PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1969 **264**, 251-261
doi: 10.1098/rsta.1969.0021

Extragalactic radio sources in the infrared

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My purpose is to describe the properties of extragalactic radio sources and to emphasize those measurements in the infrared which will contribute to our understanding of these objects. Since most of the radio sources have only been studied down to wavelengths of a few centimetres, and if an optical identification has been made they may also have been studied in the range 0·4 to 1·0 μm, observations at any infrared wavelengths between 1 μm and say 2 mm will be of value. However, only a limited number of radio sources are likely to be detectable with present-day techniques over an appreciable part of this wavelength range. We will endeavour to suggest the types of sources which most merit study and are intense enough to be detected.

Most of the sources which are identified at all can be studied at near infrared wavelengths say extending to 2 μm. Observations in this range are now commonplace. Johnson, Low, Bracassi and their co-workers have obtained extensive data on a number of interesting objects identified with radio sources. Results obtained in the near infrared are discussed more extensively in the lecture by Dr Sciama. The near infrared data can also be used to indicate the more likely objects of interest in the far infrared.

This paper will concentrate on the radio properties which can be used as pointers to interesting objects in the infrared.

Extragalactic radio sources may be more or less arbitrarily divided into five different classes and their main features will now be described.

(*a*) *Normal galaxies*

There is no precise definition of a normal radio galaxy. It can conveniently be described as belonging to a class of galaxies whose radio emitting properties are similar to our own Milky Way System or to M31. The emission comes from the regions of the galaxy occupied by stars and in some cases from a more extensive spheroidal volume surrounding the galaxy, possibly co-extensive with the halo stellar objects of the galaxy or slightly larger. In the Milky Way the major part of the radio energy output comes from a disk component about 500 pc thick and about 25 kpc in diameter. The emission originates more or less uniformly within this volume with some indication of concentration into spiral arms and with a fraction appearing to come from smaller scale structure with dimensions 1 to 100 pc. There is still debate about the existence of a large radio halo surrounding the Milky Way although M31 clearly possesses such a halo with an over-all diameter in the equatorial plane of 65 kpc, and 35 kpc in the polar direction.

The features described above (see for example, Hazard 1963) are those seen at longer wavelengths (*ca.* 1 to 10 m) and originate in the synchrotron emission mechanism. This has been confirmed in the Milky Way by the observed correspondence between the radio spectral index and the cosmic ray spectral index and also by the detection of linear polarization in this emission.

The ratio of radio to optical (photographic) luminosity in a galaxy may be defined formally as $R = m_r - m_{pg}$ where the radio apparent magnitude

$$m_r = -50{\cdot}70 - 2{\cdot}5 \log_{10} S_\nu - 1{\cdot}26 \log_{10} \nu,$$

ν being MHz. Normal spirals are found to have $R \sim 1{\cdot}3^m$ and for irregular galaxies $R \sim +2{\cdot}8^m$. The spectral index α becomes more negative at higher frequencies for most galaxies ($S_\nu = \text{constant} \times \nu^\alpha$).

Normal spiral and Magellanic-type irregular galaxies also contain emission components originating in the thermal interstellar gas. At higher frequencies the thermal emission from ionized hydrogen at 10^4 °K should predominate over the synchrotron component. In the disk of the Milky Way this transition occurs at about 10 cm wavelength. Observations of M 31 indicate that the ionized hydrogen component is less intense than in the Milky Way and that the percentage of ionized hydrogen is less. The ionized hydrogen will emit recombination lines extending from the visible to radio wavelengths. The strongest in the radio domain are the $\Delta n = 1$ transitions of the Balmer series. These lines are weak, amounting to only several per cent of the continuum thermal emission at wavelengths down to 10 cm. At shorter wavelengths the line/continuum ratio increases so that at 0·2 cm the ratio is unity. In the Milky Way the recombination lines are proving useful in investigating the kinetic temperature of ionized hydrogen regions.

The other thermal component of the interstellar gas is neutral hydrogen at a kinetic temperature of about 100 °K. This emits a ground-state hyperfine spectral line at 21 cm wavelength which gives information about the distribution and dynamics of the major component of the interstellar gas. Neutral hydrogen in the ground state has no emission lines in the infrared. However, a number of likely infrared rotation-vibration lines of astronomical interest are emitted from molecular hydrogen.

(*b*) *Irregular galaxies*

Irregular systems divide into two classes. The first which includes those irregulars discussed under the previous heading of normal galaxies are characterized by bright O and B stars and H II regions. The second class of irregulars shows no rotational symmetry, they are not resolvable into stars and often show strong absorption. They are an enigma.

An interesting object in the second class is M82 (3C231) which emits more strongly at radio wavelengths than a normal galaxy. The optical object shows radial filaments emitting intensely in Hα. Burbidge, Burbidge & Rubin (1964) estimate that 10^6 $M_\odot$ of gas is being ejected outwards at velocities of up to 450 km/s. This corresponds to a kinetic energy of *ca.* 2×10^{55} erg which was probably released $(2–3) \times 10^6$ years ago. In addition to line emission there is background continuum emission near the main body of the galaxy which is more than 50 % linearly polarized; this is possibly optical synchrotron emission.

The radio emission from this galaxy comes from a region of limited extent about 30 sec arc in diameter lying at the centre of the object. The object has a flux density spectral index of -0.17 at frequencies below 1000 MHz but this increases to -0.57 at 6000 MHz. The spectrum has the characteristics of synchrotron emission. It should be emphasized that the radio source is much smaller than the area covered by the optical filaments and possibly represents a later explosive phase of M 82.

Infrared measurements of this nearby galaxy are necessary to understand the various components of its electromagnetic spectrum. The spectral index is certainly not constant between optical and radio wavelengths as was thought by Lynds & Sandage (1963). Measurements at higher frequencies than were available to these authors have shown a turnover in the spectrum around 6000 MHz. If this high-frequency slope persists to even higher frequencies then the optical spectrum must rise to a maximum in the infrared.

(c) *Seyfert galaxies*

A class of galaxies was described by Seyfert which had intense nuclei of small dimensions. Some of these co-called Seyfert galaxies radiate more strongly at radio wavelengths than normal galaxies. The best known objects of this class are NGC 1068 (3C 71), NGC 1275 (3C 84) and NGC 4151. Since NGC 1275 has been extensively studied at optical and radio wavelengths and moreover since it has an electromagnetic spectrum which is very interesting in the infrared region it will be discussed in some detail.

Three components of this radio source can be distinguished. One component is very large having a diameter of about 30 min arc; its spectrum is steep ($\alpha = -1.25 \pm 0.10$) and it dominates the low-frequency part of the spectrum which is shown in figure 1. A second is about 10 sec arc in diameter and is presumably a younger source with a spectral index $\alpha = -0.62 \pm 0.03$. A third component has not been resolved on an interferometer baseline of 127 km at 6 cm wavelength and is thus smaller than 0.025 sec arc. At 54 Mpc the distance of NGC 1275 this corresponds to a diameter of $\leqslant$ 6 pc. This small diameter component seen at the higher frequencies is probably responsible for the high-frequency turn-up in the spectrum. The possible significance of this turn-up will be discussed in a later section.

Recent observations of NGC 1275 at centimetre wavelengths have shown it to be variable in time. In the period 1964–66 its intensity increased at the rate of 10 to 20 % per annum in the frequency interval 5000–10 000 MHz. Such variability is consistent with the small linear diameter of this source. Optically NGC 1275 also shows signs of recent activity.

The other two Seyfert galaxies which are strong radio emitters have quite different radio properties. NGC 1068 has a straight spectrum with $\alpha = -0.55$ up to 1000 MHz and $\alpha = -0.80$ above 1400 MHz, its angular diameter is 7 sec arc. NGC 4151 is of particular interest at infrared wavelengths because the spectral index of its optical emission is not consistent with its having a constant spectral index between optical and radio wavelengths. Observations of this galaxy are plotted in figure 3 and their implications are discussed in a following section.

(d) *Giant radio galaxies*

These objects (see, for example, Moffet 1966) are the most abundant of the strong radio emitters. Their power output is from 10 to 10 000 times that of either normal or Seyfert galaxies. Radio emission from these galaxies often originates far outside their optical boundaries. For example in the case of Cygnus A the radio source consists of two regions separated by 80 sec arc lying either side of the parent galaxy which has an outer diameter of about 20 sec arc. Many giant radio galaxies have this double configuration which suggests an origin in an explosion within the parent galaxy. The associated optical galaxy often shows evidence of violent disruption.

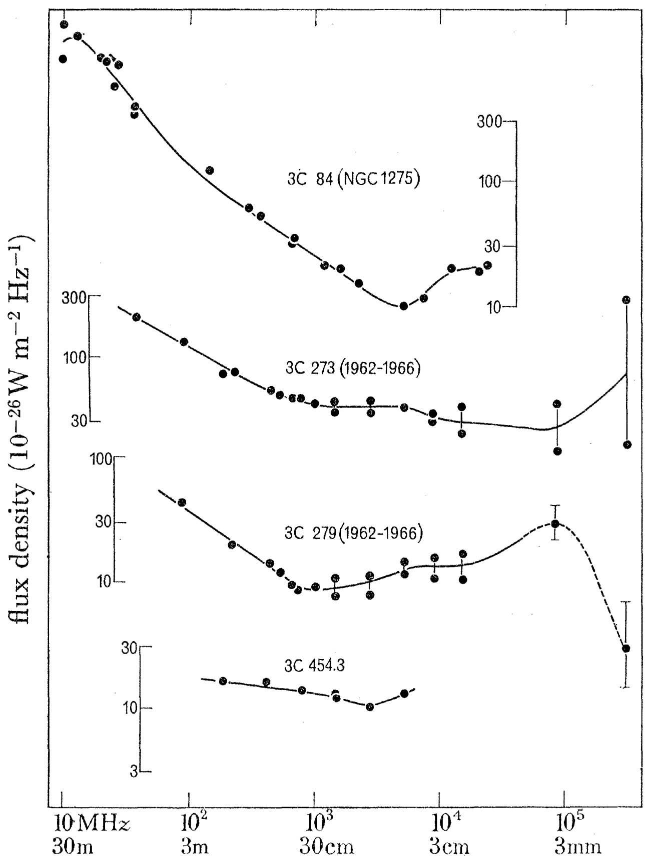

FIGURE 1. The spectra of the four sources 3C 84, 3C 273, 3C 279 and 3C 454·3 plotted where data exists in the wavelength range 30 m to 1 mm. The data for 3C 273 and 3C 279 also indicate the range of variability in intensity seen at short wavelengths during 1962–66. These sources will all be of interest in the infrared.

Spectra of these sources are generally straight or curved in the sense that they show a steeper downward slope at high frequencies. The steepening of the spectrum at higher frequencies may result from synchrotron radiation loss by the relativistic electrons in the source. At the low-frequency end of the spectrum some of the brightest radio galaxies such as 3C 171 and 3C 295 show a turn downwards in their spectra. This is interpreted as synchrotron self-absorption by the relativistic electron gas; it will be discussed below.

The general downward trend in the spectrum of giant radio galaxies towards higher frequencies would seem to make them uninteresting objects in the infrared. Their optical spectra show no peculiarities at the longwave end to indicate anything which would make any of them readily detectable in the infrared. The only source readily detectable is Cygnus A which is the brightest extragalactic object in the sky at centimetre wavelengths. An extrapolation of its flux to 1 mm wavelength would suggest a flux density of only about 5×10^{-26} W m^{-2} Hz^{-1}.

(*e*) *Quasistellar radio sources* (*quasars*)

In 1960 a radio source 3C 48 was identified with a starlike object which was later found to have a redshift of 37 %. A new class of radio object had been recognized; it was always associated with a stellar object which had an excess of blue light (see the review article by Burbidge 1967). In nearly all cases the object had recognizable emission lines which were strongly red shifted. The redshift is most probably cosmological in origin and consequently the objects are at vast distances. There is no radio property unique to the quasars. This class of radio source contains the highest proportion of small angular diameter objects.

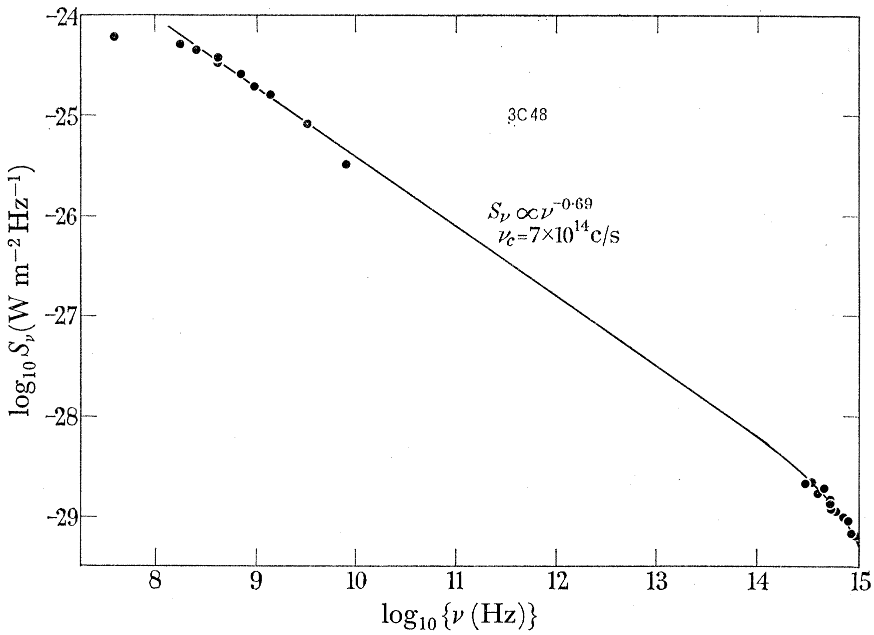

FIGURE 2. The source 3C 48 a quasar which has a radio spectrum typical of most quasars and radio galaxies. The spectrum for synchrotron emission with a spectral index $\alpha = -0{\cdot}69$ and characteristic high-frequency cut-off frequency of $\nu = 7 \times 10^{14}$ Hz is also illustrated. The observed radio frequency spectrum seems to show significant departures from this model.

Quasars are very interesting objects at short centimetre wavelengths and in the infrared. About 10 % show a spectrum at metre wavelengths which falls in the same way as the radio galaxies but which then flattens out or begins to rise again at centimetre and shorter wavelengths. 3C 273 and 3C 279 whose spectra are shown in figure 1 are representative of this group. Most quasars have spectra similar to 3C 48 which has a nearly constant spectral index at radio and optical wavelengths (figure 2).

The long wavelength spectrum and linear polarization of quasars indicate that their emission is generated by the synchrotron process. Although there is no direct proof, their short wavelength enhanced emission is also taken to be synchrotron emission. Its polarization is weak even if it is polarized at all. Interferometer measurements show that the short wavelength emission in many of the sources comes from a very small region. Moreover, the enhanced short wavelength radiation from these sources is commonly variable. This variability is also found optically for several quasars.

A summary of the properties of extragalactic radio sources

Several parameters of the emission from different types of radio sources which are useful in astrophysical discussion will now be given. One is the total light output in the photographic range which can be derived directly from the apparent photographic magnitude and the distance estimated from redshift of the object assumed to be cosmological in origin.

Table 1. Properties of extragalactic radio sources

type of source	absolute photographic magnitude (m)	rate of radio emission (W)	total energy (erg)
normal galaxies, e.g. M 31, M 33	–19·0	10^{32}	10^{55}–10^{56}
irregular galaxies, e.g. M 82	–18·5	10^{33}	10^{56}–10^{57}
Seyfert galaxies, e.g. NGC 1275, NGC 1068	–20·5	10^{33}	10^{56}–10^{57}
giant radio galaxies, e.g. Cygnus A, 3C 295	–20·4	10^{34}–10^{37}	10^{59}–10^{60}
quasars e.g. 3C 48, 2C 273	–24	10^{36}–10^{38}	10^{60} – 10

It can be seen in table 1 that the intrinsic photographic brightness of quasars is 4 to 5 magnitudes greater than that of normal galaxies. Similarly, the rate of radio emission intergrated over the radio spectrum can be estimated for each type of object. This shows that the quasars are the strongest emitters at radio frequencies. If the radio emission comes principally from the synchrotron process it is possible to calculate the total energy in the relativistic electron gas and the magnetic field on the assumption that there is energy equipartition between the relativistic gas and the field. The quasars again have the most energy in gas and field with values of 10^{60} to 10^{62} erg. These values should be compared with the total mass energy of a large galaxy of 10^{11} solar masses which is 2×10^{65} erg. There is thus a very efficient mechanism for producing relativistic electrons and magnetic fields in quasars, particularly so when it is found that the emitting volume is in many cases only several hundred parsecs in diameter and probably contains no more than 10^{9} solar masses. For this reason it could be important to obtain information about quasars over as wide a wavelength range as possible. In several cases the major part of the emission comes from wavelengths shorter than 1 cm.

The spectra of extragalactic radio sources

In the synchrotron process the emission spectrum reflects the relativistic electron spectrum in the following way. If the relativistic electrons have a power law spectrum of the type $N(E)\,\mathrm{d}E = KE^{+\gamma}\,\mathrm{d}E$, where K and γ are constants then the emission will have a power law flux density (S) spectrum of the form

$$S(\nu) = K'\nu^{+\alpha},$$

where K' is another constant and $\alpha = \frac{1}{2}(\gamma+1)$. The radio emission from 3C 48 shows a change from $\alpha = -0.2$ for $\nu \leqslant 200$ MHz to $\alpha = -1.0$ for $\nu \geqslant 3000$ MHz. The data are not consistent with a constant power law over the radio to optical range.

As mentioned above, a number of sources have radio spectra which curve downwards at higher frequencies due to radiation losses by the relativistic electrons. The change in spectral index α expected from this cause is 0·5. The spectra of many sources are consistent with this picture.

At some sufficiently high energy there will be a complete absence of relativistic electrons. This produces an exponential turnover at the high-frequency limit of the synchrotron spectrum where the flux density is given by $S_\nu \propto \exp(\nu/\nu_c)$ at $\nu \gg \nu_c$, where ν_c is this characteristic upper frequency. Figure 2 shows that the optical spectrum of 3C 48 can be fitted by $\nu_c = 7\times10^{14}$ Hz. All sources so far studied appear to have ν_c beyond the upper end of the investigated radio spectrum.

A low-frequency cut-off is also found in many spectra. This can arise in several ways which will be discussed in some detail. This turnover can occur in the interval between optical and radio wavelengths as, for example, in the Seyfert galaxy NGC 4151 illustrated in figure 3. For this source the optical flux density increases towards the infrared but must turn over to fit the radio data. The Parkes source 1934–63 has a clear low-frequency turnover in the decimetre wavelength range (Kellermann 1966). The spectral index at frequencies above 3000 MHz is $\alpha = -1.2$. The one optical point is consistent with this spectral index being maintained into the optical range, although without infrared measurements there is no way of being sure of this.

(*a*) One form of low-frequency turnover in the synchrotron radio spectrum can occur if there is a deficiency of low-energy relativistic electrons. This situation would appear to be somewhat artificial since any statistical process which would produce high-energy electrons would also produce low-energy electrons. The flux density at low frequencies in this case has the form

$$S(\nu) \propto \nu^{\frac{1}{3}}.$$

(*b*) If the brightness temperature of a synchrotron source becomes comparable with the equivalent temperature of the relativistic electrons synchrotron self-absorption will occur at low frequencies. The optical depth τ of this relativistic electron gas is

$$\tau = (\nu/\nu_0)^{+\frac{1}{2}(\gamma-4)}$$

where ν_0 is the frequency at which $\tau = 1$.

The flux density of a source of angular diameter θ is then given by

$$S(\nu) \propto \nu^{2.5}(1-\mathrm{e}^{-\tau})\,\theta^2.$$

Moreover, the following relationship can be deduced involving B the magnetic field strength since ν_0 is a function of B:

$$\theta = 9{\cdot}3\times 10^8 S^{\frac{1}{2}}_{\text{max.}}\nu^{-\frac{5}{4}}_{\text{max.}} B^{\frac{1}{4}},$$

where $S_{\text{max.}}$ and $\nu_{\text{max.}}$ refer to the maximum flux in the spectrum; S is in units of 10^{-26} W m^{-2} Hz^{-1}, ν in hertz and B in gauss. It can be seen that the low-frequency spectral

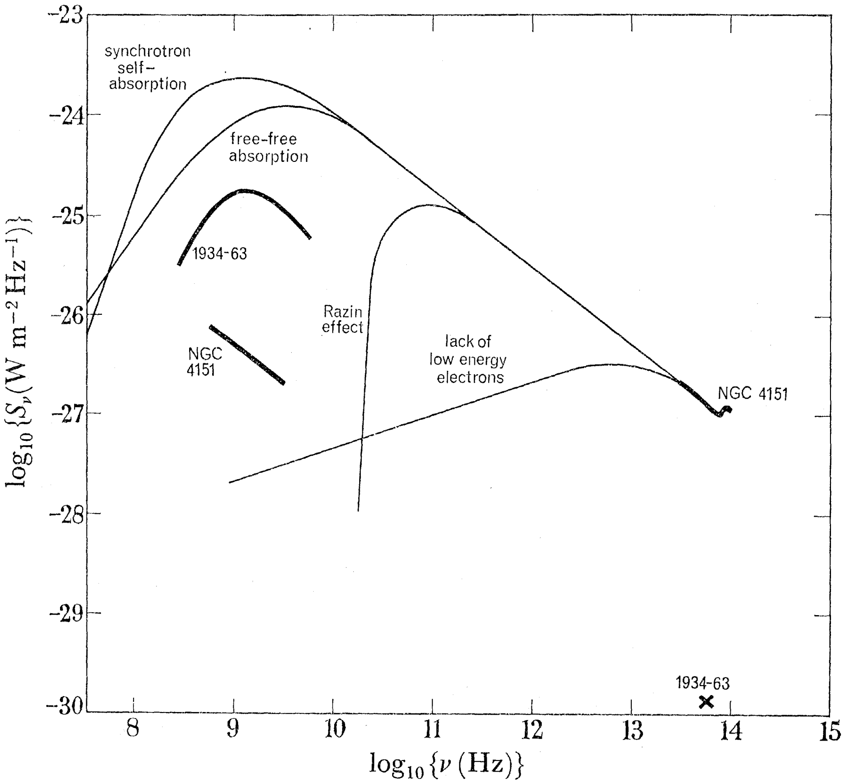

FIGURE 3. The expected spectra of four low-frequency cut-off processes compared with the observed radio and optical data for NGC 4151 and 1934–63. The theoretical spectra illustrate the characteristic shapes resulting from the four processes; the turnover frequency is arbitrarily chosen for each process.

index is $\alpha = +2{\cdot}5$ where the relativistic gas is optically thick. A measurement of the turnover point thus gives a value for $B^{-1}\theta^4$. The observed radio spectrum of 1934–63 illustrated in figure 3 could be fitted with $\theta = 0{\cdot}002$ sec arc if B is taken as 10^{-2} G.

This effect probably explains the low-frequency spectrum in many of the high brightness temperature radio sources. It could also be used to explain the maximum at high radio frequencies or in the infrared in sources such as 3C 273, 3C 279 and NGC 1275—here the angular diameter would have to be smaller and the magnetic field strength higher than in 1934–63.

(*c*) In regions of sufficiently high thermal electron density N_e the refractive index of the medium can become appreciably less than unity at low frequencies and the synchrotron emission process is modified because the velocity of the electrons becomes less than the phase velocity of electromagnetic radiation. The result is a turnover at lower frequencies and is known under the names of the Razin or Tsytovich effect. The flux density varies with frequency in the low-frequency range as

$$S_\nu \propto \nu^{\frac{3}{2}} \exp(-\nu_R/\nu)$$

where the Razin frequency is given by $\nu_R = 20N_e/B$ where N_e is in cm^{-3} and B in gauss. If the spectrum of 1934–63 is to be explained by the Razin effect $N_e = 5\times10^7 B$, so that if $B = 10^{-4}$ G, N_e would be $5\times10^3\ \text{cm}^{-3}$. On the other hand, if the required turnover of NGC 4151 between the optical and the radio was due to this effect then $N_e \sim 10^{10}B$ which is an unlikely situation.

(*d*) The final mechanism to be discussed here which will produce a low-frequency turnover is absorption in an ionized medium within the emitting source or in front of the source. The optical depth τ_ν of an ionized hydrogen region is

$$\tau_\nu = 1{\cdot}6\times10^5\, T_e^{-1{\cdot}35}\, \nu^{-2{\cdot}1}\, E,$$

where the emission measure $E = N_e^2 L\ \text{cm}^{-6}$ pc, T_e is the electron temperature and ν is in MHz.

If the ionized gas is mixed in the non-thermal emission region with a spectral index α the resultant spectrum will be of the form

$$S_\nu \propto \nu^{\alpha+2}(1-\text{e}^{-\tau}\nu).$$

In the case where the ionized material lies entirely in front of the non-thermal source the spectrum will be

$$S_\nu \propto \nu^{\alpha}\,\text{e}^{-\tau}\nu.$$

Thus an ionized medium can produce a low-frequency spectral index of $\alpha+2$ or an exponential spectrum. The 1934–63 data could be explained by absorption by regions with emission measure ranging from $\frac{1}{2}T_e^{\frac{3}{2}}$ to $8T_e^{\frac{3}{2}}\ \text{cm}^{-6}$ pc lying in front of the source. An electron cloud surrounding the source with a diameter of 1 kpc, $N_e \sim 30$ and $T_e \sim 10^4$ °K would give the observed spectrum.

It is seen that several effects can produce a low-frequency turnover in the spectrum of radio sources. The decision as to which effect applies can be made on the basis of the detailed shape of the spectrum if enough such information is available. Considerations of likely conditions within or near the source may lead to accepting or rejecting certain turnover effects. It may even be concluded from a source such as NGC 4151 that there is not enough data, in the absence of infrared measurements to even begin the process of model fitting—indeed the optical spectrum may not even be due to the synchrotron mechanism as has been assumed in the present discussion.

Properties of sources of interest in the infrared

A number of extragalactic radio sources are now known which have normal low-frequency spectra in which the flux density falls with increasing frequency but at higher frequencies the spectral index becomes more positive. Four such sources are shown in figure 2. These and several others are listed in table 2 along with a classification of the objects.

They are all objects likely to have exceptionally high infrared flux densities. The table shows that these sources possess properties that are fairly exceptional. The sources in this list which have been investigated with long base-line interferometers all have very small angular diameters being unresolved with base-lines of several million wavelengths. The corresponding linear diameters have upper limits in the range 6 to 90 pc. In addition, where observations have been made over a time-scale of several years, variability in brightness has been found in both optical and radio wavelengths for most of these sources. Variability on a time-scale of several months to a year suggests that the sources have linear dimensions of less than one parsec or so. Such dimensions are consistent with the observed upper limits on the radio diameters. As may be expected the radio emission is associated with small optical objects—quasistellar objects and the nuclear regions of galaxies.

Table 2. Extragalactic radio sources with concave spectra

source	type of object	z*	linear size (pc)† (upper limit)	variability
3C 84	Seyfert galaxy NGC 1275	0·0172	6	variable in radio
0430+05	galaxy with active nucleus	0·03	24	—
3C 273	QSO	0·158	43	variable in optical and radio
3C 279	QSO	0·538	82	variable in optical and radio
3C 345	SQO	0·595	85	variable in optical and radio
3C 454·3	SQO	0·859	90	variable in optical and radio
1252+11	QSO	0·871	no observations	—
1055+01	QSO	—	< 0·05 sec arc	variable in radio
2247+14	?	—	no observations	

* The red shift $z = (\lambda - \lambda_0)/\lambda_0$, λ and λ_0 are the observed and rest wavelengths respectively.
† The linear size is calculated on the assumption that the red-shift is cosmological.

Conclusion

Measurements in the infrared are essential for understanding the emission mechanisms of a large family of extragalactic radio sources. These include the compact sources which exhibit a turn-up in their spectra at high frequencies. The high-frequency component is probably synchrotron emission from a compact volume with a low-frequency cut-off due to synchroton self-absorption or absorption by ionized gas. A high-frequency synchrotron component clearly extends to optical wavelengths in the cases of the sources 3C 279, 3C 345 and 3C 446 where a high degree of linear polarization has been found. Consequently it is important that polarization studies should be included in infrared measurements

Infrared data are required in the broad untouched part of the spectrum lying between the radio and optical domains of sources such as 3C 48 and NGC 4151 illustrated in figures 1 and 2. It is clear that there must be at least two quite distinct spectral components in sources such as these, one being dominant at radio wavelengths and another at infrared or optical wavelengths.

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