SPACE DISTRIBUTION OF RADIO-SOURCE POPULATIONS

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This paper sets out the status of data determining the space distribution of extragalactic radio-source populations, describes some recent results from analyses of the data, and indicates why and how the analyses need revision in the light of unified models. It concludes by emphasizing the severity of the effects of large-scale structure on modern survey data.

1. Overview: the basic data N(S) and N(P)

The data required to determine the space distribution for a population of extragalactic sources consist of a) a *source count* N(S), the surface density on the sky determined directly in a survey, and b) at least one *luminosity distribution* N(P), the frequency distribution of radio powers for a complete flux-limited sample, determined by identifying and measuring redshifts for all sample members. The translation of these data into space densities can be described in simple Euclidean terms (Wall, 1983) which make evident the analogies with other analyses such as V/V_m or $1/V_m$ (Schmidt, 1968; Katgert *et al.*, 1979). To determine the spatial distribution, N(P) and N(S) are needed *for each population.* In practice N(P) can be constructed for each object-type by dividing a single N(P) according to the physical properties of its members. However a source-count for each object-type is currently too difficult – the usual approach is to divide N(P) while using a total count to constrain the luminosity-function estimates for the summed populations.

The state of the basic data N(S) and N(P) is summarized in Fig. 1. Definition of source counts at the highest flux densities has reached a fundamental limit: there is no more sky to survey. Counts at the lowest flux densities also approach a fundamental limit: the deepest surveys with the VLA and WSRT reach intensities corresponding to sky surface densities $> 10^7$ per sterad, and the confusion limit is close. All counts show general agreement, regions of overlap using totally different instruments showing

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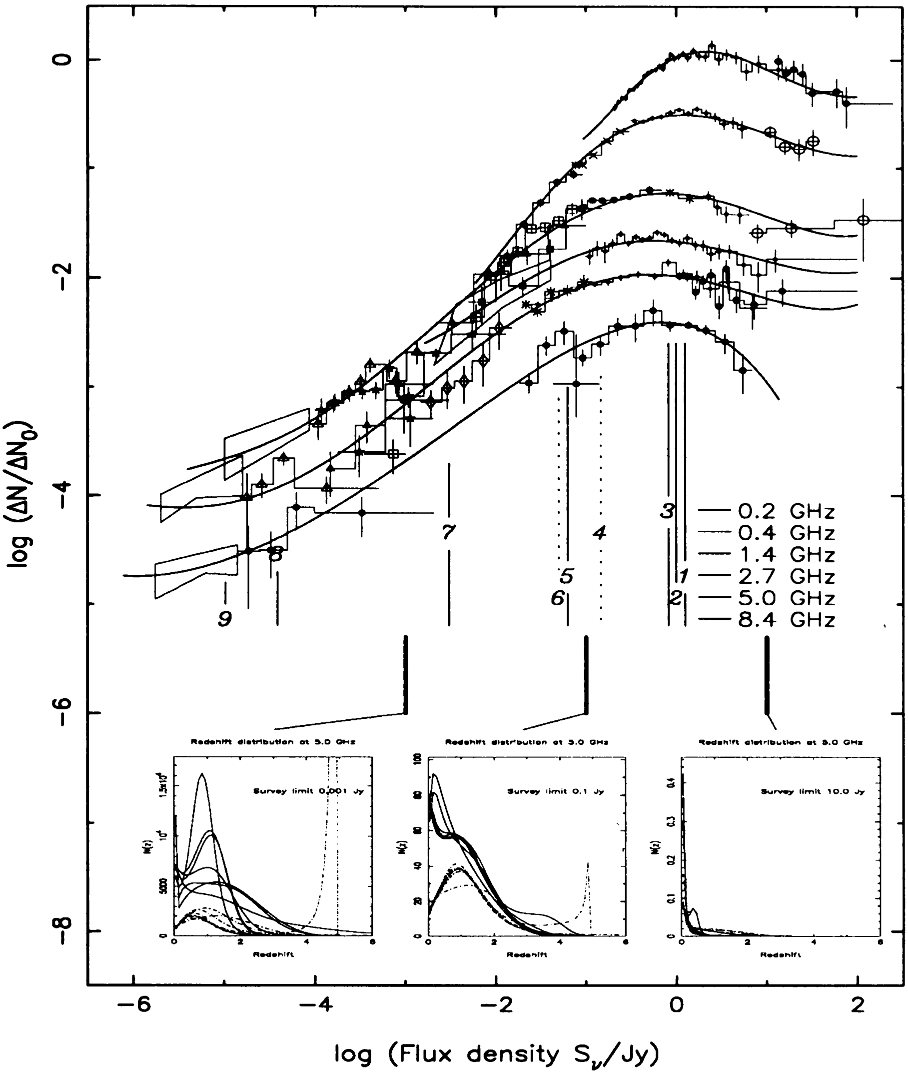

Figure 1. Source counts in relative differential form at 178, 408, 1400, 2700, 5000 and 8440 MHz, descending order. $N_o = K_\nu S_\nu^{-1.5}$, where K_ν = 2400, 2730, 3618, 4247, 5677 and 3738 for the 6 frequencies. References for the surveys are given in Fig. 1 of Wall (1994), with the 10-GHz data replaced here by an 8.44-GHz compilation (Windhorst *et al.* 1993). Polygons represent count estimates from P(D) (background-deflection) analysis. The dashed curves are polynomial least-square fits. Vertical lines indicate equivalent 5-GHz flux-density limits for samples constituting luminosity distributions available for analysis of space distribution. Dotted lines indicate samples-to-be. The limiting flux densities were 'transposed' to 5 GHz with a spectral index of -0.75; actual frequency of compilation is indicated by the row in which each reference is given. These are: 1 Wall & Peacock 1985 and unpublished data; 2 Kühr *et al.* 1981; 3 Laing *et al.* 1983 and unpublished data; 4 R.M. Athreya, this volume; 5 Downes *et al.* (1986); 6 87GB+PMN 5-GHz all-sky survey; 7 Benn *et al.* (1988) and unpublished data; 8 Benn *et al.* (1993); 9 Windhorst *et al.* (1995). Luminosity distributions predicted from the Dunlop-Peacock (1990) space-density models (solid lines for steep-spectrum, dashed for flat-spectrum) are shown under the heavy vertical bars indicating the flux-density limit for each.

few discrepancies (Wall, 1994). Fig. 1 also indicates the equivalent flux-density levels at which luminosity distributions N(P) are complete or approaching completion.

2. Space distribution and the populations

Dunlop & Peacock (1990) analysed the data then available using MEM and free-form epoch-dependent luminosity functions. The uncertainties in space density were mapped by adopting 7 start-point formulations. The analysis was carried out assuming two populations, 'steep-spectrum' and 'flat-spectrum' sources. Principal conclusions were: a) for powerful sources a decline in space density is indicated for epochs corresponding to $z > 3$, b) pure luminosity evolution was permitted by the data, and c) the space distribution for flat and steep-spectrum populations was similar. Predictions of N(P) from the 7 models are shown in Fig. 1. The extreme uncertainties shown at $S_{5GHz} = 0.001$ Jy demonstrate the impact which the new data at these levels will have in improving definition of space distribution.

However, new analyses must do better in terms of the populations: in the face of unified models, retaining 'flat-spectrum' and 'steep-spectrum' as classification is completely erroneous. The common-place populations of the literature are listed in Table 1.

TABLE 1. Extragalactic radio sources

Radio source type	Radio spectrum	Beamed	Membership
Radio galaxies FRI	steep	Y?	1
BL Lac objects	flat	Y	1
Radio-loud QSOs	flat	Y	2
Radio-loud QSOs	steep	Y	2
Radio galaxies FRII	steep	Y?	2,1
GigaHertz-Peak Spectrum sources	'flat'	N?	2
Compact Steep-Spectrum sources	'steep'	N?	2?
Compact Symmetric Objects	flat?	Y	2
High-z radio galaxies	steep	Y	2
Halos, relics	steep	N	3
Starbursters	steep	N	4

Of these 'populations', it is suggested that *memberships 1 (low power) and 2 (high power) encompass virtually all sources catalogued above 1 mJy.* (The relatively few sources of membership 3 (L. Ferretti, this volume) are not considered here, nor is membership 4, included in the tangled populations which appear below 1 mJy; see *e.g.* Windhorst *et al.* 1993, 1995 and F. Hammer, this volume). The considerations are as follows:

1. Unified-model paradigms work (Antonucci, 1993; Urry & Padovani, 1995); in simplest terms, these hold that BL Lac objects are end-on members of FRI radio galaxies (membership 1) while flat-spectrum QSOs are the end-on members of the FRII radio galaxies (membership 2). There are difficulties (*e.g.* Lawrence 1991; Singal 1993) – the picture must be oversimplistic in that (at least) age and environment must play a rôle. In particular uniform optical data for the complete 3CR sample (Laing *et al.*, 1994) show that many *bona fide* FRIIs have very low optical excitation and cannot be part of the QSO paradigm. At lower flux densities, the majority of identifications are with elliptical galaxies showing very weak or no emission lines (Rixon *et al.*, 1991; Wall *et al.*, 1993; Dunlop *et al.*, 1995); many of these have FRII radio structures. These probably represent a major component of the parent population for BL Lac objects. Further evidence is a) the FRII-type structure visible about BL Lac objects (Kollgaard *et al.*, 1992) and b) the inability of FRI galaxies in clusters to provide adequate BL Lac numbers (Owen *et al.*, 1995). FRII radio galaxies thus have membership in both paradigms, as indicated in Table 1.

2. The CSS class of sources (Kapahi, 1981; Peacock & Wall, 1982), comprising $\sim 30\%$ of all sources selected at 2.7 GHz, are either young or straight-jacketed versions of the powerful double radio sources (R. Fanti, this volume). GigaHertz-peaked-spectrum (GPS) sources (*e.g.* O'Dea *et al.*, 1991; Snellen *et al.*, 1995) and Compact Symmetric Objects (CSO) (A. Readhead, this volume) are similarly related.

3. But there are questions of taxonomy to be resolved before we understand the relation between the radio-loud classes. Some QSOs typified by 3C48 and 3C119 have distorted radio structures which do not fit comfortably into relativistically-fed double-structure models. Moreover in an investigation to determine the redshift cutoff for radio-beamed QSOs (P.A. Shaver *et al.*, this volume), a 'flat-spectrum' population of radio galaxies occupies the faint-magnitude reaches of the fully-identified sample. It is likely that these faint red galaxies are the objects which Webster *et al.* (1995) considered to be obscured QSOs. The relation of these objects to CSS and GPS sources is uncertain, let alone their rôle in any unified paradigm.

4. A spatial analysis which accounts for the physical relations sketched here is overdue; first steps have been described in the pioneering paper by Orr & Browne (1982), by Urry & Padovani (1995) and by C. Jackson and JVW (this volume). There is already indication that the memberships 1 and 2 of Table 1 are distributed very differently in space. From Longair (1966) on, analyses have found that the powerful objects (membership 2) show strong evolution, while the weaker show little or no change

in co-moving space density. The redshift cutoff of the flat-spectrum QSOs (membership 2) has been detected (Dunlop & Peacock 1990, P.A. Shaver *et al.*, this volume); the lower-power radio galaxies may show a space-density cutoff at a smaller redshift (J.S. Dunlop *et al.*, this volume).

3. Large-scale Structure

The apparent uniformity of the radio sky (*e.g.* Webster 1977) arises quite simply: to detect anisotropies, surveys must reach a level at which large structures each contribute more than one source to the survey. At a redshift of 1, flux-densities of $\lesssim 10$ mJy must be attained before this is the case (Benn & Wall, 1995a). However, surveys now exist which cover most of the sky and reach to $(3 - 5) \times 10$ mJy, close to this limit. The VLA has embarked on large surveys of the sky (Becker *et al.*, 1995) complete at levels well below that required to see structure.

Statistical investigations of radio-source distribution (Wall *et al.* 1995) have followed two routes: (a) survey analysis with the two-point correlation function, ideally suited to irregularly-shaped areas, and b) prediction of survey-to-survey variation with toy-universe models. The former has been applied to the 87GB and PMN surveys (Wall *et al.*, 1993; Kooiman *et al.*, 1995; Wall *et al.*, 1995), and the signal which is seen at angular scales $< 1°$ is two orders of magnitude stronger than that predicted from galaxy clustering. The second type of analysis modelled the structure by Voronoi tessellation (Benn & Wall, 1995a) to place limits on the scale size of the largest cells. Surveys to 1994 placed a limit of 150 h^{-1} Mpc as the mean distance between cells; analysis of the initial region of the FIRST survey indicates that the limit could be reduced to 50 h^{-1} Mpc. In the context of other constraints on large-scale structure ***this limit occupies a critical range between those provided by galaxy surveys and by COBE results.*** The imprint of large-scale structure has also been seen directly: some 60 redshifts for sources in the 5C12 survey (Benn & Wall, 1995b) show that the majority of these sources are associated with 1 to 3 other sample members. The projected diameters of these groups range from 10 to 70 h^{-1} Mpc, sizes in accord with the largest structures found in optical/IR surveys. This is the ***first direct detection of structure in an unbiassed radio survey.*** Multi-object spectrographs on large telescopes open the possibility of tracing structure directly through deep radio surveys out to $z = 1.0$.

'Cosmologically representative' samples from the FIRST and similar new surveys will have to be chosen with care. Moreover it is now no longer adequate to describe radio-source distribution in the simple radial terms of epoch-dependent luminosity functions.

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