the galactic nuclei, but then it is difficult to understand how such large amounts of energy can be repeatedly generated in such a small volume of space.

Extensive observations of variable radio sources have only been in progress for a few years, and so the variations found are necessarily restricted to time scales of a few years or less. The duration of an outburst at centimeter wavelengths is about a year, and, at least in 3C 120, the frequency of outbursts may be as high as one per year. The form and the distribution of the radio-frequency spectra of the large-diameter radio sources, which are usually, but not always, associated with radio galaxies, independently suggest that the energy release in these objects occurs at intervals of 10^5 to 10^6 years (125). Since a few per cent of radio sources are currently active, the duration of the period of activity must be of the order of 10^3 years in a typical radio source. It is probable that in objects such as the radio-quiet quasi-stellar galaxies and the nuclei of the radio-quiet Seyfert galaxies, the duration of the activity is shorter, or the interval between active periods is longer so that between periods of quiescence, no radio radiation is observed. Since the number of QSG may exceed that of QSS by a factor of several hundred (70), the active periods in the former may last only a few years or recur at intervals as long as 10^7 to 10^8 years. In any case, a single mechanism for all extragalactic radio sources, which repeatedly releases large amounts of energy, with the release occurring in many frequent outbursts, is in good agreement with the data now available on the radio spectra and time variations. The energy source, however, remains a complete mystery.

High-resolution interferometric observations made during the periods of rapid variability should (*a*) determine whether the individual events are spatially coincident or if not to what extent they are separated; (*b*) decide whether, as suggested by Rees (116), the source dimensions exceed the limit usually assumed from the light travel time; and (*c*) measure directly the rate at which the cloud of relativistic electrons is expanding and so determine the manner in which the magnetic field varies with time.

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