THE COSMOLOGICAL EVOLUTION OF RADIO SOURCES
OF LARGE ANGULAR EXTENT

B. L. Fanaroff and M. S. Longair

(Received 1972 May 8)

SUMMARY

The numbers of radio sources of large angular size ($\theta \geq 60^\circ$) found in a survey of sources having $0.5 < S_{108} < 5 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$ by Windram and Kenderdine is compared with the number expected in different world models. An excess of such sources is found in comparison with the predictions of uniform models but their number is consistent with the postulate that such sources exhibit a moderate rate of evolution. In a complete sample of 5C sources at much lower flux densities, $S_{1400} > 0.01 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$, there is an excess of sources having steep spectra and a correlation is found between these sources and those of large angular size. A model is proposed in which these sources are associated with relatively weak radio galaxies with long lifetimes. The steepening of the radio spectra is ascribed to inverse Compton losses due to scattering of the microwave background. The model enables the lifetimes of individual radio source events to be estimated.

I. INTRODUCTION

It is widely accepted that powerful radio sources evolve with cosmological epoch. Although much effort has been spent upon devising models to describe this evolution, these give no more than a general picture of the features necessary to explain the observed excess of faint radio sources (see Longair 1971 for a survey of these results). An understanding of the physical nature of the evolution can only come from the study of the properties of the sources involved. A step in this direction was taken by Longair & Pooley (1969), who used high resolution data on the angular structures of sources in the 3C and 5C catalogues to demonstrate that sources of relatively large angular extent evolve more slowly than the most powerful radio sources. In their analysis, the numbers of extended sources at very high and very low flux densities were compared and the region of the counts where the maximum excess of faint sources is found ($S_{178} \sim 1 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$) was not included. The more recent survey of Windram & Kenderdine (WK) (1969) has enabled us to study the numbers of extended sources in the latter range of flux density and we find further evidence for the evolution of large angular diameter sources, consistent with that found earlier by Longair and Pooley.

The present results, in conjunction with recent observations by Willson (1972), suggest a method for obtaining important information about radio sources at different cosmological epochs. Willson has shown that, in a complete sample of sources having $S_{1400} > 0.01 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$, there is an excess of sources having steep spectra (i.e. $\alpha > 0.8$, $\alpha$ being defined by $S \propto \nu^{-\alpha}$) as compared with samples selected at higher flux densities. In the sample having

$$S_{1400} > 0.01 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1},$$
there is a correlation between large angular size and steep spectrum. Willson proposed to explain his result in terms of a class of radio sources with steep or convex spectra which only becomes significant at the lowest flux densities. We proposed an alternative interpretation which is directly related to the evolution of large angular diameter sources and to the correlation of steep spectra with large angular size. We base our interpretation on the assumption that the extended sources are intrinsically weak radio galaxies which have relatively longer lifetimes than powerful, more compact sources. At large redshifts the dominant loss mechanism for the electrons within the components of long-lived sources is likely to be inverse Compton scattering of the photons of the microwave background radiation. Such losses result in a steepening of the radio spectra of these sources as compared with those of more powerful sources of shorter lifetime. For weak extended sources this effect will only be observed at the lowest flux densities, at which they are observed at large redshifts. If the present results and our interpretation are confirmed by future observations, they will be important in elucidating the evolution of individual sources at different cosmological epochs.

2. THE ANALYSIS OF THE OBSERVATIONS

Our approach to the problem of estimating the numbers of sources of large angular diameter at different flux densities follows that of Longair & Pooley (1969). If the angular structures and distances of a complete sample of sources at a high limiting flux density are known, the numbers of sources at lower flux densities can be predicted, assuming the sources to be uniformly distributed in co-moving coordinates. These predictions are compared with the numbers of extended sources actually observed at lower flux densities. In making this estimate various unavoidable selection effects have to be taken into account, e.g. only sources greater than a given angular size can be included in the sample of extended sources at low flux densities, sources are observed to different limiting surface brightnesses in different surveys, there is a minimum in the relation between the observed angular diameter and redshift in all non-empty world models, etc. An essential feature of this approach is that the samples must be complete down to the different limiting flux densities. At high flux densities we have used the complete sample of 199 3C radio sources which have been studied with high resolution (Longair & Macdonald 1969; Mackay 1971). The 178 MHz flux densities of these sources have been revised upwards by 8 per cent to bring them into agreement with the flux density scale of Kellermann, Pauliny-Toth & Williams (1969), which is not significantly different from that used by Windram and Kenderdine.

The WK catalogue lists faint sources which lie within about 2°·5 of 3C sources and were observed incidentally when the 3C sources were mapped with high resolution. The analysis of this sample is not straightforward because the sensitivity of the observations varied depending upon the number of spacings used for each map and the size of the synthesized beam varied considerably with declination from one area to another. Windram and Kenderdine showed, however, that their sources having flux densities in the range $0.2 < S_{408} < 5 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$ formed a representative sample of the sources in this flux density range and that there was no statistical evidence for a physical association of any of these sources with the 3C radio sources—this conclusion is entirely consistent with the isotropy of the radio sources listed in the 4C and 5C surveys (Holden 1966; Hinder &
Branson 1969; Pooley & Kenderdine 1968). The effective beam-width of the telescope at the observing frequency of 408 MHz is 80″ × 80″ cosec δ and the angular diameter information is comparable with that of the 5C surveys.

We have derived the counts of sources having angular sizes greater than 60″ arc from the WK survey areas which were mapped with four or more interferometer spacings and which have δ > 30°. The second restriction was necessary because the beam-width of the telescope was 80″ cosec δ in declination and sources having angular size greater than 60″ could have been missed for δ < 30°. Forty-nine areas were therefore available for study. Sources which had flux densities below the survey limit before correction for the primary polar diagram (those classified as ‘d’ by WK) were excluded from the counts. It was shown by Neville, Windram & Kenderdine (1969) that close to the map centres, sources were affected to some extent by the source removal programme. We have therefore excluded sources which lie within an elliptical area of semi-minor axis 15′ in R.A. and semi-major axis 15′ cosec δ in declination about the map centre. Outside an elliptical area of semi-minor axis 130′ in R.A. and semi-major axis 130′ cosec δ in declination, the sensitivity of the telescope was down to 10 per cent of that at the map centre and so we have excluded sources outside this area. With these restrictions, we obtained a sample of 225 sources with flux densities

$$0.2 < S_{408} < 5 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}.$$  

To find the total counts and the counts of large angular diameter sources we adopted the following procedure. Because of the isotropy of the distribution of the sources, we evaluated the total area of sky which was observed to different limiting flux densities (the ‘area-flux density relation’) and corrected the observed number count correspondingly. To this count we added the normalized counts from the complete sample of 3C sources themselves since these objects were explicitly excluded from the WK survey.

The total counts and the counts of sources of large angular extent are compared with the counts derived by Pooley & Ryle (1968) in Fig. 1. It can be seen that the total counts from the WK sample are in excellent agreement with the earlier observations, as was found by Windram and Kenderdine. The numbers of sources having θ > 60″ arc and 0.5 < S_{408} < 5 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} amounted to only 14 and therefore the statistical error associated with each point is large. We have estimated the probability that any of the extended sources is due to the chance superposition of two unrelated sources and find it to be negligible. Also shown in Fig. 1 is the number of large angular diameter sources found in the 5C surveys.

3. COMPARISON WITH THE PREDICTIONS OF DIFFERENT COSMOLOGICAL MODELS

The total number of sources having θ > 60″ arc which would be expected in the WK sample has been estimated assuming that sources of the luminosities and physical dimensions observed in the 3C sample are uniformly distributed in an Einstein–de Sitter universe (q_0 = \frac{1}{2}, \Lambda = 0). The details of this calculation have been described by Longair & Pooley (1969), the only difference in the present case being that, in the end, the predicted count is multiplied by the area-flux density relation. (The justification of the formula used by Longair and Pooley may be found in the review by Longair (1972).) The error in this prediction then
reflects only uncertainties in the area-flux density relation (estimated to be less than 10 per cent) and those due to the limited statistics of the 3C sample. We have also performed this calculation making various assumptions about the cosmological evolution of the population of extended sources with epoch. As representative models, we have considered those in which the comoving space density of sources of a particular radio luminosity and physical size is a function of epoch. For simplicity, it is assumed that the space density of sources of different luminosities changes in the same way with cosmological epoch and that there is no change in the physical size of sources with redshift. The results of these calculations are compared with the observed numbers of sources of large angular size in Table I, which includes the forms of cosmological evolution considered.

It can be seen (column 1) that more extended sources are found to have $0.5 < S_{408} < 5 \times 10^{-26}$ W m$^{-2}$ Hz$^{-1}$ (14) than would be predicted by the uniform Einstein–de Sitter model ($8.8 \pm 2.0$). This result is insensitive to the choice of world model since the range of flux densities is less than a factor of 10, corresponding to a factor of less than 3 in redshift.

A larger number of sources is expected if extended sources were more frequent in the past and it can be seen from the table that a moderate rate of evolution (column 2) provides better agreement with the observations. Strong evolution of the type necessary to account for the total counts of radio sources (Doroshkevich, Longair & Zeldovich 1970) and the space distribution of QSOs (Schmidt 1970),
Table I

The predicted numbers of extended sources in the WK sample

<table>
<thead>
<tr>
<th></th>
<th>Moderate evolution</th>
<th>Strong evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>No evolution</td>
<td>8.8 ± 2.0</td>
<td>β = 5.6 ± 3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.6 ± 3.0</td>
</tr>
<tr>
<td>m = 3</td>
<td>13.3 ± 3.0</td>
<td>m = 8</td>
</tr>
<tr>
<td>m = 4</td>
<td>14.9 ± 3.5</td>
<td>27.7 ± 6.0</td>
</tr>
</tbody>
</table>

Observed number of extended sources = 14

The models of cosmological density evolution have the forms:

- truncated power-law
  \[ \rho(P, z) = \rho(P, z = 0)(1 + z)^\beta \quad (z \leq 3) \]
  \[ = 0 \quad (z > 3) \]

- exponential
  \[ \rho(P, z) = \rho(P, z = 0) \exp \left( m \left( \frac{t_0 - t}{t_0} \right) \right) \]

\( t_0 = \) present epoch.

i.e. \( \beta > 6 \) or \( m > 8 \), results in too many extended sources (column 3). These results are also presented in Fig. 2, in which the predicted and observed counts are compared.

Fig. 2. The log N–log S plot for WK sources with \( \theta > 60^\circ \). The lines are theoretical predictions obtained for different models of density evolution (see text and Table I).

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Our result is in accord with that of Longair and Pooley, who found that models with $\beta \lesssim 3$ could account for the numbers of extended sources in the 5C surveys and although the present data would not on their own be compelling evidence for the weak evolution of large angular diameter radio sources, they provide further support for this hypothesis. The present results are of lesser statistical significance than those of Longair and Pooley because the comparison of the observed and predicted numbers of sources is made over a small range of flux densities whereas the previous analysis covered a range in flux density of 500 to 1. We emphasize, however, the importance of analysing the properties of sources with flux densities near that at which the maximum excess in the total source count occurs because we do not yet understand the physical cause of the excess.

4. CORRELATION OF EXTENDED SOURCES WITH THOSE HAVING STEEP SPECTRA

Willson (1972) has investigated the spectral index distribution over a wide range of flux densities at 1400 MHz. A striking feature of his analysis is that there is an excess of sources with steep spectra at the lowest flux densities,

$$S_{1400} \geq 0.01 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1},$$

in comparison with the spectral index distribution at higher flux densities. Willson has described the difficulties in explaining this result. He noted that some of the sources with steep spectra were extended and we have investigated further this correlation. The spectral index distribution for the 38 5C sources having

$$0.2 > S_{1400} \geq 0.01 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$$

is shown in Fig. 3 where those which are appreciably extended are indicated as shaded boxes. It is clear that sources having steep spectra tend also to have large angular diameters. The probability that the observed correlation of large angular sizes and steep spectra is due to chance sampling from an uncorrelated sample is estimated to be less than 2 per cent. The correlation might arise from partial resolution of the large angular diameter sources but Willson has concluded that this effect is not significant.

Fig. 3. The spectral index distribution for $S_{1400} \geq 0.01 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ (Willson 1972). Extended sources are shown hatched.
5. DISCUSSION

The above results are based upon the statistics of small numbers and no strong conclusions can yet be drawn from the data. Further studies, however, are of potential value in elucidating the time development of individual sources and their evolution over cosmological time-scales.

The features of the total source counts which are relevant to our discussion are: (a) the excess number of sources over the predictions of uniform cosmological models reaches a maximum in the range \(0.1 < S_{408} < 1 \times 10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1}\), and (b) the counts converge rapidly at lower flux densities, tending to \(N \propto S^{-0.8}\) at \(S_{408} = 0.01 \times 10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1}\) (Pooley & Ryle 1968). All models of the evolution of the radio source population associate the maximum excess with the evolution of the most powerful classes of radio sources having \(P_{178} \geq 10^{26} \, \text{W Hz}^{-1} \, \text{sr}^{-1}\) (for review see Longair 1971). This restriction results from the abrupt convergence of the counts and from the limits to the radio background emission. Sources contributing to the counts at \(S_{408} \sim 0.01 \times 10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1}\) are likely to be on average of much lower luminosity, \(P_{178} \sim 10^{24-25} \, \text{W Hz}^{-1} \, \text{sr}^{-1}\), and to exhibit much less marked evolution, certainly much less than that associated with the most powerful sources.

Although we have no direct evidence on the luminosities of the unidentified sources in our samples, the majority of the extended sources in the complete 3C sample have luminosities in the range \(10^{24} < P_{178} < 10^{26} \, \text{W Hz}^{-1} \, \text{sr}^{-1}\) which suggests that such sources do not partake in the strong cosmological evolution. Evolution of the form derived above, \(\rho(z) \propto (1+z)^{3-5}\), would be entirely consistent with the observations.

Willson (1972) has noted the problems encountered in explaining the presence of sources having steep spectra in the 3C sample. An important feature of his results is that the spectral index distribution at \(S_{1400} \geq 0.2 \times 10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1}\), the region of the maximum excess of strong sources, is similar to that at high flux densities and the excess of steep spectra only appears at the lowest flux densities, \(S_{1400} \geq 0.01 \times 10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1}\). Following the above reasoning, at this flux density these sources with steep spectra are expected to have luminosities in the range \(10^{24} < P_{178} < 10^{26} \, \text{W Hz}^{-1} \, \text{sr}^{-1}\). Willson noted that there were insufficient sources with steep spectra of the appropriate radio luminosity at high flux densities to produce the necessary excess of faint sources without assuming a moderate rate of cosmological evolution. Willson suggested that his result might be explained in terms of a class of sources with steep or convex spectra which would only become significant at the lowest flux densities.

We propose an alternative interpretation of Willson’s results which is directly related to the evolution of large angular diameter sources and to the correlation of steep spectra with large angular size described above. We base our interpretation on the reasonable assumption that weak extended sources have relatively longer lifetimes than powerful, more compact sources (e.g. Ryle 1970). The models of the evolution of the radio source population indicate that the powerful sources will be observed at large redshifts, \(1 < z < 3\), at \(S_{408} \sim 1 \times 10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1}\) whereas the weaker extended sources will only be observed at comparable redshifts at \(S_{408} = 0.01 \times 10^{-26} \, \text{W m}^{-2} \, \text{Hz}^{-1}\).

It is well known (e.g. Rees 1967; Bergamini, Londrillo & Setti 1967) that at large redshifts the dominant loss mechanism for the relativistic electrons which
produce the synchrotron radio emission in radio sources may be inverse Compton scattering of the photons of the microwave background radiation. The time scale for such losses is

\[ T_{1e} = \frac{3mc^2}{4\sigma cU_{\text{rad}} \gamma} = \frac{3 \times 10^{12}}{(1+z)^4} \gamma \text{ yr} \]

where \( \gamma \) is the Lorentz factor of the relativistic electrons

\[ (\gamma = (1 - v^2/c^2)^{-1/2} \approx E/m_0c^2) \]

\( U_{\text{rad}} \) is the energy density of radiation, \( \sigma \) is the Thomson cross-section and \( z \) is redshift. When \( T_{1e} \) becomes less than the lifetime \( T \) of the radio source, the electron energy spectrum and consequently the synchrotron radio spectrum is steepened. The exact form of the distorted spectrum depends upon the assumptions made about the supply of particles to the source components but in general a significantly steepened spectrum is expected for energies greater than \( \gamma m_0c^2 \) (Kardashev 1962; Kellermann 1966). Let us illustrate the effect of these losses upon the predicted spectral index distribution at different flux densities.

Typically, in extended sources the electrons which radiate at radio wavelengths have \( \gamma \approx 3 \times 10^3 \) and therefore at a redshift, \( z = 2 \), \( T_{1e} \approx 10^7 \text{ yr} \). Thus, if the time scale of a radio source event \( T \) is \( < 10^7 \text{ yr} \), as is often assumed for powerful radio sources, the spectra will remain undistorted whilst if \( T > 10^7 \text{ yr} \), as we suppose for weaker sources, their spectra will be steeper. Thus, at

\[ S_{408} = 1 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \]

where powerful sources at large redshifts make a dominant contribution to the counts and weaker sources are observed at small redshifts, the spectral index distribution is expected to be similar to that at higher flux densities. On the other hand, at \( S_{408} = 0.01 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \) we expect a significant contribution from weak sources at large redshifts and, according to our model, these will have steeper spectra because of the inverse Compton scattering losses than those observed at higher flux densities. In this way we can account for the observed excess of extended sources with steep spectra at the lowest flux densities without invoking the existence of a new class of source. We also note that the observed rate of evolution of extended sources can account for the numbers of sources observed.

The essential feature of this interpretation is that the observations suggest differential evolution of the spectral properties of powerful and weak sources and we attribute this to the different time scales associated with these sources. Since the inverse Compton scattering is only significant for weak radio galaxies, we expect only a small contribution to the X-ray background intensity amounting to no more than \( 10^{-8} \) of the observed figure (cf. Longair 1970).

If we now accept this model for the evolution of the radio source population, we can invert the argument to derive useful information about the time scales of strong and weak radio sources at different cosmological epochs. Let us give an improved version of the above calculation which illustrates how the model can be used once more information becomes available.

The sources with steep spectra have \( 0.01 \leq S_{1400} < 0.2 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \) and since we expect \( P_{178} \approx 10^{25} \text{ W Hz}^{-1} \text{ sr}^{-1} \), \( z \approx 1.5 \). The time scale for losses due to the combined effect of synchrotron radiation and inverse Compton scattering
of the photons of the microwave background at an observing frequency $\nu$ can readily be shown to be

$$T_e = 2.6 \times 10^4 \frac{H^{1/2}}{(H^2 + 8\pi U_{\text{rad}})} [(1 + z) \nu]^{-1/2} \text{yr}$$

where $H$ is the magnetic field in the source and $U_{\text{rad}}$ is the energy density of the photons of the microwave background (Rees 1967; van der Laan & Perola 1969). It is well known that if the number of photons is conserved and interactions with matter are negligible

$$U_{\text{rad}} = U_0 (1 + z)^4 = 0.25 (1 + z)^4 \text{eV cm}^{-3}.$$ 

A maximum time scale is found when $U_{\text{rad}} = 3H^2/8\pi$. Thus, for $\nu = 1$ GHz and $z = 1.5$, $T_1 \leq 5 \times 10^6$ yr. It is interesting to compare this figure with the harmonic mean lifetime $T_h$ of sources of similar luminosity. The harmonic mean lifetime describes the total time for which a galaxy must be a radio source in order for there to be the correct probability that it will be observed as a radio source (Schmidt 1966). The individual events which give rise to observed radio sources may have time-scales shorter than $T_h$ but then the galaxy must have undergone a number of similar events in the past so that the total active lifetime is equal to the harmonic mean value. For sources having $P_{178} \sim 10^{25}$ W Hz$^{-1}$ sr$^{-1}$, Schmidt quotes $T_h = 10^9$ yr and if this value does not change appreciably with redshift, we find $T_h/T_1 \sim 20$. This ratio could be interpreted as indicating that the harmonic mean lifetime of these radio galaxies is composed of 20 radio source events of similar intensity throughout the last $10^{10}$ yr. Evidently, at the present time there are considerable uncertainties in this argument but these can be greatly reduced by further observations. Of particular importance are optical studies of radio galaxies to very faint apparent magnitudes.

ACKNOWLEDGMENTS

We thank Dr M. A. G. Willson for allowing us to use his results before publication. B.L.F. acknowledges an Isaac Newton Studentship.

Mullard Radio Astronomy Observatory, Cavendish Laboratory, Free School Lane, Cambridge

Received in original form 1972 April 5

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