COMPACT RADIO SOURCES

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SUMMARY

The observational data on the radio properties of compact radio sources are presented, including their radio spectra, their occurence, and their structures, as well as the variations of the structures in the "superluminal" sources.

INTRODUCTION

During the past decade, observations made with various antennas, both single dishes and synthesis instruments, have shown that the radio emission from radio galaxies and quasars spans a wide range of dimensions, from a fraction of a parsec in nearby galaxies such as M81, to several million parsecs in the giant radio galaxies such as 3C 236 or DA 240. The range of observed sizes thus extends over at least 9 orders of magnitude. The emission from extended radio sources is dealt with elsewhere (Fomalont, 1980) and we are concerned here with compact sources of radio emission, that is, with emission on linear scales significantly smaller than a kiloparsec, and frequently on a scale of parsecs. The existence of such sources became clear some fifteen years ago, first from the observation that the radio spectra of some objects showed evidence of self-absorption and, second, from the discovery of rapid time-variations in their flux densities (Dent, 1965), both indicating the presence of very small emitting regions.

RADIO SPECTRA

Most of the extragalactic sources found in surveys made at metre wavelengths have radio spectra which can be represented by simple power-laws, i.e. the flux density S depends on frequency ν according to

$$S \propto \nu^{\alpha}$$

where the spectral index, α is typically -0.8. Frequently, the spectrum steepens at short cm wavelengths, that is, α becomes numerically larger. These sources are typically extended, double sources, in which most of

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the radio emission originates in radio-transparent regions some hundreds of kiloparsecs apart. The spectral index, α, is related to the index of the energy distribution of the relativistic electrons, γ, by

$$\alpha = -(\gamma-1)/2$$

The brightness temperatures of the extended regions at centimetre wavelengths are of the order of 10^4 K, but may reach 10^5 K in bright "hot-spots" located at the outer edges of the extended regions. An example of the radio spectrum of such a source is shown in Fig. 1a.

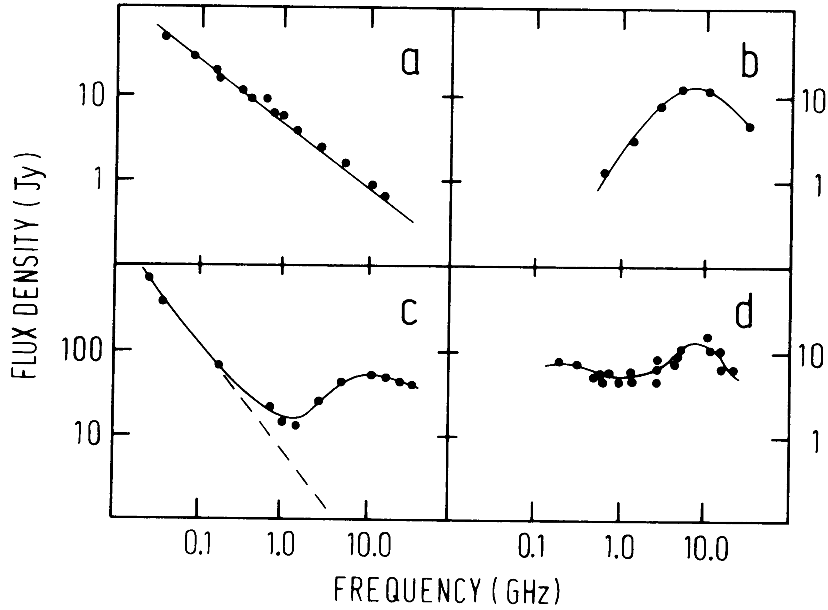

Fig. 1: Four radio spectra: a) 3C 2, a transparent source, b) 2134+004, a self-absorbed, opaque source, c) 3C 84, with both extended, transparent components, and a self-absorbed component, d) 3C 120, containing several self-absorbed components.

The compact sources, on the other hand, are characterised by flat spectra ($\alpha \gtrsim 0$), typically with a cutoff at centimetre wavelengths, below which the source is opaque to its own radiation and the value of α is positive (Fig. 1b). For a homogeneous source and a power-law electron energy distribution, the value of α below the cutoff frequency should be +2.5, but such extreme values have not in fact been observed.

The cutoff frequency, ν_m is related to the flux density S_m (Jy) of the source at that frequency, to the angular size θ (arcsec), and the magnetic field, B (gauss), by

$$\nu_m = f(\gamma)\ S_m^{2/5}\ \theta^{-4/5}\ B^{1/5}\ (1+Z)^{1/5}\ \text{MHz}$$

where Z is the redshift of the source, and $f(\gamma) = 34$ for $\gamma = 1.5$ and 33 for $\gamma = 2.5$. The relation can also be written in terms of the brightness temperature T_m at the cutoff frequency as

$$\nu_m \sim 2.3 \times 10^{-17}\ T_m^2\ B(1+Z)$$

for $\gamma = 1.5$.

A measurement of the cut-off frequency and the angular size can thus be used to determine the magnetic field in the compact sources. For sources having cutoff frequencies in the range $\sim$100 MHz to 10 GHz, the magnetic fields so derived lie in the range 10^{-1} to 10^{-5} gauss and the corresponding brightness temperature between 10^{10} and 10^{12} K (Kellermann and Pauliny-Toth, 1969). No brightness temperatures much in excess of 10^{12} K have been measured directly, and are, in fact not expected to occur, because of the resulting inverse-Compton cooling (Kellermann and Pauliny-Toth, 1969).

In some sources, both extended, transparent components with power-law spectra, and compact, opaque components are present. The resulting spectrum (Fig. 1c) is a power-law well below the cutoff frequency of the compact components, but becomes inverted and reaches a local maximum at the cutoff frequency. If several opaque components, with different cutoff frequencies are present, a complex spectrum results (Fig. 1d)

Some compact sources show flat spectra which are smooth over a wide range of frequencies (Owen et al., 1980). These are probably the result of a gradient in electron density or magnetic field through the source, so that the source becomes opaque over a large frequency range (Condon and Dressel, 1973, Spangler, 1980).

OCCURRENCE

Compact sources are found in both radio galaxies and quasars. Although it is not possible, from the radio spectrum alone, to place the object in one class or the other, statistically, most sources which show flat spectra at centimetre wavelengths are identified with quasars.

The spectral index distribution of radio sources found in surveys at centimetre wavelengths is double peaked: about half the sources have flat spectra ($\alpha \sim 0$) characteristic of compact sources, and half have the steep spectra ($\alpha \sim -0.8$) characteristic of extended sources. Most of the former group are quasars, but a significant fraction ($\sim$16 percent) are identified with radio galaxies (Pauliny-Toth et al., 1978). Optically, such galaxies have bright nuclei and are of the Seyfert or N type. The nucleus contains a compact, opaque radio source which dominates the emission at centimetre wavelengths.

The compact radio sources are opaque and weak at metre wavelengths; sources detected in surveys at these wavelengths are dominated by the emission from the extended regions and have "normal" power-law spectra. Nevertheless, many (perhaps all) of the sources found in such surveys contain compact components with flat radio spectra, located in the nucleus of the optical galaxy, or in the quasar. These "central components" of extended double sources are generally weak at metre and decimetre wavelengths, but become more prominent at short wavelengths. They frequently show time-variations in their flux density (e.g. Hine and Scheuer, 1980) and are in general similar to the stronger compact sources found in short wavelength surveys.

There appears to be a difference in the spatial distribution of sources with flat and steep spectra. For example, quasars with steep spectra ($\alpha<-0.5$) show evidence for strong evolution, in the sense that their space density, or luminosity, was higher at past epochs, whereas quasars with flat spectra ($\alpha>-0.5$) show little, or no evolution (e.g. Schmidt, 1976; Masson and Wall, 1977). The difference is apparent both in the results of the $<V/V_m>$ test (Schmidt, 1968) for the two classes of quasars and in the source counts for sources with flat and steep spectra in centimetre wavelength surveys, where the former show a more rapid convergence at low flux densities than the latter (Kühr, 1980).

SOURCE STRUCTURE

The development of mapping techniques using "closure" phase (Readhead and Wilkinson, 1978) has made it possible to derive reliable maps of compact radio sources on a milliarcsec scale from VLBI data. We may distinguish between sources in which the emission at centimetre wavelengths is dominated by a compact component, and those in which emission from an extended symmetrical double source dominates.

The former class includes the "superluminal" sources and covers a wide range of structures, including core-halo sources, simple doubles, core-jet sources and complex sources. Some typical structures are shown in Fig. 2.

Among core-halo sources are such different objects as the BL Lac-type source OJ 287 and the nucleus of the giant elliptical galaxy M 87. The cores in both have an angular extent of $\sim$0.4 milliarcsec (Kellermann et al., 1977), which corresponds to a linear size of $\sim$1.5 light-months in the latter. Whereas the flux density of the core varies strongly in OJ 287, no variations have been detected in the core of M 87 (Kellermann et al., 1973). The halo sizes are about 10 times larger than the core sizes in both sources. It is interesting to note that although the structure of M 87 on a scale of arc seconds (i.e. of kiloparsecs) is highly asymmetric, the compact nuclear source shows no significant asymmetry.

Examples of simple double sources are the quasars 4C 39.25 and 2134+004. In both sources, the two components are of comparable strength and show cutoffs in their radio spectra between 5 and 15 GHz. Both sources appear to be "stable": the component separations have not changed significantly over several years, although the flux densities of the components have changed (Shaffer et al., 1977, Bååth et al., 1980, Pauliny-Toth et al., in prep.).In the case of 4C 39.25, which has been observed extensively, the upper limit on the rate of separation is 0.2 c, for 2134+004, where the observations are sparser, the limit is 10 c. The magnetic fields derived from the component sizes and cutoff frequencies are in the range 10^{-1} to 10^{-3} gauss, and the brightness temperatures are near 10^{11} K, close to the "inverse-Compton limit".

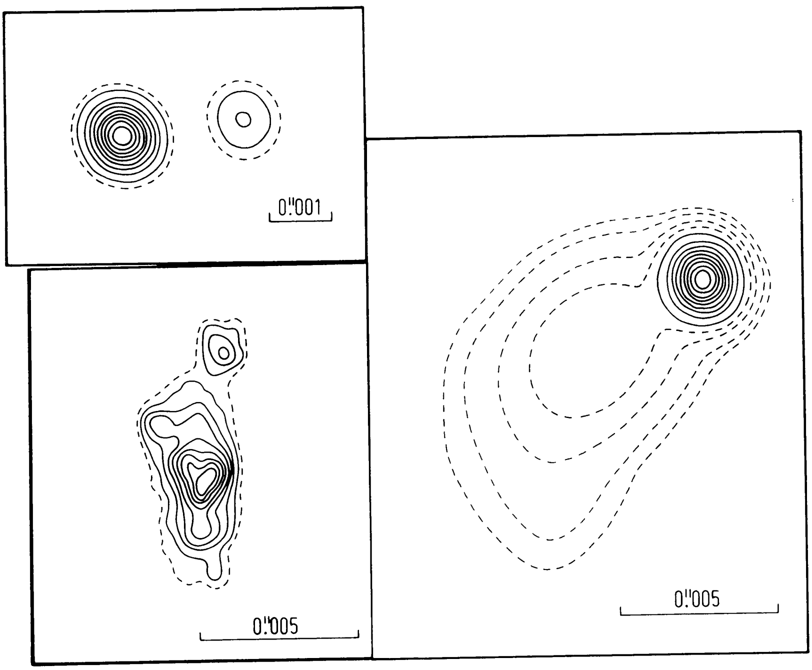

Fig. 2: Structures of 3 compact sources, where emission from the compact structure dominates: left top, 4C 39.25, a stable double source; right, 3C 454.3, a core-jet source with a variable core; left bottom, 3C 84, a complex, expanding source. Maps are at 6 cm wavelength (Pauliny-Toth et al., in preparation).

The highly asymmetric "core-jet" structure appears to be common in the sources with "superluminally" separating components, but is not confined to them. Examples are the superluminal sources 3C 345, 3C 273 and 3C 120 (Readhead et al., 1979), but also "stable" sources such as 3C 147 and 3C 380 (Readhead and Wilkinson, 1980). A characteristic of these sources is a curvature of the jet, with a change of P.A. of up to 40° between the innermost part of the jet and the extended structure (Readhead et al., 1978a). The extended ($\gtrsim$1") structure in these sources is also one-sided. The curvature of the jets has been explained by Readhead et al. (1978) as the amplification of a smaller curvature by projection effects. A further characteristic of the core-jet compact sources is a systematic variation of the spectral index along the source axis: the spectrum of the core is flat, or inverted, and steepens along the jet (Readhead et al., 1979).

A source with a more complex structure is the nucleus of NGC 1275 (3C 84), which has been shown to consist of three main centres of emission, lying approximately in a straight line, the position angle of which corresponds to that of larger-scale structure (Pauliny-Toth et al., 1976b). The three main regions of emission appear to be stationary relative to each other, with an upper limit of 10^4 km sec^{-1} on the relative velocities, but do appear to be expanding at a rate of about 3 x 10^4 km sec^{-1} (Preuss et al., 1979). The rate of expansion, as well as the rate of increase of flux density suggest some "initiating event" in the source about 20 years ago. The limit on the relative motion, the source extent of ∿10 light years and the age of ∿20 years suggest that particles are injected into, or accelerated in stationary regions.

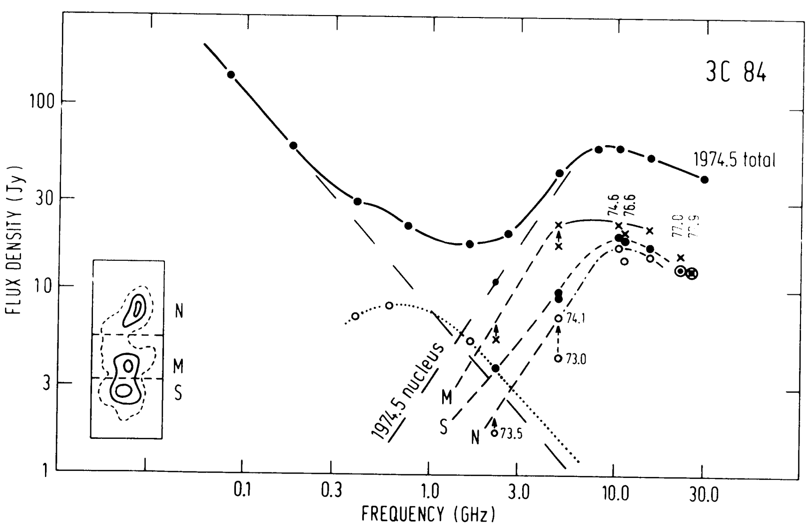

Fig. 3: Spectrum of the compact source in the radio galaxy 3C 84. VLBI data at several wavelengths give spectra for three main emission regions, labelled N, M, and S in the schematic map at the left.

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Maps of the compact source are available at wavelengths between 13 and 1.3 cm, and permit a crude spectrum of the three main emission regions to be derived (Fig. 3). In contrast to the core-jet sources, the nuclear source in NGC 1275 does not show a systematic change in the spectrum along the axis. All three emission regions have similar spectra and all become self-absorbed, the middle region at a somewhat lower frequency than the outer two, implying a lower magnetic field in the central region. The magnetic fields are in the range 10^{-1} to 10^{-3} gauss.

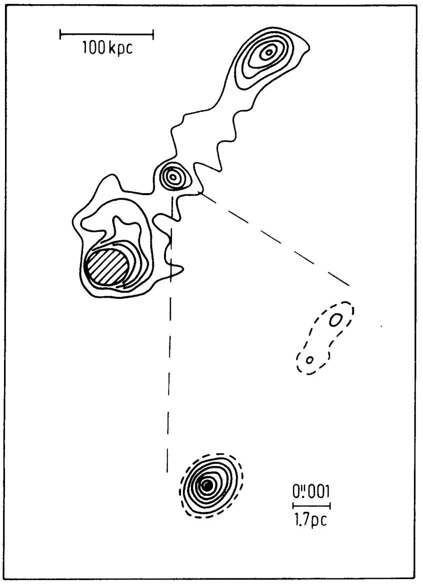
Maps of the compact central components of a number of symmetric, extended double sources are now available. These include 3C 111 (Pauliny-Toth et al., 1976a), 3C 236 (Schilizzi et al., 1979), NGC 6251 (Readhead et al., 1978b), 3C 390.3 (Preuss et al., 1980) and 3C 405 (Kellermann et al., 1980). Figure 4 shows the structure of the central components in the last two of these sources, together with the extended structure.

In spite of the symmetry of the extended double structure, the central components in all these sources show an asymmetric structure, with an extension towards one of the lobes. The compact structure is aligned with the extended structure to within a few degrees, although in the case of 3C 405 (Cygnus A) the deviation is about 10°. This is in contrast to the strong core-jet sources referred to earlier. There is as yet no direct evidence that any of these central components show superluminal expansion. The alignment, which extends from scales of $\sim$1 pc to $\gtrsim 10^{6}$ pc shows that the directive mechanism acts over a large range of dimensions and over long times.

SUPERLUMINAL SOURCES

In four radio sources, the quasars 3C 273, 3C 279 and 3C 345, and one radio galaxy, 3C 120, VLBI observations have shown that the components separate at rates which, when translated into linear velocities, appear to exceed the speed of light.

In 3C 345, the compact core consisted of two components, of approximately equal strength at short centimetre wavelengths, in 1974 (Shaffer et al., 1977). VLBI observations between 1970 and 1976 showed that the components separated at a constant rate of 0.17 milliarcsec per year (Cohen et al., 1977), the corresponding linear velocity being 6.7 c (H_o = 55 km s^{-1} Mpc^{-1}, q_o = 0.05). There was no dependence of the separation on the wavelength of observation. After 1976, the structure of the source changed, and one of the components became weaker, until, in 1977, the structure was of the core-jet type (Readhead et al., 1979; Cohen et al., 1979) and the rate of separation seemed to have decreased, or stopped. Data obtained at wavelengths of 1.3 cm and 6 cm in 1978/1979 (Bååth et al., 1981; Kellermann et al., 1981) show that the separation of the brightest regions in the source was $\sim$1.3 milliarcsec, rather than the 2.2 milliarcsec expected from an extrapolation of the data of Cohen et al. (1977). Possibly, this may represent a new "event" in the source.



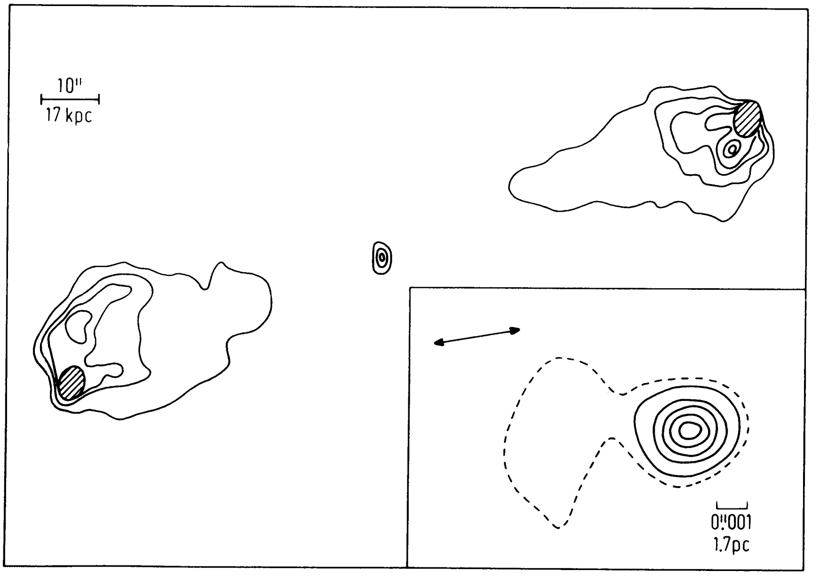


Fig. 4: VLBI maps of the central components in the galaxies 3C 390.3 (top) and Cygnus A = 3C 405 (bottom), shown together with the extended double structure. The extended structure is adapted from Harris (1972) and Hargrave and Ryle (1974); the VLBI maps are at 2.8 cm wavelength, from Preuss et al. (1980) and Kellermann et al. (1980).

3C 273 has a complex structure, consisting of three compact components and a large "jet-like" structure ∿7 milliarcsec (50 pc) away, in the direction of the optical jet. Cohen et al. (1977) derived a separation rate for the components of 0.32 milliarcsec per year, or 4.2 c, from the movement of the first minimum of the visibility function in the Fourier transform plane. This represents the relative motion of the main centres of emission in the source. Again, the structure appears to have become more asymmetric in 1976/1977, although the expansion appears to have continued (Cohen et al., 1979).

3C 120 has shown several outbursts in the total flux density between 1970 and 1978 and at least two clear cycles of expansion. The separation velocities for these were 5 c and 8 c (Cohen et al., 1977). Recently, activity in the source has decreased and the structure is of the core-jet type (Readhead et al., 1979).

3C 279 has not been observed as intensively as the other three sources. Cotton et al. (1979) have analysed data taken between 1970 and 1972 and have shown that they were consistent with a double source, with components separating at a rate of 21 c. Data taken between 1972 and 1974 show that this expansion continued, but that the source was now triple, with the most compact components separating at a rate of ∿40 c (Pauliny-Toth et al., in preparation).

In the cases where more than one "event" or cycle of expansion has occurred (3C 120, 3C 279) the motion has been along the same position angle. The rates of separation for different events in the same source are, however, different. This places restrictions on possible theoretical models for the sources, as discussed elsewhere (Kellermann, 1980).

Further restrictions on theoretical models are placed by the "stationary" sources. For example, the sources 4C 39.25 and 2134+004 have structures and luminosities similar to that 3C 345 had at one stage in its expansion, yet do not expand superluminally.

Yet another problem are the central components of symmetric doubles. They appear to have the one-sided structure typical of the core-jet and superluminal sources. The one-sided structure is unlikely to be the result of relativistic motion nearly along the line of sight, since the compact structure is aligned with the outer lobes, and the latter are not likely to have a preferential orientation along the line of sight. The detection of superluminal motion in such sources would exclude any model which requires a special orientation of the source with respect to the observer.

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