The Redshift Distribution of Extragalactic Radio Sources

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Abstract.
Extragalactic radio sources are a unique cosmological probe in that they trace large-scale structure on scales inaccessible to other wavelengths. However as radio survey data is inherently 2D, the redshift distribution, $N(z)$, is necessary to derive spatial information. To obtain this distribution either we measure thousands of radio source redshifts to directly determine $N(z)$ or we derive $N(z)$ from statistical analyses of radio source count and identification data.

In this paper we show how the dual-population unification scheme can be incorporated into a rigorous statistical analysis of radio source count data, with the result that our simple parametric evolution and beaming model revises previous estimates of $N(z)$, specifically at low flux densities. This revision is particularly pertinent given that the new generation of radio surveys extend to milli-jansky flux density levels: sampling source densities high enough to reveal spatial structure. In turn, these new radio surveys will provide potent tests which will refine our model.

1 Extragalactic radio sources as cosmological probes

The development of large-scale structure had to take place at epochs corresponding to redshifts greater than 0.2; moreover structure is now known to extend beyond scales of $\sim 200h^{-1}$ Mpc. Both factors place the extent and evolution of large-scale structure beyond the reach of current optical and IR surveys and we must look outside these bands to address such key cosmological issues.

It has now been established that extragalactic radio sources can trace structure both to very early epochs and on very large scales \cite{1,2,3}. This is a direct result of their uniform selection function: away from the Galactic plane extragalactic radio sources are visible to very high redshifts ($z > 4$) with detection unaffected by obscuration. Moreover the high radio luminosities and strong space-density evolution yield a peak selection range of very high redshifts ($1 < z < 3$).

It was \cite{2} who showed how to determine the 3D 2-point spatial correlation function from 2D information in radio surveys themselves, a cosmological Limber’s equation, and an estimated redshift distribution for the radio sources to the survey limit. This and more recent analyses use the best estimates of $N(z)$ available, namely those from the comprehensive analysis of \cite{4}, in which all the then-known redshift and source-count data were synthesized into a determination of the epoch-dependent luminosity functions. These in turn can be used to predict $N(z)$ at any frequency and flux-density level. The statistical accuracy becomes rapidly poorer below flux densities equivalent to $S_{1.4 \, \text{GHz}} = 100 \, \text{mJy}$, as the results are then an extrapolation. Moreover the analysis
considers steep- and flat-spectrum populations separately and independently, while not including at all the starburst galaxy population which dominates at levels below a few mJy.

Our recent analysis of radio source evolution in terms of a dual-population unified model [5, 6] describes how the flat and steep-spectrum populations are physically related, and includes this latter starburst population. Accordingly it promises to predict \( N(z) \) with somewhat greater reliability, particularly at the lower flux densities.

2 Evolution and beaming of the radio source populations

Our dual-population unified model is based on the two Fanaroff-Riley (1974) classes of radio galaxies as parent populations. Anisotropic radiation mechanisms of relativistic beaming along the radio axes and dusty tori shrouding the nuclei result in core-dominated quasars and BL Lac objects from these, when radio axes coincide closely with our line-of-sight. We determined the cosmic evolution history of the two populations FRI and FRII from low-frequency (151 MHz) survey statistics. We then determined beaming models for the related quasars and BL Lac objects by matching predicted and observed source counts at 5 GHz using Monte Carlo orientation of the parent population. In this process we adopted the pure luminosity evolution model for the starburst galaxy population derived by [7]. In the process we found that a combination of strong cosmic evolution of the FRII sources coupled with no evolution of the FRI population is required to fit the low-frequency count data, while the best-fit beaming models for the two populations have parameters, jet-speeds in particular, which match those observed in VLBI observations of individual sources. The composite model which we found for evolution and beaming gave a natural explanation of the change in source count shape with frequency, while showing good agreement with several other independent data sets.

3 The redshift distribution of radio sources \( N(z) \)

Our evolution and beaming model can be used predict at any frequency the intensity-dependent mix of the three underlying radio-source populations: the starburst galaxies, and the FRI and FRII radio galaxies together with their beamed (on-axis) counterparts. Figure 1 shows this mix for 1.4 GHz.

The model can also be used to predict the redshift distribution \( N(z) \) for any frequency and in a given intensity range. Figure 2 shows the \( N(z) \) derived for 1.4 GHz in the flux-density range \( 1 < S_{1.4\text{GHz}} < 100 \text{ mJy} \). The dominant populations in this range (see Figure 1) are the FRI sources (beamed and un-beamed versions) at moderate redshifts, with starburst galaxies at low redshift; the high-power FRII sources make only a minor contribution. The implication for the latest generation of radio surveys which extend to \( S_{1.4\text{GHz}} \sim 1 \text{ mJy} \)
is that these surveys completely sample this the most powerful radio-source population; one entire population is uniformly sampled across its entire evolutionary history to the highest observable redshifts by these sensitive radio surveys.

The difference between this estimation of \( N(z) \) and those used previously - in particular those from the models of \[4\] - can be attributed to (i) the ‘spike’ at \( z \sim 1 \) due to the starburst galaxies, a population not included in previous analyses, and (ii) the lower median redshift due to the dominance of the unevolving FRI population at this level.

**Table 1. Deep radio surveys**

| Survey   | Frequency (MHz) | Area (sq deg) | Resolution (″) | Detection limit (mJy) | Coverage | Sources / sq deg |
|----------|-----------------|---------------|----------------|-----------------------|----------|------------------|
| FIRST    | 1400            | 10,000        | 5″             | 1 mJy                 | NGP      | ~90              |
| NVSS     | 1400            | 33,700        | 45″            | 2.5 mJy               | \( \delta > -40^\circ \) | ~60              |
| SUMSS    | 843             | 8,000         | 43″            | \~5 mJy               | \( \delta < -30^\circ \) | ~40              |

**Figure 1.** The predicted integral population mix at 1.4 GHz from our dual-population unified model \[5\], \[6\]. The contribution from the FRII population (FRII radio galaxies and quasars) is almost negligible at \( S_{1.4\text{GHz}} = 1 \text{ mJy} \).
Figure 2. The total predicted $N(z)$ for sources in the flux density range $1 \leq S_{1.4\,GHz} \leq 100 \, \text{mJy}$ (solid line) from evolution models of [4] (average of models 1-4,6 & 7) (dashed line), and [6] (dotted line).

Our evolution model (and in consequence the $N(z)$ predictions) will be further refined by (i) incorporating the results from a multi-object spectroscopy campaign (WYFFOS + WHT, 2dF + AAT) which targets FIRST survey sources, and (ii) redefining the local radio luminosity function using spectra obtained by the 2dF galaxy redshift survey (M Colless, these proceedings).

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