RADIO EMISSION FROM COMPACT OBJECTS

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Abstract. Compact radio stars are associated with both galaxies and quasi-stellar objects; and there appears to be no way to distinguish between the radio galaxies and the quasi-stellar radio sources from their radio properties alone.

The compact radio sources are opaque at the longer radio wavelengths and have spectra that are either peaked or complex. They have a complex brightness distribution and often contain components less than 0.001 arc sec in size.

Many of the compact sources show large intensity variations and in NGC 1275 there is evidence for a change in the angular size during one year.

1. Introduction

Radio emission is observed from all of the various types of compact extragalactic objects. These include not only quasi stellar objects, but also the nuclei of compact, Seyfert, and N type galaxies.

There are, at present, insufficient systematic data to determine accurately the radio luminosity function of any of the compact objects or the probability that any particular object can be detected as a radio source above some given flux limit.

A. SEYFERT GALAXIES

Because two of the earliest identified radio sources (3C 71 and 3C 84) are identified with Seyfert galaxies (NGC 1068 and NGC 1275 respectively), it has been widely thought that the Seyfert phenomenon is associated with intense radio emission. Although at least one other galaxy, 3C 120, is identified with a compact radio source and exhibits the Seyfert phenomenon, there is no evidence that Seyfert galaxies are particularly likely to be strong radio sources. NGC 1068 (3C 71), for example, has an absolute radio luminosity near 10^{40} erg s^{-1} or only slightly more than a normal spiral galaxy.

Attempts have been made to observe most of the other known Seyfert galaxies (Heeschen and Wade, 1964; de Jong, 1967; Pauliny-Toth and Kellermann, 1968a). Although most of the known Seyfert galaxies are weak radio sources, their radio luminosity in general does not significantly exceed that of normal spiral galaxies. The fraction of Seyfert galaxies which are strong radio sources in fact does not appear to differ significantly from that of giant elliptical galaxies (e.g. Rogstad and Ekers, 1969).

B. COMPACT GALAXIES

Similarly, the compact galaxies of the type described by Zwicky (1964) and Sargent (1970) do not in general appear to be particularly prominent as radio emitters. Only

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two of these, Zw 1727+50 (Pauliny-Toth and Kellermann, 1968a) and III Zw 2 (Kellermann and Pauliny-Toth, unpublished), have been detected as radio sources. Both have relatively flat spectra, suggesting that the radio sources are compact.

C. N GALAXIES

The probability of radio emission from N-type galaxies is difficult to discuss, since most of the galaxies of this type were first recognized in the identification of known radio sources.

D. QUASI-STELLAR OBJECTS

In this paper we shall use the term quasi-stellar radio source, or QSS, to refer to a radio source associated with a quasi-stellar object (QSO) independent of the size or nature of the radio source. More than 150 such QSS are known. Most of these are the result of identification of a catalogued radio source with a quasi-stellar object, based essentially on the good agreement in the position of the radio source and QSO.

Other QSOs have been isolated as a result of multicolor photometry (e.g. Sandage and Luyten, 1967; Braccesi *et al.*, 1970). These do not appear to differ in any obvious way from the QSS except that they are not in existing radio catalogues and are usually referred to as 'radio quiet' QSOs. Several groups have attempted to observe radio emission from these objects and a small number have been detected (Braccesi, 1967; Pauliny-Toth and Kellermann, 1968a; Lang and Terzian, 1969; Grueff, 1970). Although the statistics are still poor, it appears that 10 or 15% of the optically discovered QSOs may be detected as radio sources. The higher fraction of detection found by Lang and Terzian (1969) appears to be incorrect as more recent observations made with higher resolutions have shown these to be mainly due to chance coincidence (Grueff, 1970).

All of the known QSS have significant red shifts, generally of the order of unity. Thus, if the red shifts are cosmological, even the QSS with very low measured flux density have large absolute radio luminosities, typically in the range of 10^{44-45} erg s^{-1}, which is comparable to the strongest radio galaxies such as Cygnus A and 3C 295. Since the QSOs are thought to be at great distances, the absence of detectable radio emission usually implies only a modest limit to the radio luminosity of about 10^{43} erg s^{-1}. Because their space density is low, there are very few nearby QSOs and there is therefore little chance of detecting intrinsically weak QSS if they exist. Figure 1 shows the distribution of absolute monochromatic radio luminosity at 6 cm for identified galaxies (Figure 1(a)) and for identified QSS (Figure 1(b)). Figure 1(c) shows a similar histogram for those objects initially thought to be radio quiet.

It has often been suggested that the radio-quiet objects may show significant emission at very short wavelength. There is no evidence that this is the case. Most of the 'radio-quiet' objects which have been subsequently detected have normal spectra and were missed in the early surveys simply because their flux densities are small.

The radio luminosity function of identified QSS in the 3CR catalogue has been investigated by Schmidt (1970) who finds that the space density of QSS is approxi-

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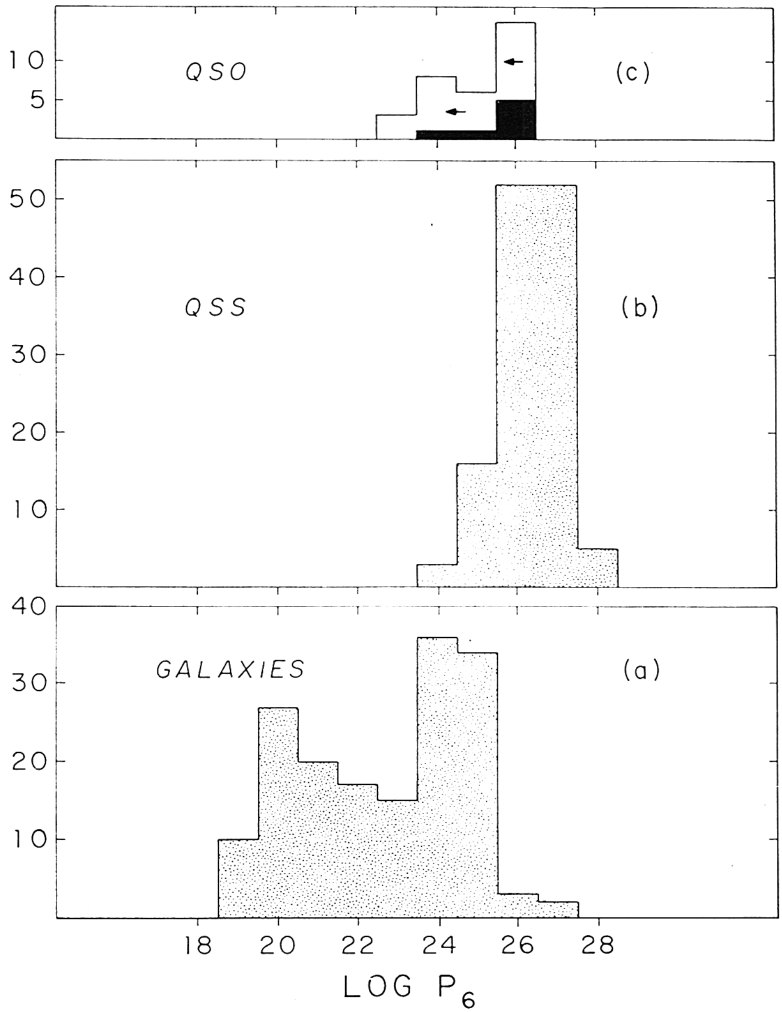

Fig. 1. Histograms showing the distribution of absolute monochromatic luminosity (P_6) at 5 GHz (6 cm) for (a) galaxies and (b) QSS which have measured redshifts. The upper histogram, (c), also shows the distribution of upper limits for radio quiet QSOs. The filled in part of (c) indicates radio quiet QSOs which have subsequently been detected or recognized as radio sources. The absolute luminosities are calculated assuming the redshifts are cosmological, $H = 100$ km s^{-1} Mpc^{-1}, and $q_0 = 1$. These histograms are in no way intended to represent a luminosity distribution as the sources are taken from an inhomogeneous sample. They are intended to show only the range of luminosity covered by the various objects.

mately inversely proportional to absolute luminosity. Only about 1 QSO in 300 is strong enough to be in the 3C catalogue (e.g. Schmidt, 1969). Thus, if Schmidt's luminosity function can be extrapolated by several orders of magnitude, most QSOs should be stronger than a few hundredths of a flux unit at 178 MHz or a few milliflux units at centimeter wavelengths. This is not inconsistent with the fraction of QSOs which have been detected at intermediate flux density levels. However, systematic

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surveys of radio quiet QSOs down to a very low flux density level are clearly important the better to establish their radio luminosity function. On the basis of existing data, it appears that the probability of finding radio emission from compact objects such as QSOs, Seyfert, compact, or N galaxies is comparable to that of giant elliptical galaxies.

E. CLASSIFICATION OF THE RADIO EMISSION FROM COMPACT OBJECTS

It is perhaps surprising to note that of the identified radio sources which have been studied in some detail, there is no clear difference in the radio emission from galaxies and from QSOs or other compact objects. Both classes of objects have similar radio frequency spectra, similar radio structure and polarization, and assuming that the redshifts are cosmological, a similar range of linear dimensions.

A rough separation of all extragalactic sources can be made into two groups:

(1) The compact radio sources which have angular dimensions much less than 1 arc sec and are opaque over at least part of the radio spectrum; and

(2) the extended radio sources which typically are greater than 1 arc sec in angular extent and are optically thin throughout the observable spectrum.

It must be emphasized, however, that this division is based on the observed radio properties, and in no way separates radio galaxies from QSS. Small radio sources are found not only in QSS but in galaxies as well (e.g. Heeschen, 1970) and QSS often have dimensions comparable with the classical extended radio galaxies (e.g. Hogg, 1969).

It is true that the majority of the *identified* radio galaxies are extended and have optically thin radio spectra, while the majority of the *identified* QSS are small and often have components which are optically thick (Bolton, 1966; Pauliny-Toth and Kellermann, 1968b). The unidentified sources generally have angular dimensions and spectra similar to those of the identified radio galaxies, and it has been thought that the unidentified sources must therefore be radio galaxies beyond the 48-in. plate limit (e.g. Bolton, 1966). An alternative interpretation, however, is that there is no relation at all between radio properties and optical identification, but that in the process of identification, the association with a stellar object is only accepted if the position agreement is very good, and this will discriminate against the identification of extended radio sources with stellar objects. More complete samples of identified sources are required before definite conclusions can be made. However, the identification of faint optical objects with extended radio sources will always be uncertain, particularly if the centroid of radio emission does not coincide with the optical object. It is interesting to note, as shown in Figure 2(a) and (b), that if the QSS redshifts are presumed to be cosmological, then in the 3CR catalogue where the identifications are most complete, there is no systematic difference between the linear dimensions of galaxies and QSOs. As has been pointed out many times, this gives great weight to the interpretation of QSO redshifts as being cosmological.

Because the radio properties of galaxies and the more compact objects appear to be indistinguishable, the emphasis in this review will be on the compact radio sources independent of their optical identification.

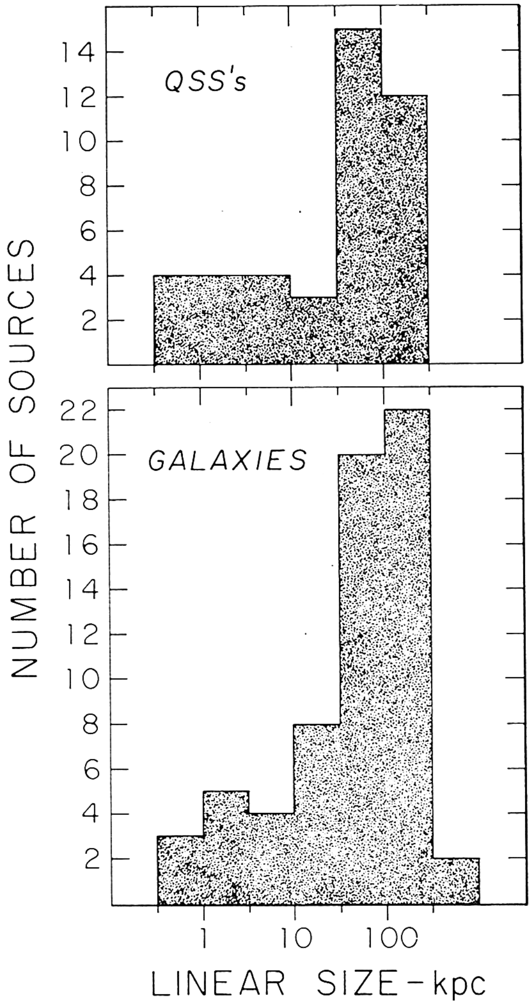

Fig. 2. Histograms showing the distribution of linear dimensions of QSS and radio galaxies in the 3CR catalogue which have measured redshifts. The sizes are computed from published and unpublished (Miley, 1970) measurements of angular sizes and assume that the measured redshifts are cosmological, $H = 100$ km s^{-1} Mpc^{-1}, and $q_0 = 1$.

2. Radio Spectra

A. CLASSIFICATION OF SPECTRA

Many extragalactic sources have been observed over a very wide range of wavelengths, typically from 3 cm to 10 m, but in some cases extending from 3 mm to 30 m. This range of 10^4 in wavelength may be compared with the range of only 2:1 covered by conventional optical spectra. It is not surprising therefore that a wide variety of spectral shapes is found. Nevertheless, no distinction can be made between QSS and radio galaxies either from a statistical comparison of the spectra (e.g. Kellermann *et al.*,

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1969) or on the basis of the detailed radio spectra. This is illustrated in Figures 3, 4 and 5, which show the spectra of a number of galaxies and QSS for which there are data over a wide range of wavelength. The spectra are conveniently divided into three groups:

(i) Sources where the flux density decreases monotonically over the entire range of observed frequencies. These sources are optically thin at all wavelengths (Figure 3);

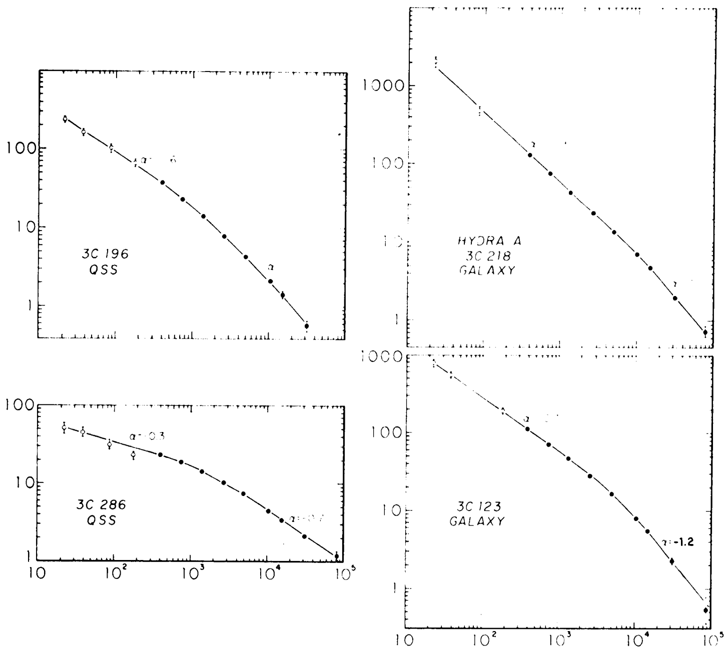

Fig. 3. The radio spectra of several galaxies and QSS which are optically thin over the entire range of observed frequencies. The data between 3 mm and 75 cm are taken from published and unpublished measurements made at NRAO by Pauliny-Toth and the author and are shown with closed circles. Data at longer wavelengths come from published observations made at several observatories and are shown as open circles.

(ii) Sources where the flux density decreases with frequency at high frequencies but has a sharp cutoff at low frequencies which is probably due to self-absorption (Figure 4);

(iii) Sources which have complex spectra with one or more relative minima and maxima. These are thought to be composed of several distinct components which become opaque at different wavelengths (Figure 5).

B. OPTICALLY THIN SOURCES

The spectral index, in the optically thin part of the spectrum, is directly related to the electron energy distribution through the well-known relation $\alpha=(1-\gamma)/2$ where α is the spectral index defined by $S \propto \nu^{\alpha}$, and γ is the energy index defined by $N(E) \propto E^{-\gamma}$, where S is the flux density, ν the frequency, and $N(E)$ the number of electrons

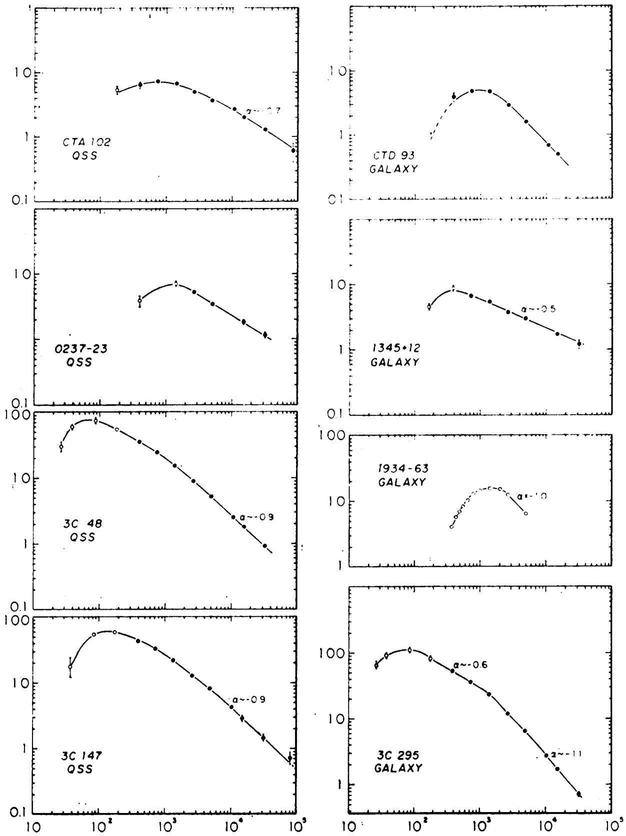

Fig. 4. The radio spectra of several galaxies and QSS which become optically thick at long wavelengths. The source of data is the same as in Figure 3.

with energy, E. At wavelengths where the sources are optically thin, the spectra are typically power law or dual power law with indices usually in the range $\alpha = -0.7$ to -1.2. In the case of the dual power law spectra, the curvature in the spectrum generally extends over one decade or more of wavelength. At significantly longer or shorter wavelengths the sources usually have well defined power spectra with a difference in index close to 0.5 which is the value expected when relativistic particles are continuously supplied and the rate of injection is balanced by the losses due to radiation (e.g. Kardashev, 1962).

In none of the sources with optically thin spectra is there sign of a high frequency cutoff due to a cutoff in the electron energy distribution. An upper limit to the electron energy must exist due either to the acceleration mechanism or to energy losses by synchrotron radiation or inverse Compton losses. In particular, as pointed out by Rees and Setti (1968) and emphasized by van der Laan and Perola (1969), the inverse Compton scattering by photons of the 3K background will limit the lifetime of the high energy particles, especially at large redshifts where the effective background

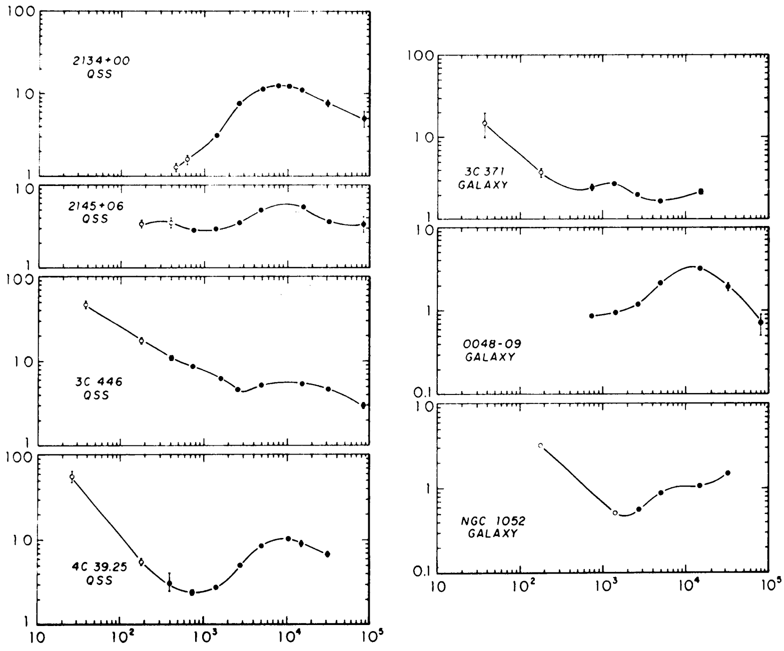

Fig. 5. The radio spectra of several galaxies and QSS which have complex spectra. The source of data is the same as in Figure 3, except for NGC 1052 (Heeschen, 1970).

temperature is increased by a factor of $(1+z)$ and the Compton lifetime is decreased by $(1+z)^4$.

The available data show no evidence of a cutoff in any of several hundred sources out to 10 GHz, or in the smaller number which have been studied at 15 or 30 GHz. In a few cases data exist near 100 GHz still with no evidence of the expected cutoff (Kellermann and Pauliny-Toth, 1971).

C. OPTICALLY THICK SOURCES

Many of the more compact sources are opaque over at least part of the radio spectrum. Contrary to several published remarks that such sources are rare or unusual (e.g. Shimmins *et al.*, 1968, MacLeod and Andrew, 1968), they are in fact quite numerous, with approximately one-half of all sources observed in centimeter wavelength surveys being of this type (Kellermann *et al.*, 1968; Brandie, 1970).

Because the compact sources are partially opaque, their spectral indices are flat or even inverted so that they are relatively inconspicuous at meter wavelengths where all of the earlier radio surveys have been made. Most of the known opaque sources have therefore been initially found in the limited surveys made at shorter decimeter or centimeter wavelengths, and it is becoming increasingly clear that compact opaque radio sources having complex radio spectra are quite common and comprise a significant fraction of all radio sources that can be detected with current instruments.

The number of identifications of these sources is limited, but they are with both galaxies and QSOs.

Many of the compact sources have now been studied at millimeter wavelengths where, although few sources remain opaque even at 3.5 mm, most are becoming optically thin and show a turnover in their spectra near 1 cm (Kellermann and Pauliny-Toth, 1971). For the same reason that these sources are undetected in long wavelength surveys, sources which may be opaque at short millimeter wavelengths might only be detected in surveys made at wavelengths less than 1 cm. Presently available sensitivities do not, however, yet permit reasonably efficient surveys to be made at wavelengths less than a few centimeters.

For the extended radio sources, the spectral index is always steeper than -0.5, corresponding to an index $\gamma > 2$. In nearly every case where flatter spectra are observed, accurate flux measurements or long-baseline interferometry indicate that the flat spectrum is due to the superposition of several optically thick components, and not to a flat electron energy distribution. The only exception to this is in the optically thin part of the spectrum of the very young variable components; these appear to have indices between 0 and -0.25 or, $1 < \gamma < 1.5$.

In a recent paper based on observations at Ohio State, Andrew and Kraus (1970) have remarked that some of the sources with flat spectra appear to have smooth power law spectra, and they suggest that these are optically thin and do indeed indicate a flat electron energy distribution. More accurate flux density measurements (Jauncey *et al.*, 1970a) of many of these sources, however, show fine structure in the spectra suggesting the presence of several separate opaque components. In addition, some of these sources have been observed with high resolution interferometers and show the expected complex structure (e.g. Kellermann *et al.*, 1970).

D. RELATION BETWEEN RADIO, INFRARED OPTICAL, AND X-RAY EMISSION

It is by no means clear what relation there is, if any, between observed radio emission from compact objects and the radiation observed at infrared optical, or X-ray wavelengths. It is perhaps significant that the three extragalactic X-ray sources, M87, 3C 273 and Centaurus A (e.g. Bowyer *et al.*, 1970) all contain a very small diameter radio source*, suggesting that the X-ray emission may be due to inverse Compton scattering in the compact radio source (e.g. Burbidge, 1970). Since the ratio of inverse Compton emission to synchrotron emission depends only on the peak radio brightness temperature, detectable X-ray emission may also be expected from other radio sources, with equally great brightness temperature and comparable radio flux density such as 3C 279, 3C 345, and 3C 454.3.

A number of compact objects are particularly strong in the far infrared (Kleinmann

* Observations of the small radio source in M87 have been published (e.g. Cohen *et al.*, 1969). The small source in Centaurus A was found in unpublished measurements made with the NRAO three element interferometer. The small source contains a few percent of the total flux density at 3.7 cm; it appears to be unresolved at a resolution of one arc sec. The spectrum between 3.7 and 11 cm indicates that it is opaque at centimeter wavelengths and thus most likely $\theta \lesssim 0.''001$.

and Low, 1970a). In none of these objects is there any evidence of an increase in the radio flux density at short millimeter wavelengths toward the very large infrared flux density. This is illustrated in Figure 6 which shows the combined radio and infrared spectrum of the galaxies NGC 1068 (3C 71) and NGC 3034 (M82, 3C 231). Schorn

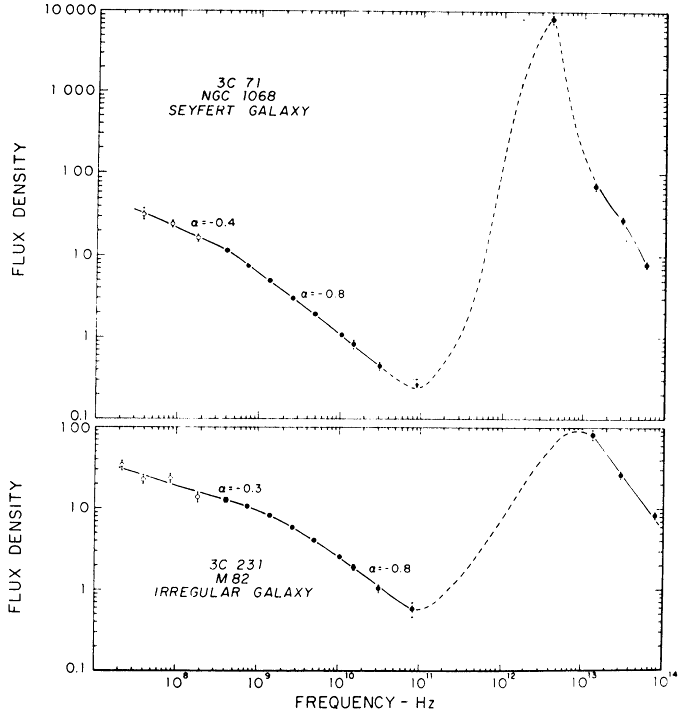

Fig. 6. Spectrum of NGC 1068 (3C 71) and NGC 3034 (3C 231, M82) at radio and infrared wavelengths. The source of data at radio wavelengths is the same as in Figure 3, and the infrared data are taken from Kleinmann and Low (1970) and Low (1970).

et al. (1968) have measured a flux density of about 10 flux units* for NGC 1068 at 3.4 mm. This has not been confirmed by more recent measurements made at NRAO at the same wavelength and with considerably greater sensitivity, or by measurements made near the same time but at the longer wavelength of 2 cm (Kellermann and Pauliny-Toth, 1971).

The NRAO limit of a few tenths of a flux unit combined with the high flux density of about 10000 flux units measured by Low (1970) near 100μ requires a spectral index in this wavelength range near the limit of +2.5 of an opaque synchrotron source. It has also been suggested that the low frequency cutoff of the infrared emission may be due to free-free scattering in a dense electron core (Weymann, 1970).

NGC 3034 (M82) is of particular interest since the infrared and radio sources coincide and have similar dimensions of approximately 20 × 10 arc sec (Kleinmann

* 1 flux unit = 10^{-26} W m^{-2} Hz^{-1}.

and Low, 1970b) suggesting that the emission at radio and infrared wavelengths may be in some way related. The radio spectrum, however, at centimeter and millimeter wavelengths is a power law with an index of -0.8 and shows no evidence of enhanced emission even at 3.5 mm. Future work in the difficult range 100μ to 1 mm will clearly be important in establishing the relation between radio and infrared emission in M82 and other galaxies.

3. Radio Intensity Variations

Many of the compact radio sources show pronounced variations in intensity on time scales extending from a few weeks in case of the unusual object, BL Lac (Andrew *et al.*, 1969; Olsen, 1969) to a few years. Since the initial discovery of intensity variations by Dent (1965), a number of sources have been regularly monitored at several observatories at wavelengths from 3 mm to 40 cm. The data show no simple pattern to the observed variations; in particular, there is no evidence for any periodic phenomena. Rather, the variations appear to be in the form of random outbursts which often appear first at short wavelengths and then at a later time at longer wavelengths and with reduced amplitude.

There is no obvious difference in the pattern of intensity variations observed in radio galaxies or in QSS. The typical change in radiated power in the variable radio galaxies such as NGC 1275 and 3C 120 is of the order of 10^{41-43} erg s^{-1} in one year. Because the QSS are generally considered to be at very great distances, their change in radiated power appears to be as great as 10^{45} erg s^{-1} in one year, although the observed changes in apparent intensity are comparable in amplitude and frequency with those of the radio galaxies. Assuming they are at cosmological distances, the change during a few months in radiated power in some of the QSS is comparable with the entire radio luminosity of the strongest radio galaxies such as Cygnus A.

A. THEORIES OF INTENSITY VARIATIONS

There are many reasons why the compact radio sources may be expected to vary with time. These include changes in the rate of production or acceleration of relativistic particles, the loss of energy of the particles due to synchrotron emission, inverse Compton scattering, or adiabatic expansion, and changes in the magnetic field strength or in the size of the source. Probably all of these factors contribute in varying degrees to the variations that are observed in the different sources, and at different epochs in individual sources.

B. EXPANDING SOURCE MODEL

Soon after the initial discovery of intensity variations it was realized (Kellermann and Pauliny-Toth, 1966; Moffet, 1966; Pauliny-Toth and Kellermann, 1966) that the observed variations could be approximately described by a simple model first discussed by Shklovsky (1965). This model assumes that the variations occur as the result of the expansion of a cloud of relativistic particles which is initially opaque out to short wavelengths, but which, due to expansion, becomes optically thin at successively longer wavelengths. If, as supposed by Shklovsky, the magnetic flux is conserved, the magnetic field will decrease and so the peak flux density will decrease with time and increasing wavelength.

The immediately obvious applicability of the expanding source model to explain the observed intensity variations led van der Laan (1966) to reformulate in detail the behavior expected from the simple case where all of the particles are generated instantaneously in an infinitesimal volume of space, where the magnetic field and electron cloud is homogeneous and isotropic, where the expansion occurs at a constant rate or with constant deceleration, and where the magnetic flux is conserved.

At least several events observed in the galaxy 3C 120 (Pauliny-Toth and Kellermann, 1968) and in 3C 273 (Dent, 1968) have followed remarkably closely the quantitative form expected from the simple model. In general, however, most sources show repeated outbursts or a continuous but variable acceleration of relativistic particles, so that individual events are not sufficiently isolated either in frequency or time to permit a detailed analysis. But to the extent that comparison between observation and theory is possible, the variations are reasonably well explained by the 'expanding source model'. The fact that there are sources which deviate from the simplest form of the model described by Pauliny-Toth and Kellermann (1966) and by van der Laan (1966) is not surprising. What is surprising is that the observed variations in most sources do follow remarkably well the theory outlined by Shklovsky (1965) at a time when to most others the very possibility of observable intensity variations in extragalactic radio sources seemed remote.

C. INITIAL CONDITIONS IN VARIABLE SOURCES

In the simple model which assumes the instantaneous production of particles, the source is initially opaque at infinitesimally small wavelengths. In a real source, however, particle production must occur over a finite period of time, and throughout a finite volume of space. Thus below some critical wavelength, λ_c, the source must be always optically thin and the observed intensity variations will reflect the rate of acceleration of relativistic electrons as well as changes in the magnetic field strength and electron energy distribution. For $\lambda < \lambda_c$, there is no expected delay in the time when the peak amplitude is reached at different wavelengths, and the maximum flux density reached is less than expected from extrapolation of the simple model. The data at millimeter wavelengths (Schorn *et al.*, 1968; Kellermann and Pauliny-Toth, unpublished; Simon, 1969) suggest that $\lambda_c \gtrsim 1$ cm. The extensive data obtained by the Canadian observers at 2.8 and 4.6 cm (Locke *et al.*, 1969, 1970) indicate a number of sources for which $\lambda_c \gtrsim 4.6$ cm.

In all of the variable sources, the peak flux density observed at wavelengths where $\lambda < \lambda_c$ is very nearly the same indicating a spectral index in the range $-0.25 \lesssim \alpha \lesssim 0$ or $1 \lesssim \gamma \lesssim 1.5$. A similar value of γ is found in those cases where detailed analysis of the rate at which the peak amplitude changes with wavelength or time has been possible. There is, therefore, growing evidence, that in both galaxies and QSS, the initial electron energy distribution is very flat with an index in the range $1<\gamma<1.5$. Since in the older, more extended sources $2.5<\gamma<3.5$ electron energy losses must sometime steepen the spectra.

Synchrotron radiation losses will produce a cutoff or a bend in the spectrum at a frequency given by

$$\nu_0 = t^{-2}B^{-3}\,\mathrm{GHz},$$

where t is the age of the source in years and B the magnetic field in gauss. Since some sources clearly show no steepening of the spectrum even at 3.5 mm (85 GHz) for a year or more following an outburst, the initial magnetic field cannot greatly exceed 1 G.

D. MOTION OF VARIABLE COMPONENTS

An interesting variation on the expanding source model has been suggested by Ozernoy and Sazonov (1969) who propose that the observed multiple outbursts are the result of several expanding sources which are 'flying apart' at relativistic velocity. In their model the delay between different observed 'events' is due to the different propagation time from each cloud rather than to independent outbursts. However, contrary to observation, this model predicts that the time between observed outbursts should increase with increasing wavelength, since the radial distance between the separate clouds will increase with time. Figures 7 and 8 show, however, that at least for the sources 3C 120 and 3C 273, where good data exist, the time between different events remains essentially constant. This, of course, does not imply that relativistic motions do not play some role in determining the detailed nature of the light curves of some sources. High resolution interferometer observations made over a period of time and a range of wavelengths are required to determine whether or not the different outbursts are spatially separated and, if so, whether or not there are significant proper motions of the individual components.

E. POLARIZATION VARIATIONS

Another sensitive test of models of intensity variations is the observation of polarization variations. It is well known that in a source of synchrotron emission from a uniform magnetic field and power law distribution of relativistic particles, the fractional polarization, P, for optical depth $\tau \ll 1$ is

$$P = (3\gamma + 3)/(3\gamma + 7) \sim 0.60 \qquad (\gamma = 1)$$

with the electric vector perpendicular to the direction of the magnetic field, and for $\tau \gg 1$

$$P = 3/(6\gamma + 13) \sim 0.16 \qquad (\gamma = 1)$$

and is parallel to the magnetic field (Le Roux, 1961). Thus, in an expanding source, when $\tau \sim 1$, a large increase in the degree of polarization accompanied by a 90° rotation is expected (Kellermann and Pauliny-Toth, 1968). In practice, the situation may not be so simple, since, when $\tau \gg 1$, we observe radiation from only a thin layer

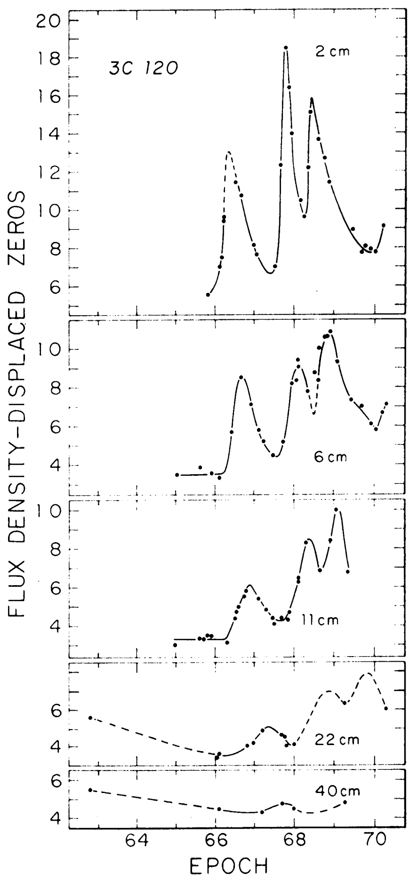

Fig. 7. Intensity variations observed in the radio galaxy 3C 120 at 2, 6, 11, 22, and 40 cm. The data are taken from measurements made by Pauliny-Toth and the author. The vertical axis gives the flux density at each wavelength and the horizontal axis the epoch.

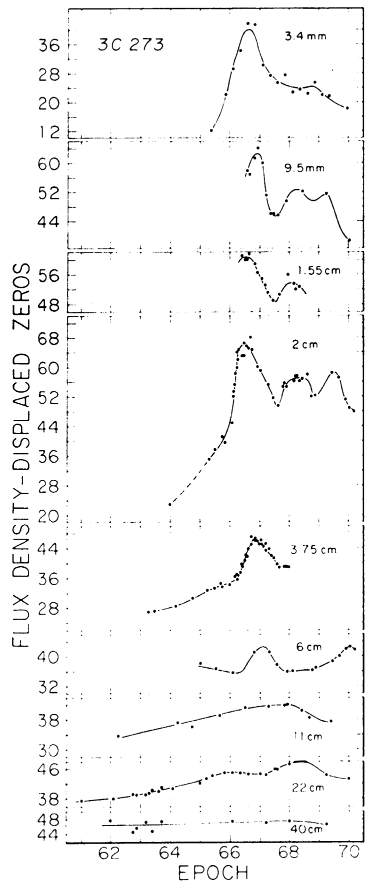

Fig. 8. Intensity variations observed in the QSS 3C 273 at 3.5 and 9.5 mm 1.5, 2, 6, 11, 22 and 40 cm. The axes and the source of the data are the same as in Figure 7 plus Schorn *et al.* (3.5 mm), and Hobbs *et al.* (9.5 mm, 1.5 cm).

of the source where the magnetic field may be expected to be more uniform than when averaged over the whole volume that is involved when $\tau \ll 1$.

Measurement of polarization variations is very difficult, since the polarization is typically only a few percent. Observations of polarization variations by Hobbs *et al.* (1968), Hobbs *et al.* (1969), Olsen (1969), McCullough and Waak (1969), and Aller (1970a, b) generally are consistent with the expanding cloud model, but the uncertainties are large and more accurate observations are still required.

F. RELATION BETWEEN RADIO AND OPTICAL VARIATIONS

Many compact objects also show significant variations at optical or infrared wavelengths as well. It is not clear, however, if there is any relation between the variations observed at optical and radio wavelengths. There is no evidence for any correlation but there are in fact very little overlapping data. One of the best studied sources is 3C 345, for which the observed radio and optical variations are shown in Figure 9. No relation is apparent, but it is clear that considerably more data are required before any conclusions can be made.

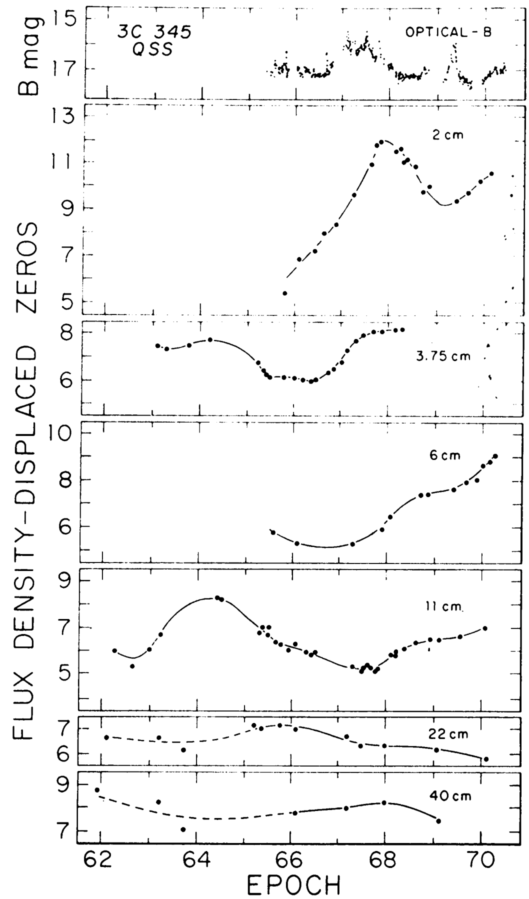

Fig. 9. Radio and optical intensity variations observed in the QSS 3C 345. The axes and radio data are the same as in Figure 7. The optical data are from Kinman (1970).

In general, those sources which have been most active at radio frequencies are those which have been described as also showing large optical variations (e.g. Penston and Cannon, 1968). But there are exceptions such as 3C 273 which has been one of the most active radio sources during the past five years but has had only very small optical variations. On the other hand NGC 4151, which has demonstrated large optical and infrared variations (e.g. Fitch *et al.*, 1967), is a normal weak radio galaxy with no evidence for variable radio emission.

4. The Structure of Compact Radio Sources

It has been realized for some time that radio sources which are opaque at short wavelengths, or which show significant intensity variations, must be very small (e.g. Slish, 1963; Williams, 1963; Shklovsky, 1965). The expected small size has now been directly confirmed using tape recording and radio link interferometers and it appears that of the stronger sources at decimeter wavelengths about 15% have significant structure on a scale of 0.001 arc sec or less (Kellermann *et al.*, 1970). This includes not only QSS but a number of radio galaxies as well.

It is difficult, however, to determine in detail the small scale structure of the sources, since the available interferometer observations are insufficient to allow a full synthesis of the brightness distribution. Although extensive measurements have been made over the wavelength range 6 to 75 cm (e.g. Clark *et al.*, 1968; Kellermann *et al.*, 1968; Clarke *et al.*, 1969; Jauncey *et al.*, 1970; Kellermann *et al.*, 1971) only a crude picture of the small scale structure exists.

These data, together with the measurements of interplanetary scintillations (e.g. Little and Hewish, 1968; Harris and Hardebeck, 1970) indicate a continuous scale of dimensions from 1 to less than 0.001 arc sec. Often sources show up to three or more components which may differ by up to 100:1 in angular dimensions. It is not clearly established whether or not the individual components are spatially separated or are concentric. There is some evidence from the long-baseline interferometer observations made by the Canadian group at 75 cm of component separations in the range 0.01 to 0.1 arc sec, but this is not firmly established (Clarke *et al.*, 1969).

It is clearly very important to measure in greater detail the small-scale structure, particularly to determine the minimum size of the characteristic multiple separated components, and to see whether in fact this type of structure is found in the smallest sources as would be predicted from the theory of Ozernoy and Sazonov (1969).

The core-halo structure described above is found in both radio galaxies and QSS which have flat or complex radio spectra. The smallest components show cutoffs at the shortest wavelengths, as is expected if the cutoffs are due to synchrotron self-absorption. The smallest angular dimensions which are observed are of the order of 0.0004 arc sec or less (Kellermann *et al.*, 1971). The smallest linear dimension which has been directly observed is the source in the nucleus of M87 which contains only about 1% of the total flux density of the galaxy at 13 cm and is about 0.1 pc or less in extent (Cohen *et al.*, 1969). Although no other such small components have been directly observed, it may be inferred from the frequent presence of optically thick radio sources in nearby elliptical galaxies that small intrinsically weak radio sources are not infrequently found in the nuclei of elliptical galaxies (Heeschen, 1970).

Two of the best studied sources are the radio galaxy 3C 84 (NGC 1275) and the QSS 3C 273. Both show the characteristic hierarchal core-halo structure. Figures 10 and 11 show the spectra of the individual components based on published and unpublished long-baseline interferometry measurements made between 6 and 75 cm, conventional interferometry (Ryle and Windram, 1968), observations of lunar occul-

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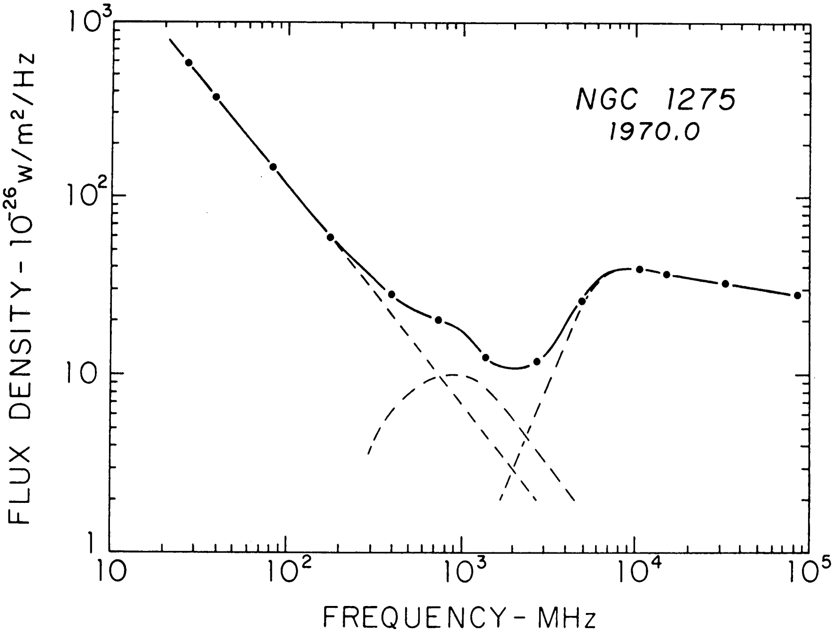

Fig. 10. Radio spectrum of the galaxy NGC 1275 (3C 84) showing the separation into components.

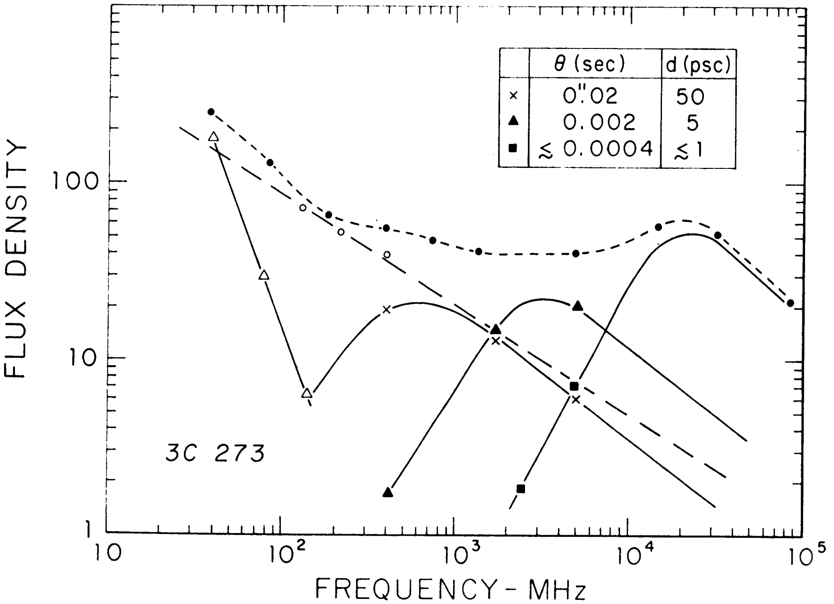

Fig. 11. Radio spectrum of the QSS 3C 273 showing the separation into components.

tations (e.g. Hazard, 1965), and interplanetary scintillations (e.g. Bell and Hewish, 1969). The smallest component in 3C 273 is less than 0.0004 arc sec corresponding to less than 1 pc at a distance of 500 Mpc. This is significantly smaller than the probable dimensions of the optical emission-line region (Bahcall and Kozlovsky, 1969).

The small component in 3C 84 is completely resolved at the longest baselines and appears to be circularly symmetric with dimensions about 0.002 arc sec or 2 light years.

5. Energetics

For those sources where there are accurate measurements of the self-absorption cut-off frequency, ν_c, the peak flux density, S_p, and angular size, θ, it is possible to determine directly the magnetic field strength, B, from the expression

$$B \sim 2.4 \times 10^{-5} S_p^{-2} \theta^4 \nu_c^5 (1 + z)^{-1} \,\mathrm{G}.$$

It must be emphasized that the magnetic field determined in this way does not require knowledge of the distance to the source and is independent of any assumptions of equipartition. The accuracy with which the field strength is determined, however, is poor since it depends on large powers of the measured quantities θ and ν_c.

A. EVOLUTION OF COMPACT SOURCES

Figure 12 shows a plot of self-absorption cutoff frequency, ν_c vs surface brightness, S/θ^2, for radio source components for which there are good observational data. Most sources appear to have magnetic field strengths in the range $10^{-4\pm1}$ G and a peak brightness temperature between 10^{11} and 10^{12} K. This appears to be the limiting brightness temperature of a source of incoherent synchrotron emission from relativistic particles because of inverse Compton cooling (Kellermann and Pauliny-Toth, 1969).

This type of cutoff frequency-surface brightness diagram is a useful way of displaying the evolution of compact radio sources. Individual components are thought to be born in the upper right hand part of the diagram. If the expansion occurs with conservation of magnetic flux, then the peak brightness temperature remains approximately constant (Kellermann and Pauliny-Toth, 1969) and the source evolves toward the lower left part of the diagram.

B. ENERGY REQUIREMENTS

If the distance of the source is known, the energy contained in relativistic electrons, E_e, and in the magnetic field, E_m, may be calculated without any assumption of equipartition between the energy in particles and in the magnetic field. The uncertainties, however, are very great, and depend on approximately the 10th power of the angular size and cutoff frequency (Kellermann and Pauliny-Toth, 1969).

Several investigators have noticed that some sources with small measured size do not show the expected low frequency cut-off and have estimated $10^{-7} \lesssim B \lesssim 10^{-6}$ G and $E_e/E_m \gg 1$ (e.g. Bridle, 1967). More recent measurements, however, indicate that low frequency emission does not come from the small components, which do in fact

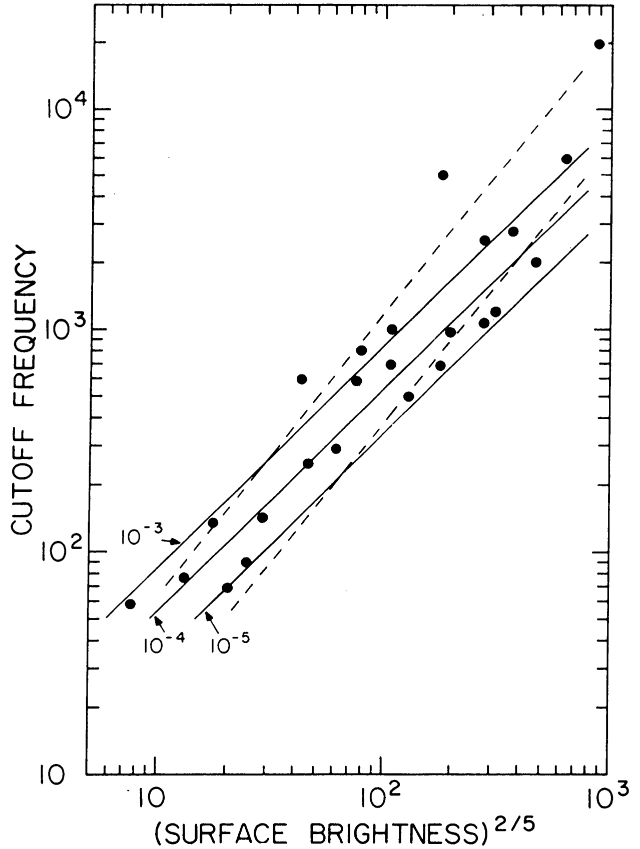

Fig. 12. Relation between observed cutoff frequency and surface brightness. The surface brightness is measured in units of 'flux units arc sec^{-2}'. The solid lines are lines of constant magnetic field strength and the upper and lower dashed lines represent lines of constant peak brightness temperature of 10^{11} and 10^{12}K.

become optically thick at a frequency corresponding to magnetic fields near 10^{-4} G and values of E_e/E_m which do not differ significantly from unity. We must bear in mind, however, that the uncertainty in the value of E_e/E_m is at least a few orders of magnitude.

The total energy in the form of relativistic particles and magnetic field in the small components of radio galaxies such as NGC 1275 determined in this way is about 10^{52} ergs. If the compact QSS are at cosmological distances, their energies are considerably greater and are about $10^{56\pm2}$ ergs. These values are both very much less than the minimum energy of 10^{58-61} ergs estimated for the extended components based on equipartition arguments (e.g. Macdonald *et al.*, 1968). It is therefore clear that it is not possible for a single compact radio source to evolve into an extended source, unless particles are continuously accelerated.

There is, of course, direct evidence of repeated particle accelerations from the observation of intensity variations, and it is clearly important to ask "What is the energy required in a single outburst?". This is difficult to answer, however, since generally it has not been possible unambiguously to resolve the variable components.

A possible procedure in this case is to estimate the maximum linear size from the time scale of the variations, and the limits placed by the light travel-time across the source. Knowing the distance, it is possible to estimate the angular size and thus B, E_e, and E_m. Application of this procedure generally results in relatively weak magnetic fields and the requirement that up to 10^{58} ergs of relativistic particles (Pauliny-Toth and Kellermann, 1966; Moffet, 1966) are repeatedly released in individual outbursts in QSS such as 3C 273 in a time of a few months or less. Not only does this appear to be an unreasonable energy requirement, but because of the high relativistic particle density, inverse Compton radiation causes a very rapid loss of energy (e.g. Hoyle *et al.*, 1966).

C. EXPANSION VELOCITY

Rees (1967), and Rees and Simon (1968) have pointed out that if the cloud of relativistic particles is expanding with relativistic velocity, then because of the finite speed of light the apparent rate of increase of angular size may be very much greater than given by the simple light travel-time argument. E_e can then be reduced by several orders of magnitude for $v/c \gtrsim 0.9$. Van der Laan (1970) has emphasized, however, that there is a limit to the amount that the energy requirements can be reduced since E_m will increase about as rapidly as E_e decreases. The minimum total energy occurs for values of v/c such that $E_m \sim E_e$. In the case of the 1966 outburst in 3C 273 this occurs for $v/c \sim 0.95$ which gives $E_e \sim E_m \sim 10^{54}$ ergs, or about 4 orders of magnitude less than given by the simple light travel-time argument.

Future long-baseline interferometer measurements of variable sources made over a sufficient length of time to determine the expansion velocity will be important in determining whether or not super-relativistic expansion velocities actually do occur. At the present time there are only a few relevant observations, and their interpretation is ambiguous.

The variable component of NGC 1275, which has been steadily increasing in intensity for about 10 years (Kellermann and Pauliny-Toth, 1968), is well resolved at 6 cm and has a diameter about 0.002 arc sec corresponding to a radius of 1 light year. If all the particles were produced when the intensity increase began in about 1960, and if the expansion has been at constant velocity then $v \sim 0.1\ c$. However, the intensity variations show considerable structure (e.g. Hobbs *et al.*, 1968) suggesting recent recurrent activity in this source, so that the 0.002 arc sec component may be considerably younger than 10 yr and thus $v/c > 0.1$.

The only case where direct experimental evidence of a relativistic expansion velocity has been reported is from long-baseline interferometer measurements made at 13 cm (Gubbay *et al.*, 1969) which showed no change in fringe amplitude of 3C 273 during a time when the total flux density decreased by more than 4 flux units. The authors conclude that the variable component was completely resolved by their interferometer and was therefore greater than 0.002 arc sec in diameter in November 1967. They assume that the intensity variations observed at 13 cm between November 1967 and June 1969 are due to the same event which produced the large variations which were observed in 1966 at centimeter wavelength. This event apparently originated in late 1965 (Kellermann and Pauliny-Toth, 1968; Dent, 1968), and therefore was about 2 yr old in late 1967 when the radius of the variable source was greater than 6 light years, and so an apparent expansion velocity of at least 3 times the velocity of light was derived. Figure 8 indicates, however, that the intensity increase observed at the nearby wavelength of 11 cm in 1967 was not of the form expected from the 1965 outburst, but was due to a more slowly varying component, in no way related to the 1965 outburst so that the age estimate of 2 yr is probably incorrect.*

Nevertheless, these measurements do appear to establish the simultaneous presence of a variable component which was resolved by the interferometer and at the same time a smaller unresolved component, which did not vary significantly. In the analysis of intensity variations, it is usually tempting to assume that the most rapid variations occur in the smallest components; the observations of Gubbay *et al.* suggest that this is not always true.

6. Summary

There appears to be no significant difference in the radio emission observed from compact objects such as QSOs or from galaxies, so that it is not possible to distinguish from the radio measurements alone, a galaxy from a QSS. But perhaps more important is the growing realization that the same phenomena are occurring both in galaxies and QSOs.

There is no evidence that the classical theory of incoherent synchrotron emission from ultra-relativistic electrons does not adequately explain all of the observed radio phenomena. In particular there is no evidence for any coherent or collective process as had been frequently suggested (e.g. Ginzburg and Ozernoy, 1966; Papadopoulos and Lerche, 1969).

It is of course widely accepted that the radio emission from extended radio sources is due to incoherent synchrotron emission. The good agreement between observed angular dimensions and those calculated from the spectral cutoff frequency, the limiting observed brightness temperature of 10^{12} K, and the success of the expanding source model in explaining the observed intensity and polarization variations all give weight to the same interpretation of the radio emission from the compact sources.

The energy contained in these compact components is of the order of 10^{52} ergs in the nuclei of galaxies, and considerably more in the QSS if they are at cosmological distances. The variable source observations indicate that energies of this order are released in repeated events lasting from a few weeks to a few years and in volumes of space having diameters of the order of one light year or less across. The observations

* Evidence for a highly relativistic expansion in 3C 279 is given by Moffet *et al.* in this volume, p. 228.

also determine the initial energy index, $\gamma \sim 1.5$ and initial magnetic field $B \lesssim 1$ G.

Further observations of intensity and polarization variations, particularly at short wavelengths corresponding to early epochs after particle generation will help determine more accurately the rate at which particles gain and lose energy and the initial electron energy distribution and magnetic field strength. The direct determination of the size of the variable components using very long baseline interferometry will measure directly the rate of change of angular size and thus the manner in which the magnetic field strength varies with time. By such studies of the behavior of the very young compact radio sources, we may hope better to understand the source of energy and the way it is converted into relativistic particles, and the relation between the quasi-stellar objects and the nuclei of galaxies where these energetic events appear to occur.

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Discussion

Scheuer: Which sources have the smallest diameters you quoted, of about 3×10^{-4} arc sec?

Kellermann: 3C 273, 3C 279, 3C 454.3 and PKS 2145+06 have components smaller than 3×10^{-4} arc sec. 4C 39.25 and 3C 345 also have very small components, but the limits are about 30% greater.

Scheuer: You mentioned a compact source in Centaurus A. Is this the well-known double, or something smaller discovered recently?

Kellermann: Observations with the NRAO 3-element interferometer at 3.6 cm and 11.3 cm indicate a component which is less than about 1 arc sec, is optically thick at centimeter wavelengths, and is a few flux units. There have not yet been any very long baseline observations of Centaurus A, but the large optical depth implies that the angular size is probably about 10^{-3} arc sec.

Felten: You said something to the effect that the occurrence of flat radio spectra among the 'normal' radio galaxies does not imply flat electron spectra, but rather that the electron spectra are all like the galactic cosmic rays; you attributed these flat radio spectra to spatial distribution. Would you add a little more about this?

Kellermann: I said that the flat spectra were due to partial self-absorption and varying optical depth through the source and did not reflect a flat electron energy distribution.

Felten: But you did say that the electron spectra occurring in outbursts of *variable* sources are flatter, $n(E) \sim E^{-1}$. So are you saying that sources can be divided cleanly into these two groups?

Kellermann: Yes.

Noerdlinger: Did your energy estimates include an allowance for relativistic protons?

Kellermann: No, only electrons, that is what we need to explain the observed emission. The amount of energy in protons or the kinetic energy of expansion is another question.

Miss Harris: What is the reality of the low-frequency spectrum component shown in your slide of 3C 273? If real, do you attach any significance to its steep spectrum?

Kellermann: It comes from occultation measurements at Arecibo. I see no reason to question it. The spectrum is very similar to that of the small low-frequency component in the Crab Nebula.

Shakeshaft: The low-frequency component in 3C 273 has been confirmed by Hewish and Bell by means of studies of interplanetary scintillation of source at a frequency of 81.5 MHz.