Structural variations of extragalactic radio sources over large frequency ranges

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Summary. I study the frequency variations of the structures of extragalactic radio sources by comparing 81.5-MHz interplanetary scintillation data and 408-MHz long-baseline interferometer visibilities with 5-km telescope results at 5 GHz. Over the range 81.5 MHz–5 GHz, extended components (≥2 arcsec) are generally more dominant at the lower frequency. Over the range 408 MHz–5 GHz, there is good evidence for the existence in some cases of extended, steep-spectrum regions which are visible at 408 MHz but which contribute a negligible fraction of the flux at 5 GHz.

1 Introduction

Frequency dependence of the structure of radio sources is to be expected for at least two reasons. Firstly, current radio source models, including both slingshot (Saslaw, Valtonen & Aarseth 1974) and beam (Rees 1971; Scheuer 1974; Blandford & Rees 1974) models, call for the energy within the extended ‘tails’ of the outer components of a double radio source to be continuously supplied through the compact ‘heads’ associated with these regions. Since the relativistic particles responsible for the synchrotron emission from extended regions are older than those in the compact regions, the extended components are expected to have the steeper high-frequency radio spectra because of synchrotron losses. Secondly, the more compact features will become synchrotron self-absorbed at higher frequencies than the extended regions, and so should have the flatter spectra at low frequencies.

Because of poor angular resolution at low frequencies, there has until recently been no general way of comparing spectral indices of different components of a radio source over a large frequency range, although various authors have compared structures of a few sources usually either at close frequencies or with poor resolution. Much of the existing evidence for such changes in structure relates to the weaker, more diffuse sources. Thus, Jaffe & Perola (1973) show for the ‘head–trail’ type of radio-galaxy (3C 129, NGC 1265) that the 408–1407-MHz spectrum steepens along the trail; in addition, 3C 465 is well known to exhibit spectral steepening along its length (Riley & Branson 1973). Where data are available for the stronger sources, which exhibit head–tail structure, the same pattern is followed in some cases, such as Cyg A, for which the spectral index of the tails from 2.7 to 15 GHz is about 0.5 greater than that of the heads (Hargrave & Ryle 1974, 1976), whereas in others
the expected change of structure with frequency is absent: for example, the structure of 3C 61.1 is the same from 1.4 to 5 GHz (Branson et al. 1972), and there is no change in the lengths of the tails of 3C 172 between 327 MHz and 5 GHz (Jenkins & Scheuer 1976).

Clearly it is important to establish for a large number of radio sources whether or not the structures are frequency-dependent and in this paper I present the results of two different methods of comparing source structures at widely-spaced frequencies, which establish the general existence of structural changes with frequency.

2 Structural changes over the frequency range 81.5 MHz—5 GHz

2.1 Method

The determination of radio source structure by interplanetary scintillation (IPS) has been discussed by Little & Hewish (1966) and Readhead (1971) among others. 81.5-MHz IPS provides a measure of the flux density associated with all components of a source which are smaller than about 2 arcsec. The ratio $R_\nu$ of this flux density at frequency $\nu$ MHz to the total flux density $S_0$ of the source is given (Readhead & Hewish 1974) by

$$R_\nu^2 S_0^2 = \Sigma S_0^{i/2}$$

(1)

where the summation extends over the $i$ components of the source smaller than 2 arcsec. Size-dependent weighting factors on the right-hand side are unknown; I neglect them for the present and comment in the next Section on their relevance.

Since 2 arcsec is comparable to the resolution of the 5-km telescope at 5 GHz, maps made with the latter permit identification of components small enough to scintillate at 81.5 MHz. Thus from 5-km maps at 5 GHz it is possible to estimate $R_{5000}$, which can then be compared with $R_{81}$ measured by IPS. It is clear that a difference between $R_{81}$ and $R_{5000}$ indicates a difference between the mean spectral indices of compact and extended features: if $R_{81} < R_{5000}$, the compact components have flatter spectra and vice versa.

2.2 Results and Discussion

The values calculated for a sample of 64 sources, mapped by Pooley & Henbest (1974) and Riley & Pooley (1975), are given in Table 1. Column 1 gives the source number, column 2 the value of $R_{5000}$, column 3 the value for $R_{81}$ and column 4 the scintillation class of the source (which is a measure defined by Readhead & Hewish (1974) of the quality of their IPS data). Where there is doubt as to whether or not components on 5-km maps will scintillate, column 2 gives an upper limit to $R_{5000}$. The few triple sources, which have dominant central components at 5 GHz, have been excluded from this sample because the central components are already known to have very flat high-frequency spectra and their low-frequency behaviour is uncertain: their presence would confuse the results for the remainder of the sample.

Fig. 1 is a plot of $R_{81}$ against $R_{5000}$ for all the sources in the sample. It is immediately apparent that there is a trend for points to lie below the line $R_{81} = R_{5000}$: most of the points above this line represent poor scintillators (class C) or non-scintillators (class N) and are upper limits for $R_{81}$. These naturally tend to lie near $R_{5000} = 0$ as there is little flux from structure < 2 arcsec in size.

There are two possible reasons for this result. Firstly, it could be an instrumental effect related to the factors ignored in equation (1). For example, a core—halo source with two components 0.2 and 1 arcsec in size would be unresolved by the 5-km telescope, but the smaller component would scintillate much more strongly than the larger component. The
### Table 1.

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**Note:**
- Scintillation class: A, B, C, P, N, Non-scintillator
- Error on $R_{81}$: 15 per cent, 25 per cent, 40 per cent, 50 per cent
- Errors in $R_{5000}$ are typically about 20 per cent.

Scintillations of the larger component are then masked by those of the smaller, and the observed value of $R_{81}$ is correspondingly reduced (Hewish & Readhead 1976). The magnitude of the effect would depend on the size, $\theta$, of the source estimated from IPS, and a correlation between $R_{5000}/R_{81}$ and $\theta$ would be expected. No correlation can be seen in a plot of $\theta$ against $R_{5000}/R_{81}$ (Fig. 2); this is not therefore the main effect, although it cannot be ruled out as a possible contribution.

The differences between $R_{81}$ and $R_{5000}$ may alternatively be ascribed to differences in spectral index between scintillating and non-scintillating components. Let this difference be $\Delta \alpha$, defined so that $\Delta \alpha > 0$ means that the extended regions have the steeper spectra. $\Delta \alpha$ is then related to the number, $N$, of scintillating components (assumed identical) and the ratio, $K = (81/5000)$, of the two observing frequencies by

$$\Delta \alpha = \frac{\log [(R_{81}/R_{5000}) - R_{81}N^{1/2}] - \log (1 - R_{81}N^{1/2})}{\log K}.$$
Figure 1. A plot of $R_{81}$ against $R_{5000}$ for the whole sample of sources. The line drawn is for $R_{81} = R_{5000}$. The symbols relate to the scintillation class of the source as follows: X class A; • class B; ○ class C; □ class P; ◊ class N. Arrows denote limits.

Figure 2. A plot of size of scintillating component, $\theta$, against $R_{5000}/R_{81}$ for the class A, B, and C scintillators. The symbols are the same as those for Fig. 1.
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Δα is fairly sensitive to the values of R₈₁, R₅₀₀₀ and N, and so the errors in evaluating it are generally quite large: in any case, the components are not all equal and the formula is not strictly valid. However, for a typical source with R₈₁/R₅₀₀₀ = 0.7, R₅₀₀₀ = 0.6 and N = 2, Δα ≈ 0.2.

Such a spectral index difference may be ascribed to two causes, already mentioned in the Introduction:

(i) Synchrotron losses in the extended regions. With Δα = 0.2 and a magnetic field of 3 × 10⁻⁶ G, and assuming continuous injection of relativistic particles, a source age of ~ 5 × 10⁶ yr is obtained. This is similar to previously suggested source ages (e.g. Hargrave & Ryle 1974; Hargrave & McEllin 1975). However, Scott & Readhead (in preparation) show that there are no significant differences in average high-frequency spectral indices for strong (R₈₁ > 0.4) and weak (R₈₁ < 0.2) scintillators and conclude that the ages of strong and weak scintillators are not very different. Thus it is improbable that the spectral index differences are due to synchrotron losses in the extended regions. The spectral index difference, if it exists, is probably due to

(ii) Synchrotron self-absorption in the compact components, which causes a flattening of their spectra at low frequencies: strong scintillators do have flatter low-frequency spectra on average than weak scintillators (Scott & Readhead, in preparation).

4 Comparison of data from Jodrell Bank and the 5-km telescope

4.1 Method

I use mainly 408-MHz data from the Jodrell Bank (JB) Mk I–Mk III interferometer (Rowson 1973), a single-spacing instrument oriented roughly north-east—south-west, and 5-GHz data from the Cambridge 5-km telescope (Ryle 1972), which is nearly east—west and provides 16 different spacings simultaneously.

The 5-km telescope provides all the amplitude and phase information to map the sources under consideration. It is therefore possible to find a range of baselines and hour angles for which the instruments have the same baselines (expressed in terms of the observing wavelength) projected in the direction of a given source. The interferometer visibilities at these baselines may then be compared to search for structural differences over the range 408 MHz to 5 GHz. These spacings may involve all hour angles, including those between 06 and 18 hr, and the Jodrell Bank telescopes can track a source for a greater part of this range than the 5-km telescope, which is limited to the range 18–06 hr. However, the 5-km telescope is sufficiently near the east—west direction that the visibilities at hour angles Hₑ and (Hₑ + 12 h) (suffices C and J will be used throughout to denote Cambridge and Jodrell Bank) would be the same were both available, except for sources near dec 0°. For an east—west interferometer, such a difference in hour angle merely changes the interferometer phase by 180°. Thus, where necessary, the values of Hₑ required have been adjusted by 12 hr.

Sources were chosen from the 3CR catalogue on the basis of:

(i) the quantity of JB data available — often sources were only observed for short periods;
(ii) the precision of visibility measurements at both JB and Cambridge. The integration time used for the JB observations was only 10 min and so the Cambridge visibilities were smoothed for this period; thus only fairly strong sources are suitable for consideration;
(iii) availability of 5-km amplitude and phase plots. A minor consideration is that at high declinations the telescopes rarely have the same projected baselines, while at low declinations, the projected baselines all have similar position angles. Also, for low-declination sources, the slight departure of the Cambridge instrument from the east—west direction

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Figure 3. Polar plots of the visibilities at 5 GHz ($\gamma_j$) and 408 MHz ($\gamma_c$). The filled circles are for fringe periods of 6–8 arcsec, and the open circles for >8 arcsec and up to 24 arcsec in the worst case. Note that the resolution is the same for corresponding points on the pairs of diagrams. The outer circle corresponds to unit visibility.
means that the alteration of hour angles by 12 hr is not strictly valid. Sources at declinations between 15° and 60° were thus preferred.

4.2 Results

The results are displayed in Fig. 3 as polar graphs of visibility, $\gamma$, against position angle: each pa is that of the baseline projected onto the sky, and the visibility is given by the length of the radius vector. The minimum fringe spacing is 6.5 arcsec: points with fringe spacing worse than 8 arcsec are plotted as open circles in the diagrams. It must be emphasized that the resolution is not the same for all the points on the diagrams, although it is the same for corresponding points on the pairs of diagrams, which are thus useful for comparative purposes. Since the phase of the signal does not affect these results, the diagrams must show symmetry about the origin, and each point has accordingly been plotted twice. The lines shown have been fitted by eye to the filled circles. Because of the 180° ambiguity, all position angles given in the text have been reduced to the range $-90°$ to $+90°$.

JB calibration errors are stated to be $<10$ per cent, and systematic errors in the 5-km visibilities should be $<10$ per cent: the total systematic error in $\gamma_j/\gamma_c$ is thus less than about 15 per cent.
Figure 4. 15-GHz map of 3C 380. The beam is 0.65 x 0.95 arcsec. The cross marks the position of the 17-mag QSO (Argue & Kenworthy 1972).

The JB fringe visibilities have been taken from the JB Annals (Wraith 1973; Wilkinson 1973; Wilkinson, Richardson & Bowden 1974a). The data concerning source maps at 5 GHz are either from Pooley & Henbest (1974) or from Jenkins, Pooley & Riley (in preparation). The interplanetary scintillation data are from Readhead & Hewish (1974).

4.3 Comments on the Sources

4.3.1 3C 380

This source has also been observed at 15 GHz with the 5-km telescope and the map is shown as Fig. 4. It is a double of separation 1.2 arcsec in pa – 37°. From the plots of \( \gamma_j \) and \( \gamma_c \) against pa – Fig. 3(a) – it can be seen that there is a large discrepancy between the 408-MHz and 5-GHz visibilities near pa 90°, whereas good agreement obtains near pa 10°.

The 408-MHz visibility has a peak of 0.9 near hour angle 15.5 and drops to 0.3 at other angles. This is interpreted (Wilkinson, Richards & Bowden 1974b) as being due to a source with \( \sim 30 \) per cent of the flux at 408 MHz coming from an unresolved \(< 1.5 \) arcsec core and \( \sim 70 \) per cent from a halo 7 x 3.5 arcsec in pa – 67°. The 5-GHz visibilities do not change much either with spacing or with hour angle, and are not consistent with the source structure observed at 408 MHz, but are consistent with the 15-GHz structure with the possible addition of a small \(< 2 \) arcsec ‘bridge’ of uncertain flux density.

The source is not significantly resolved with the Cambridge One-Mile Telescope at either 408 or 1407 MHz, \(< 5 \) per cent of the flux coming from regions larger than \( \sim 11 \) arcsec at 408 MHz and 3 arcsec at 1407 MHz.
For compatibility with the JB 1407-MHz observations, the width of the extended region must be > 1 arcsec at this frequency, and the region must give rise to 40 per cent of the source's flux.

Thus the extended region has the following characteristics:

(i) 81.5 MHz (IPS): 65 per cent of the total flux,
(ii) 408 MHz: 70 per cent of total flux, size $7 \times 3.5$ arcsec,
(iii) 1407 MHz: 40 per cent of flux, size $< 3 \times$ between 1 and 3 arcsec,
(iv) 5 GHz: $< 5$ per cent of flux in the extended region.

The region is extended along $\alpha - 70^\circ$ approximately, which is significantly different from that of the double source observed at 15 GHz.

Thus the spectral index (defined by $S \propto \nu^{-\alpha}$) for the extended region is greater by one than that for the whole source. The ends of the region have steeper spectra than the parts near the middle — possibly the 2-arcsec component observed at 5 GHz (also visible at 2.7 GHz with the 5-km telescope) is the remains of the extended region when the outer parts have become too faint to see. The source is a weak (class C) scintillator, and the 81.5-MHz result is probably consistent, within the errors, with a large fraction of the flux originating in the non-scintillating component. Further evidence for the existence of extended regions with steep spectra is provided by the visibilities measured at 158 MHz (Allen et al. 1962) and the 38-MHz observation by Slee & Wraith (1967). Allen et al. suggest a size of between 5 and 11 arcsec at 158 MHz with possibly 10 per cent of the flux coming from a small core; Slee & Wraith, using baselines of between 14 000 and 16 000 $\lambda \lambda$, find a 38-MHz visibility $< 0.4$.

It is not obvious on current source theory why the region should have a steeper spectrum towards the ends although this effect is seen in at least one other source, 3C 465 (Riley & Branson 1973). If the halo is a remnant of a previous burst of activity of the source, then both beam and slingshot models predict that the ends of the region are younger than the parts near the centre of the radio source, so the spectrum should steepen in the middle. Perhaps some relativistic electrons leak from the current regions of activity into the region remaining from previous activity: this could counteract the steepening expected from synchrotron losses and give the observed spectral changes; or there may have been several outbursts, each one reaching to a smaller extent than the last.

4.3.2 3C293

Polar plots of $\gamma_j$ and $\gamma_c$ are given in Fig. 3(b). The source is weak ($S_{5000} = 1.7$ Jy) and the $\gamma$'s are correspondingly uncertain. The 408-MHz plot is characteristic of that for a close double together with a well-resolved halo: the JB 408 MHz model is a core–halo source unresolved in $\alpha - 1^\circ$, which is not completely consistent with the data, although in his comments on the source, Wilkinson (1972) suggests that about 20 per cent of the 408-MHz flux is missing. At 5 GHz, the source is resolved into a double in $\alpha - 85^\circ$ (it has a size 2.2 arcsec) but not appreciably in $\alpha 5^\circ$. The differences between $\gamma_j$ and $\gamma_c$ may be explained by putting 40 per cent of the 408-MHz flux into a component extended along $\alpha 30^\circ$. If the extended region contributes <10 per cent of the 5-GHz flux, then its spectrum must be $\sim 0.5$ steeper than the overall spectrum for the source. IPS suggests 60 per cent of the flux comes from a non-scintillating component at 81.5 MHz. This implies a spectrum $\sim 0.3$ steeper for the extended component than for the integrated spectrum — very close to the difference over the range 408 MHz to 5 GHz.

Thus it appears likely that, as in several of the other sources considered in this paper,
there is a halo with a relatively steep spectrum around the source. It is difficult to say
whether or not this component is related to the faint component with a steep spectrum
detected by Branson et al. (1972) at 5 and 2.7 GHz. Alternatively, the difference between
the γ plots may be explained by each component having an extension perpendicular to the
axis of the main source at 408 MHz but not at 5 GHz. This explanation also involves the
existence of regions within the source with steep spectra.

4.3.3 3C19

This source is well resolved by the 5-km telescope into two components of separation about
5.5 arcsec, with about 30 per cent of the flux coming from an extended bridge of emission.
The interpretation of the results presented is correspondingly more difficult. Fig. 3(c) pres-
tsents the polar plots of γ₁ and γₑ. The four lobes in the γₑ plot are due to the combination
of the extended region and the double components. The maxima near pa = 60° occur when
the baseline is perpendicular to the source axis, and the source is unresolved. The bridge
alone would give a smooth variation between the maxima, with no further maxima in the
plot (as does γ₁). However, the separation of the double components at 5 GHz is compar-
able to the fringe spacing involved here, and so there is an additional pair of maxima. These
would occur when the baseline is at right angles to the other maxima, but the extended
region has a perturbing effect and shifts the position slightly. The difference between the
plots could exist because the effective centres of emission of the components have moved
between the two frequencies. The source is a weak (30 per cent) scintillator. The results
may be most easily explained if the bridge of emission is more prominent in the source at
the lower frequency than at the higher: this will shift the centres of emission in the required
manner.

4.3.4 3C216

Polar plots of γ₁ and γₑ are given in Fig. 3(d). The plots are similar, except that the source
is more resolved in pa 60° at 408 MHz than at 5 GHz, and also the source structure appears
to have rotated by about 15° between the two frequencies. The source is clearly resolved in
pa 50° at the lower frequency, and in pa 30° at 5 GHz. Thus there may be an extended
region aligned along pa 50° at 408 MHz. This would be misaligned with the high-frequency
structure: such misalignment is remarked on in connection with 3C 380 (Section 4.3.1).

At 408 MHz, about 35 per cent of the flux must come from a region > 7 arcsec along
pa 50°, while only ~ 20 per cent of the 5-GHz flux can come from such a region. This
assumes that the central ‘core’ remains unchanged in shape, although since its size is < 0.7
arcsec such a change would have a small effect. The source is a good (70 per cent) scintillator.
The observations may be accounted for if the extended region has a structure which is
steeper than that of the remainder of the source, but the difference is not very marked and
may be due solely to calibration errors in the equipment. Alternatively, the size of the
source may simply have increased along pa 50°: a change from 1.7 to 2.5 arcsec at 408 MHz
will produce such a result and gives better agreement with the near-equality of the IPS and
JB results for the fractions of flux in the compact features. It seems, a priori, unlikely that
a component will change its size in one direction and not another, so that the former expla-
nation is to be preferred. Either explanation is indicative of spectral index differences within
the source.
4.3.5 3C171

There are few data for this source from the 5-km telescope, but those available indicate that $\gamma_1/\gamma_c \approx 0.35$ near $\theta_a 70^\circ$. About 30 per cent of the 5-GHz flux comes from a region of size $\sim 20$ arcsec, and the JB model of the source only accounts for about 7 per cent of the flux at 408 MHz and 30 per cent at 1407 MHz. From the observed ratio of $\gamma_1$ to $\gamma_c$ it seems possible that the halo round the source may have a spectral index larger by one, and the compact components flatter by $\sim 0.4$, than that of the source as a whole. The source is a 55 per cent scintillator at 81.5 MHz — this, together with the $\gamma_1$ indicated above, implies a spectrum for the extended region $\sim 0.3$ steeper than the overall spectrum.

4.3.6 3C184

The 5-GHz map reveals two components, each unresolved, separated by 4.4 arcsec. The JB 408-MHz model is a slightly asymmetric double, with components of size 2.5 arcsec, and separation 4.2 arcsec. Comparison of the polar visibility plots — Fig. 3(e) — shows that they are generally similar, with $\gamma_1/\gamma_c \approx 0.6$: the low value of 0.23 for $\gamma_1/\gamma_c$ near $\theta_a 41^\circ$ is probably spurious. Thus it seems probable that the structure at 408 MHz is basically the same as at 5 GHz, with the addition of a well-resolved region. There could be either one such region, or one associated with each component. In view of the JB model, the latter is more likely. In either case, to be visible at the lower frequency but not the higher, the region(s) must have spectra which are steeper than the spectrum for the source as a whole. If $< 10$ per cent of the 5-GHz flux is contained in these extended regions, and about 40 per cent of the 408-MHz flux, then they must have spectral indices $> 0.6$ more than that for the source as a whole.

The source is a reasonably good scintillator, with $R_{81} = 0.65 \pm 0.16$, which appears high in view of the effective $R_{408}$ of 0.4 — allowing for the factor $2^{1/2}$ for a double source, equation (1). However, the observational errors are such as to make the results consistent.

5 Conclusions

Two methods have been used to derive further information on the frequency variation of the structures of a number of sources over wide frequency ranges and with good resolution. The comparison of structures at 81.5 MHz and 5 GHz shows that the structures are generally similar, but that within a source, regions of size $> 2$ arcsec tend to have steeper spectra than regions smaller than this size. Detailed examination of a few sources, using principally 408-MHz and 5-GHz data, has confirmed this tendency. The difference is probably generally due to synchrotron self-absorption in the more compact components, although in some cases it is due to synchrotron losses in the extended regions. The magnitudes of the differences in spectral indices of the extended and more compact components are often less than expected on the simple source models. Possibly this is because particles are being reaccelerated in the extended regions.

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