THE ANGULAR SIZE DISTRIBUTION OF RADIO SOURCES AT LOW FLUX DENSITIES

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ABSTRACT Observations of complete samples of extragalactic radio sources at low and intermediate flux densities are described. Many types of source are found. The angular sizes form a smooth extrapolation from higher flux densities, and can be predicted from the known properties of samples at high flux density either with linear size evolution (for $\Omega=1$ or $\Omega=0$ Universes) or without linear size evolution (for $\Omega=0$). The question of whether such evolution is required therefore remains open.

1. INTRODUCTION

It is now possible to study extragalactic radio sources at low and intermediate flux densities in detail comparable to that which has hitherto been available only for the brightest sources. While the ultimate aim of the work described here is the definition of the radio source population down to flux densities of 55 mJy at 408 MHz and 20 mJy at 1407 MHz, the present paper concentrates on the angular size distribution down to these levels and, in particular, on the problem of whether linear size evolution with cosmological epoch is required. Such evolution was inferred from the small angular size θ of quasars at high redshifts z in bright samples. Subsequent studies indicated that it might also explain the small values of θ found at low flux densities S, and linear size evolution as $(1+z)^{-N}$ where N=1-1.5 has been suggested (Kapahi 1975, 1977). On the other hand, the θ-z result may simply reflect an inverse correlation between linear size and radio luminosity, and the radio luminosity function used by Kapahi provides a poor fit to the source counts at low S (Swarup 1977) so that conclusions based on this distribution of sources should be treated with caution.

Observations of complete samples of sources at low and intermediate flux densities are described here and compared with new predictions. These samples overlap those used by Kapahi as well as extending to significantly lower flux densities.

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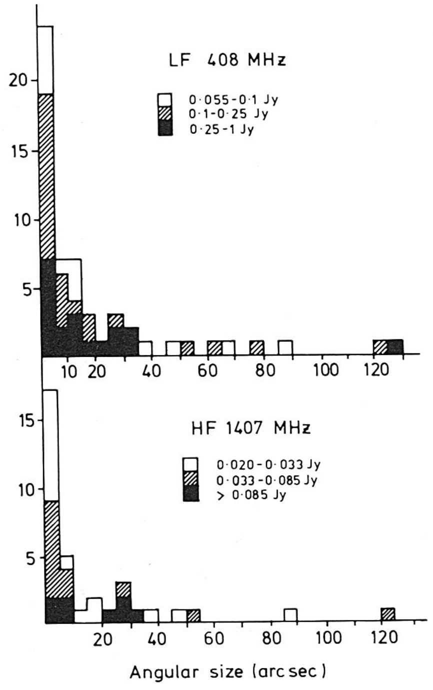

Figure 1 Angular size distributions for radio sources at low flux densities (Fielden et al.)

(a) Low frequency (LF) sample of sources in the flux density range .055-1 Jy (for 5C6 and 7) and 0.1-1 Jy (for 5C12) at 408 MHz.

(b) High frequency (HF) sample of sources in the flux density range above 20 mJy at 1407 MHz.

2. THE SAMPLES OF SOURCES AND THE OBSERVATIONS

At low flux densities the brightest sources were selected from the 5C6 and 7 (Pearson and Kus 1978) and 5C12 (Benn et al. 1982) deep radio surveys. These were chosen from areas well inside the primary beam to ensure accurate flux densities and to prevent discrimination against low brightness sources. Samples complete at 408 MHz to 55 mJy (5C6 and 7) and 100 mJy (5C12) and at 1407 MHz to 20 mJy (5C6, 7 and 12) were thus formed. In the original 5C surveys most of these sources were unresolved at 408 MHz (HPBW 80"x80"cosec δ) while about 30% were extended at 1407 MHz (HPBW 23"x23"cosecδ). High-resolution radio observations of the samples with the 5-km telescope and the VLA are described by Downes et al. (1981) and Fielden et al. (1982).

The distribution of angular sizes at both frequencies (Fig. 1) extends up to about 2'. A wide range of radio morphologies is found among the well-resolved sources, with clear examples of both classical doubles (indicating a high radio luminosity) and sources whose structure is characteristic of a low radio luminosity. At 408 MHz about 30% of the sample is unresolved, and 25% is both steep-spectrum (α>0.5) and unresolved; the corresponding figures at 1407 MHz are 46% and 34%. This reflects the increased number of flat-spectrum objects at the higher frequency, but also shows a substantial conribution from compact steep-spectrum sources in both samples.

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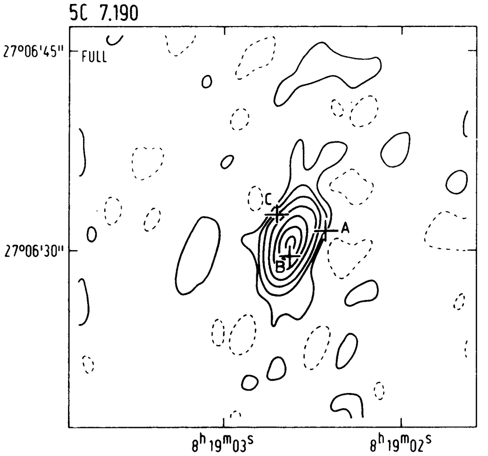
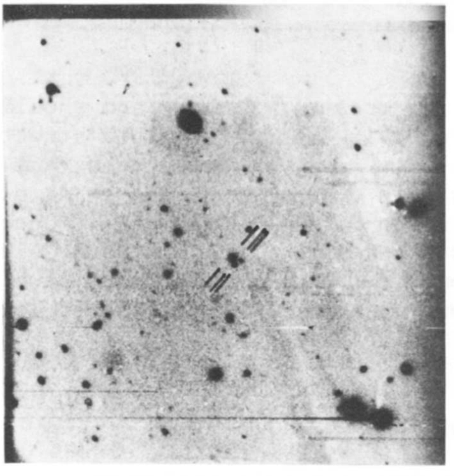


Figure 2 5C7.190: a flat-spectrum source in the 1407-MHz sample.
(a) 1.4-GHz map made at the VLA (Downes et al.). Contours are at ±2,5,10, 30,50,70,90% of the peak 30.2 mJy/beam. The positions of candidate identifications are marked with crosses. Further observations at 5 GHz (Fielden et al.) confirm B, a stellar object with m_r=20.7 as the identification.



(b) CCD image of the 3.6'x3.6' field around 5C7.190 (Perryman et al.). The three candidates for the identification are marked.

The accurate positions and structures for sources in 5C6 and 7 have been used together with optical observations with a CCD detector in a continuation of a deep identification program begun by Perryman (1979a, b). The CCD observations reach a limiting magnitude m_r=23 and are described by Perryman et al. (1982). Fig. 2 shows, as an example, a radio map and CCD image of the field of 5C7.190. Approximately 30(-55)% of the sources are identified (the fraction is slightly higher for unresolved than for resolved sources). Only two sources (including 5C7.190; Fig. 2) are identified with stellar objects. It is therefore likely that, if the properties of the sources are similar to those at high flux density, a large fraction of the sample must lie at redshifts $z \gtrsim 0.6$.

At intermediate flux densities, Allington-Smith (1982) has observed a complete sample of 59 B2 radio sources in the range 1-2 Jy at 408 MHz. This corresponds to the region in which the source counts exceed non-

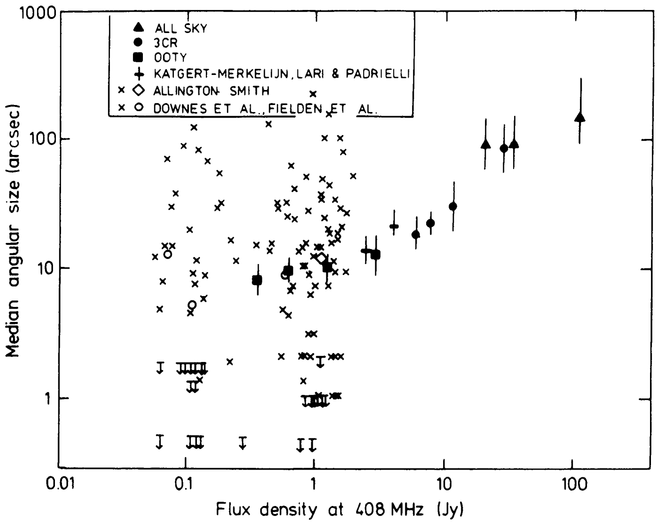


Figure 3 The angular size-flux density distribution at 408 MHz, adapted from the diagram by Swarup (1975). The medians are from Swarup, Katgert-Merkelijn et al. (1980) and the present observations (unfilled symbols), for which individual measurements are also shown (x). Allington-Smith's values are plotted using his measurements of the flux density at 408 MHz.

evolutionary predictions by the greatest amount, and should therefore represent the most strongly evolving sources. Radio structures have been determined with the One-mile and 5-km telescopes, and have been used to help identifications with CCD observations to magnitudes similar to those for 5C6 and 7 (Allington-Smith et al. 1982). Once again a large variety of source structures was found, with an angular size distribution ranging up to 4' and many compact sources. The fraction of identified sources is, however, considerably higher than at the 5C levels, with a preliminary estimate of 70-75% identified.

3. THE ANGULAR SIZE-FLUX DENSITY DIAGRAM

The angular sizes of individual sources in the 408-MHz samples are plotted in Fig. 3 together with the medians for both the present samples and previous measurements. The median is 7.5" in the range 0.1-1 Jy and 12" for 1-2 Jy, and the results form a smooth extrapolation from higher flux densities, with excellent agreement where the samples overlap with occultation measurements made at Ooty. At 1407 MHz the median angular size is 7". The angular sizes again agree with extrapolation from high flux densities and with those inferred from indirect measurements (Ekers and Miley 1977, and references therein).

The distribution of θ at low S can be synthesised from a complete "parent sample" at high S if the members of this sample are taken as representative of the overall population and all the redshifts are known. The track followed on the θ-S diagram by a single source of given size as the redshift is increased is shown in Fig. 4. It is harder to predict small angular sizes for Ω=1 than for Ω=0, as the angular size is larger for given flux density, and the redshift required for a given drop in flux density is higher. On the other hand, if linear size

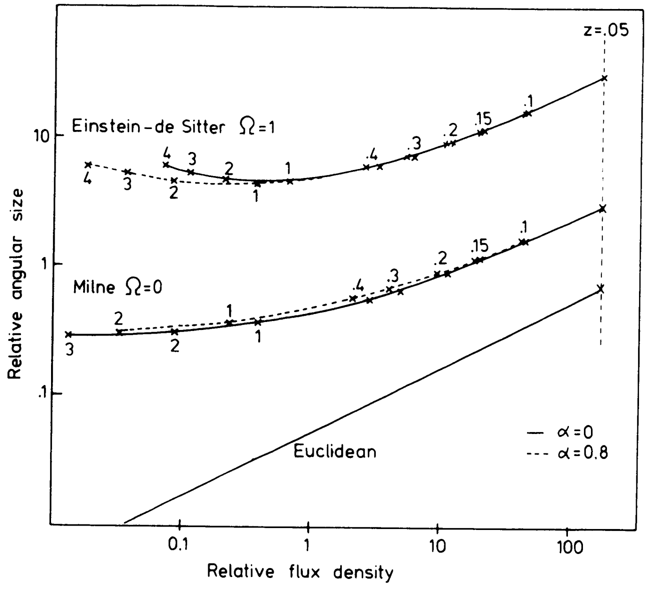


Figure 4 The angular size-flux density track obtained by moving a single source (with no linear size evolution) to higher redshifts. The curves are aligned at redshift z=0.05, and the increasing redshift is marked along each. Predictions for both a steep-spectrum (α=0.8) and a flat-spectrum (α=0) source are shown.

evolves as $(1+z)^{-N}$, this decrease will be more rapid with decreasing S for Ω=1 because of the higher values of z.

The space density of each source is taken to follow an evolving radio luminosity function (RLF). The relative numbers of each type of source at given flux density vary because the strength of evolution is dependent on both radio luminosity and redshift, so the distribution of angular sizes changes with flux density (thus direct comparison of Fig. 4 with Fig. 3 is not sufficient proof of linear size evolution).

Previous attempts to model the distribution at low S using a subset of the 3CR "166 sample" (Jenkins et al. 1977) as parent and the RLF of Wall et al. (1980) suggested that although the median angular size could be predicted if linear size evolution was invoked, the distribution then became too compressed, so that another method of obtaining small angular sizes was required (Downes et al. 1981). The present modelling uses the evolving RLF of Peacock and Gull (1981), which is derived from the source counts, V/Vmax, local RLFs and known redshift distributions, and treats steep- and flat-spectrum sources separately. Two parent samples have been used:

(i) the 3CR "166 sample" at 178 MHz (plus 5 giant sources whose low surface brightness prevented their inclusion in 3CR)

(ii) a complete sample of 168 bright sources at 2.7 GHz (Peacock and Wall 1981, 1982).

The higher number of flat-spectrum sources in the latter should not prejudice the result because of their separation in the RLF. On the other hand, the sample contains 36 steep-spectrum (α>0.5) compact sources 10 of which are excluded from the "166 sample" only because of spectral curvature. Significant numbers of such sources have also been found by Kapahi (1981) at 5 GHz. As the 5C sample is likely to lie at substantial

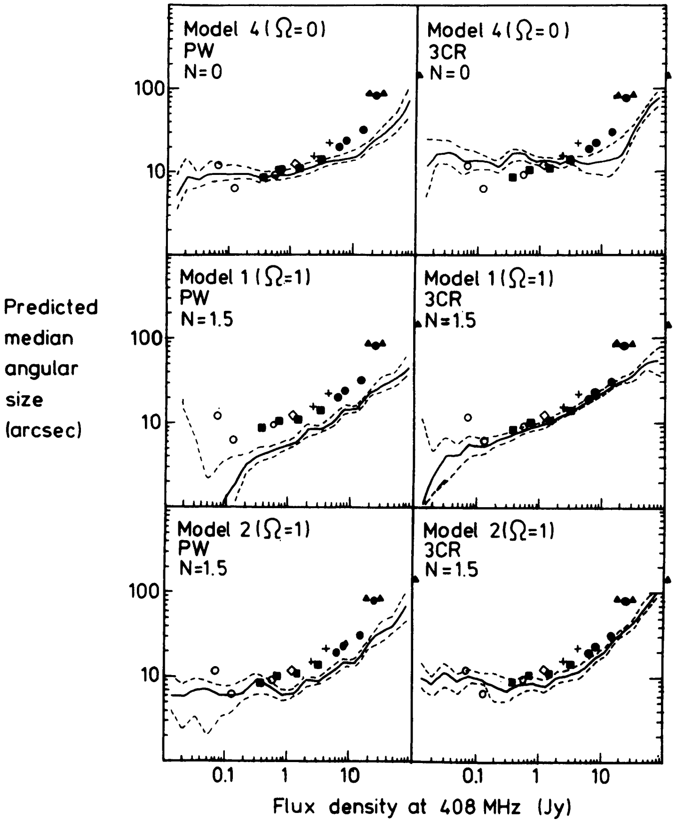


Figure 5 The predicted median angular size (solid line; errors are shown by dashed lines) as a function of flux density (Fielden et al.). The medians from Fig. 3 are shown for reference. Predictions are for a parent sample at 178 MHz (3CR "166 sample" plus 5 giant sources) on the right and at 2.7 GHz (Peacock and Wall 1981, 1982; PW) on the left. Evolving radio luminosity functions 4 (top pair), 1 (middle pair) and 2 (lower pair) of Peacock and Gull (1981) can all provide a good fit. Linear size evolution as $(1+z)^{-N}$ was used and N is shown for each prediction.

redshifts, it is equivalent to selection at a higher frequency (possibly above the turnover of these steep-spectrum compact sources) so that the second parent sample may be more appropriate.

The modelling was both with linear size evolution as $(1+z)^{-N}$ where N=1.5 and with no linear size evolution (N=0). Fig. 5 shows the results of the most successful attempts to model the medians at low flux densities. The errors in Fig. 5 are determined from the number of sources in the parent sample which dominate the behaviour at any flux density (in the sense that the errors are increased if the distribution is defined by very few sources).

For Ω=0, model 4 of Peacock and Gull (which has a redshift cutoff at z=5) provided a good fit to the observations at low flux densities with no linear size evolution and the parent sample at 2.7 GHz. This model was the most successful of those for Ω=0; results for N=1.5 predicted angular sizes lower than observed, though N<1.5 for the 3CR parent sample should give a reasonable fit. For Ω=1, no models with N=0 provided a satisfactory match to the data. Predictions with N=1.5 were too low, suggesting that less strong evolution (Kapahi, 1977, favoured N=1-1.1) may be more appropriate. The medians predicted at 5C

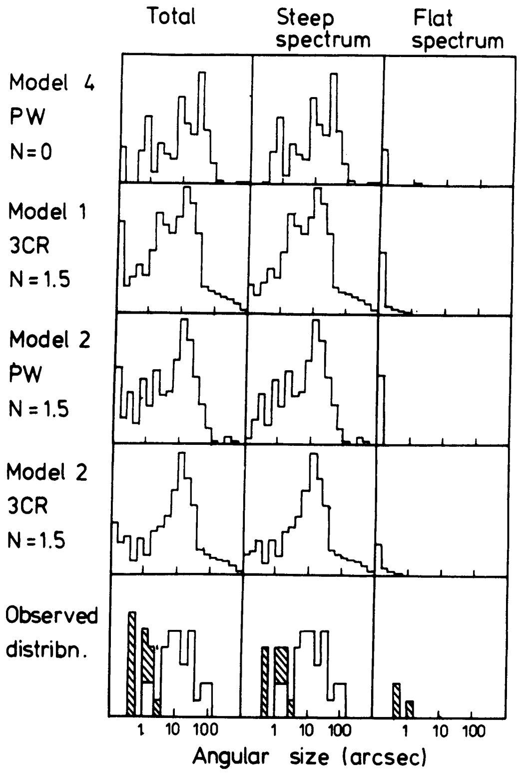


Figure 6 The angular size distribution at 408 MHz in the range 0.05-1 Jy for four of the models in Fig. 5 (Fielden et al.). The observed angular size distribution is plotted at the bottom, in which hatched areas represent upper limits. The distribution is shown separately for all sources (left column), for steep-spectrum (α>0.5) sources (centre) and for flat-spectrum sources (right column).

levels were lower for the 2.7-GHz sample than for the 3CR sample, by a factor up to $\sim$2. In addition, the predictions for the same parent sample and form of linear size evolution can vary by a similar amount according to the choice of RLF.

The predicted distribution of angular sizes in the range 0.05-1 Jy at 408 MHz is plotted in Fig. 6 for the four most successful models in Fig. 5, together with the observed distribution. In all cases the predictions are consistent with the observations to within the errors. In particular, the number of flat-spectrum (compact) sources is correct, confirming that the small angular sizes are not a result of an increased fraction of these sources when the 2.7-GHz parent sample is used. Also, all the angular size distributions extend to sufficiently large values to match the data.

The observed angular size distributions can therefore be modelled for Ω=0 either with or without linear size evolution, depending on the choice of parent sample. Models for Ω=1 require linear size evolution (though less strong than $(1+z)^{-1.5}$) to match the observations. The predicted angular sizes are dependent on the selection of cosmological model, the assumed RLF and the parent sample. Refinement of the RLF by the inclusion of new data on the identification content (or redshift

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distribution) at low and intermediate flux densities may resolve these uncertainties.

4. CONCLUSIONS

On the basis of present knowledge of the radio source population, and its behaviour at different epochs, linear size evolution is sufficient but not necessary in order to explain the small observed angular sizes at low flux densities.

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