Aust. J. Phys., 1994, **47**, 625–55

Populations of Extragalactic Radio Sources*

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Abstract

In the late 1950s and early 1960s, radio sky surveys were the centre of an intense and public debate—Big-Bang versus Steady-State cosmology—the arguments revolving about source counts and statistical interpretations in the face of instrumental complications. The 1965 discovery of the microwave background took the fire from the debate, but left the momentum in place for large-area radio surveys at different frequencies, and for extensive identification/redshift-measurement programs. By the 1970s the data enabled us to start disentangling the different populations of extragalactic radio sources. We could refine our taxonomy, and we could view the possibility of delineating individual cosmic histories and evolutions. We could at least describe a goal to elucidate the birth–life–death cycles of the objects involved [quasi-stellar objects (QSOs) and radio galaxies: together the 'active galactic nuclei' (AGNs)] whose unaccountably prodigious energies somehow produce the beautifully aligned radio structures with which we are now familiar. One part of John Bolton's vision was to see how distorted a view of the AGN universe the original long-wavelength surveys provided. One legacy is thus the 'short-wavelength survey' for extragalactic radio sources, which has done so much to balance our picture of the radio sky. And indeed the legacy continues in the form of the immense sky surveys at present under way, complete with their sub-industries of radio-positioning and identification. From these, yet further results are emerging on spatial distribution and the skeleton structure of the universe. It is the purpose of this paper to outline something of this current view of the populations, their differences, similarities and unifying concepts.

1. Introduction

John Bolton and I met in the depths of Canadian winter, and he interviewed me—although I didn't know it at the time—during a 15-minute chat in the back seat of Allan Yen's car as we travelled from Richmond Hill Observatory south towards Toronto, banks of snow towering on either side of the road. We talked about circulators, Dicke switches, cold loads, ground radiation and spillover, the nuts and bolts of absolute-background measurements in radio astronomy. I was considering taking up an Athlone Fellowship in the UK to do radio astronomy instrumentation; he was on the way back to Australia. Two weeks later I received a letter from Bart Bok, Director of the Australian National University's Mt Stromlo Observatory, offering me a studentship from the ANU to do a doctorate

* Refereed paper based on a contribution to the John G. Bolton Memorial Symposium held at the Parkes Observatory, 9–10 December 1993.

0004-9506/94/050625$10.00

with John Bolton via the Stromlo/Parkes Telescope collaboration. Looking up a map to find Canberra and Parkes, and indeed Australia, and looking out at the driving snow, I made a decision that I have never regretted.

2. Historical Introduction: The World in 1967

When I began work with JGB in 1967, the state of our knowledge of extragalactic radio sources was something like the following:

- Radio surveys at low frequencies ($\nu \leq 408$ MHz) covered the entire sky, principally through the efforts at Cambridge (3CR and 4C) and Parkes. The first synthesis surveys had been performed (Ryle and Neville 1962; Kenderdine *et al.* 1966). Several hundred radio sources had been catalogued.
- The surveys were dominated by steep-spectrum radio sources whose structures, determined primarily from interferometry at Jodrell Bank and the California Institute of Technology, were essentially double, or double with a third compact component near the centroid. Synchrotron emission was firmly established as the radiation mechanism; the double structure probably arose from ejection or channelling of energy from the nucleus (e.g. Scheuer 1967), but how? Relativistic bulk motion (Rees 1966, 1967) had been suggested. Confinement by the intergalactic medium was important (De Young and Axford 1967). Polarisation of radio emission (Mayer *et al.* 1962) and its Faraday rotation (Cooper and Price 1962) had been discovered in extended radio sources.
- A few sources with flat or inverted radio spectra [e.g. PKS 1934–63 (Bolton *et al.* 1963) and 3C 273] were known; synchrotron self-absorption in optically thick components was identified as the cause (e.g. Slysh 1963; Shklovskii 1965; Kellermann 1966*a*). Flux-density variations (Dent 1965) had been found in 3C 273.
- Large programs of radio-source identification were in progress, the most ambitious being led by JGB at Parkes. The programs showed that many of the radio sources could be identified with faint early-type galaxies [e.g. the seminal identification of Cyg A by Baade and Minkowski (1954) with its redshift measured at 0·16; the identification of 3C 295 and measurement of its redshift of 0·46 by Minkowski (1960), a galaxy record that stood for 10 years; and the identification by Matthews *et al.* (1964) of many radio sources with D-galaxies, large 'diffuse' galaxies in rich clusters]. A few nearby spirals, e.g. NGC 253 = PKS 0045–25, figured amongst the brightest radio sources, as did a few of the brightest ellipticals, as Mills and colleagues (e.g. Mills *et al.* 1960) had noted. But the majority of host objects, some three-quarters of them, lay at optical magnitudes too faint to be reached by the Palomar Observatory Sky Survey, the first-generation Schmidt Telescope survey covering a significant fraction of the sky.
- Quasi-stellar objects (QSOs or 'quasars') had been discovered; the Parkes telescope was instrumental in identifying 3C 273 (Hazard *et al.* 1963; Schmidt 1963). Radio-quiet QSOs had been found in numbers many times greater than those of the radio-loud ones (Sandage 1965), but were not quite as plentiful as originally envisaged (Lynds and Villere 1965). Only a few tens of redshifts were known for radio sources, QSOs, radio galaxies and bright galaxies inclusive.

- The identification statistics and the surface-density statistics (source counts or log$N$–log$S$ curves) indicated, on a conventional interpretation of redshifts, that radio sources formed preferentially in early epochs of the universe (e.g. Longair 1966). This conclusion was not without controversy, and indeed the source-count debate continued for some years; Scheuer's (1990) outline of the history is fascinating. The $V/V_{\rm max}$ (luminosity–volume) test was on the way (Rowan-Robinson 1968; Schmidt 1968), supporting the strong cosmic evolution inferred from the source counts. However, the discovery of the 3 K cosmic background radiation (Penzias and Wilson 1965) had taken the steam from the argument; the hot Big Bang universe no longer relied upon the radio-source surveyors to support it.

The recognised populations of extragalactic radio sources thus consisted of:

(i) bright nearby galaxies, some spirals and Seyferts (NGG 1068 = PKS 0240–00), some peculiar and roundish (Cen A = NGC 5128; For A = PKS 0320–37);

(ii) QSOs, some of which had suggestively flat or inverted radio spectra, although statistical differences between QSOs and radio galaxies were disputed; and

(iii) faint radio galaxies, whose relation to the bright radio galaxies was unknown.

It was still some time before: twin-exhaust models, the picture of collimated energy beaming from a massive gyroscopic energy-converter at the nucleus (Rees 1971; Scheuer 1974; Blandford and Rees 1974); BL Lac objects (MacLeod and Andrew 1968); the Fanaroff and Riley (1974) discovery of the radio-structural dichotomy as a function of luminosity; superluminal expansions (Moffet *et al.* 1972) and relativistic beaming (Rees 1971; Scheuer and Readhead 1979; Blandford and Königl 1979).

The relation (if any) between the populations was completely unclear. But what JGB knew instinctively was that the way forward needed massive and systematic expansion of our database. He was a hunter (and not a surveyor, that aspect was left to the rest of us). He wanted to find QSOs; radio galaxies would do as a distant second-best. His instinct was that the higher frequencies would find them because of their spectral curiosities; and moreover—as an ardent Steady-State proponent—he suspected that we might find inverted-spectrum sources in sufficient numbers to build up the microwave background. If he was disappointed in this, he never showed it (but he wouldn't, would he?); and in any case the tens of years of effort which subsequently went into cm-wavelength surveys received ample reward.

It is something of that reward that I will describe here. Thanks to the hunting urges by which JGB drove us to survey the sky, we now know far more about how the different radio constituents fit together. The most fundamental data from sky surveys are source counts, the plots of the numbers of sources found per unit area as a function of observed intensity. Therefore, to set a context, I first present a new compilation of source counts whose general features provide a framework in which to describe the populations. Section 3 discusses the populations and sub-populations which lead the counts to look as they do, after which I present

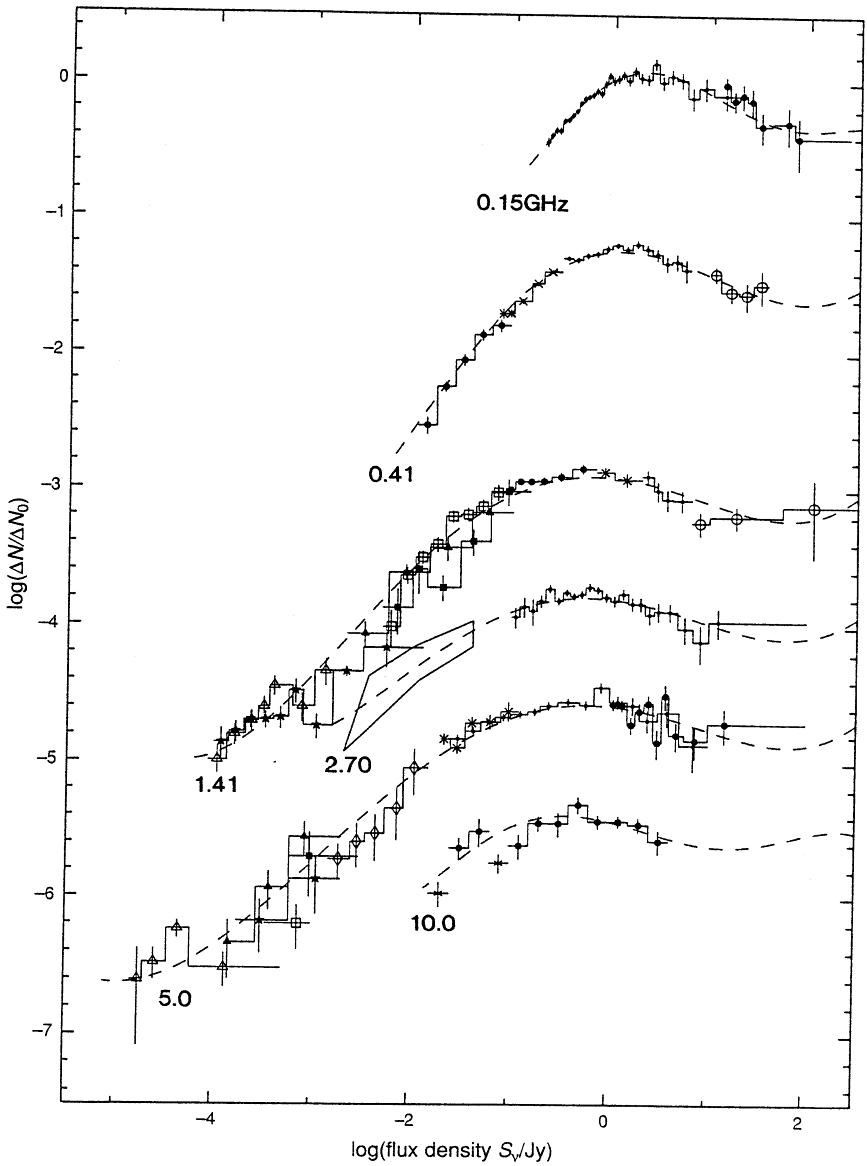

Fig. 1. Source counts at the frequencies indicated. The counts are in relative differential form $\Delta N/\Delta N_0$, where N is the number of sources per sterad with flux density S_ν between S_2 and S_1, while $\Delta N_0 = K_\nu S_\nu^{-1 \cdot 5}$, the number expected for a uniformly filled universe of Euclidean geometry. The horizontal line corresponding to each data entry corresponds to the flux-density bin-width S_2 to S_1, and the error bar represents the $\sqrt{n}$ error; bins which are joined are from the same survey data series. The constants K_ν are 2400, 750, 200, 100, 60 and 20 for each of the six frequencies from 0·15 to 10·0 GHz shown; an additional displacement of $3\log_{10}(0 \cdot 151/\nu)$ has been added to disentangle the counts for display purposes. The data sources are as follows. 0·151 GHz: filled circles, Laing *et al.* (1983); dots, Hales *et al.* (1988); 0·408 GHz: open circles, Robertson (1973); dots, Grueff (1988); crosses, Grueff (1988); filled circles, Benn *et al.* (1982); 1·41 GHz: open circles, Bridle *et al.* (1972); dots,

two digressions describing results from recent investigations, each dealing with a particular aspect of JGB's intuition which made him the great scientist that he was.

3. Surveys, Counts and Populations

The surface-density counts $[N(S)]$ of extragalactic radio sources carry substantial amounts of cosmological and astrophysical information, and thus provide a convenient frame in which to discuss surveys and the populations which are discovered. A compilation of counts from surveys is shown in Fig. 1, presented in the now-standard 'relative differential' form.*

The set comprises the most extensive and most detailed counts, at the most popular (best-protected and best-instrumented) wavelengths; the chosen frequencies cover the radio spectrum at approximate octaves from 0·2 to 10 GHz. Perhaps the most notable omissions in the compilation are counts/surveys at 0·61 GHz (e.g. Katgert-Merkelijn *et al.* 1985); 0·84 GHz (Subrahmanya and Mills 1987); and 8·4 GHz (Windhorst *et al.* 1993).

The diagram shows the following features.

(i) At each frequency, surveys from different instruments and using different techniques overlap. The overlaps agree, providing verification that major discrepancies between counts in different areas of sky and with different types of instrument are no longer serious. Some discrepancies do exist to

* It was Jauncey (1967) who first drew attention to the statistical dangers of using the *integral count*, the infamous log$N$–log$S$ curve, which up to then had been the standard way of presenting such data. In such a presentation, the plot is simply of the total number of sources (per unit area) with flux density greater than S, as a function of S. One of the statistical problems is that the $\sqrt{N}$ error bars are not independent, each bin at a lower flux density containing the sources at all higher intensities; and there are other inadequacies as well. But the *differential count*, the number of sources ΔN in a flux-bin of width ΔS, has the disadvantage of being extremely steep; the *relative differential count* now used is the number of sources ΔN normalised by ΔN_0 where ΔN_0 is the number predicted from a universe whose geometric framework is static Euclidean, with radio sources of all luminosities uniformly distributed in it. Momentary manipulation of the inverse-square law and the cube law for volume as a function of radius shows that the source count in such a universe has a slope of $-\frac{3}{2}$ in integral form, $-\frac{5}{2}$ in differential form. In practice, while we believe that the universe is governed by relativistic geometry, we do not know just which one; and we settle on the Euclidean universe for the comparison as one which we all agree cannot exist, but for which the sums are simple. In particular, for such a universe the relative differential source count is a horizontal line in Fig. 1. But it is crucial to note how dramatic the relativistic effects are (e.g. Wall 1983); in a uniformly filled universe in which redshifts indicate distance, the count does not approach the Euclidean count even at the very brightest flux densities.

Bridle *et al.* (1972); asterisks, Fomalont *et al.* (1974); filled circles, Machalski (1978); filled squares, Condon *et al.* (1982); filled triangles, Benn *et al.* (1982); open squares, Oosterbaan (1978); stars, Oort (1987*a*); open triangles, Mitchell and Condon (1985); 2·70 GHz: dots, Wall and Peacock (1985); solid area [from background deflection or $P(D)$ analysis, Wall and Cooke (1975 and unpublished data); 5·0 GHz: filled circles, Kühr *et al.* (1981); dots, Gregory and Condon (1991); asterisks, Altschuler (1986); open diamonds, Wrobel and Krause (1990); filled square and open square, Fomalont *et al.* (1984); stars, Partridge *et al.* (1986); filled triangles, Donnelly *et al.* (1987); open triangles, Fomalont *et al.* (1991); 10·0 GHz: filled circles, Aizu *et al.* (1987); crosses, Aizu *et al.*, possibly incomplete. The dashed curves are polynomial least-squares fits to the counts.

the point of significance, particularly amongst 5·0-GHz data; but such discrepancies no longer indicate basic indeterminacy in the form of the $N(S)$ law. Polynomials, least-squares-fitted through the data (Fig. 1), confirm the general agreement.

(ii) The form of the law is similar at all frequencies. All counts show a flattened ('Euclidean') region at the highest flux densities, followed progressively to lower intensities by a steep rise, a plateau, and then a roll-off from the plateau towards the lowest intensities. The two deepest counts at 1·41 and 5·0 GHz both show a point of inflection below 1 mJy, flattening towards the horizontal yet again. Three portions of the count are thus evident: the initial Euclidean section (Section 3·1), the bulge due to source evolution (Sections 3·2 to 3·5), and the flattening sub-milliJansky tail (Section 3·6).

(iii) The form may be the same, but there are significant differences as a function of frequency. The central plateau broadens as frequency increases, demonstrated in Fig. 2 which shows (for the four best-defined counts) the polynomials of Fig. 1 normalised to the same maximum in count and in flux density. Fig. 3 plots the flux density corresponding to the maximum of each relative differential count as a function of frequency; a monotonic decrease in flux density of the maximum is evident to ~1·5 GHz, beyond which the relation flattens. The differences are discussed in Section 3·2.

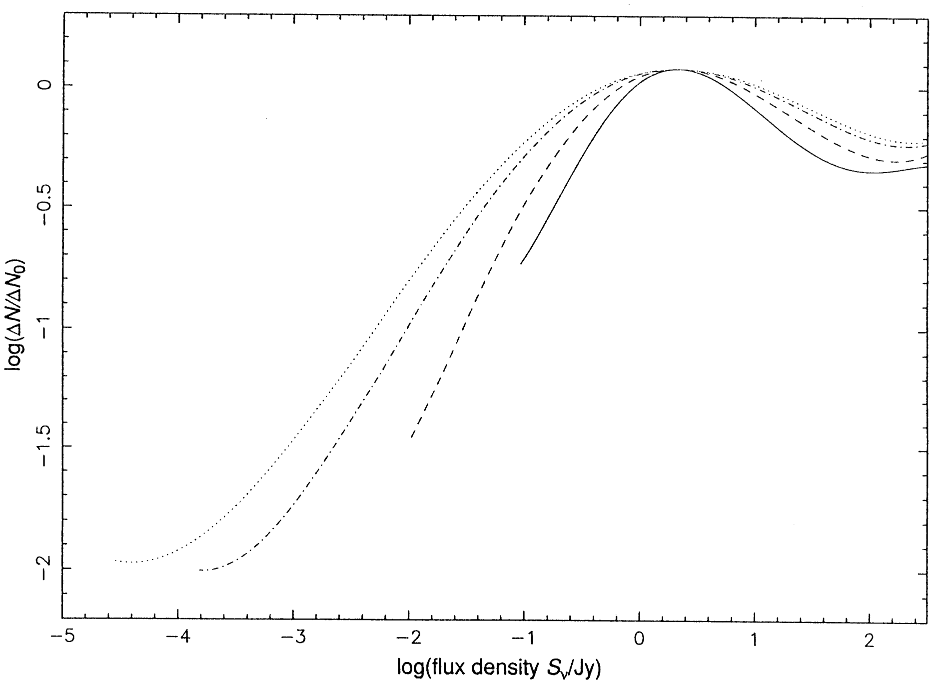

Fig. 2. Polynomial representations of the four best-defined source counts of Fig. 1: solid curve, 0·151 GHz; dashed curve, 0·408 GHz; dot-dashed curve, 1·41 GHz; dotted curve, 5·0 GHz. The curves have been normalised in count and shifted in flux density so that maxima coincide to demonstrate the progressive shape-change with frequency.

(iv) Fig. 4 shows the results of integrating the polynomials of Fig. 1. Although the integral count is in statistical disrepute, it serves at least one useful purpose by indicating total *sky surface densities*, essential for many calculations. The figure shows the counts crowding together towards the higher frequencies, another statement of the levelling-off of the relation in Fig. 3; and it also shows that the deepest surveys now reach intensities which correspond to sky surface densities well in excess of 10^7 sources/sterad.

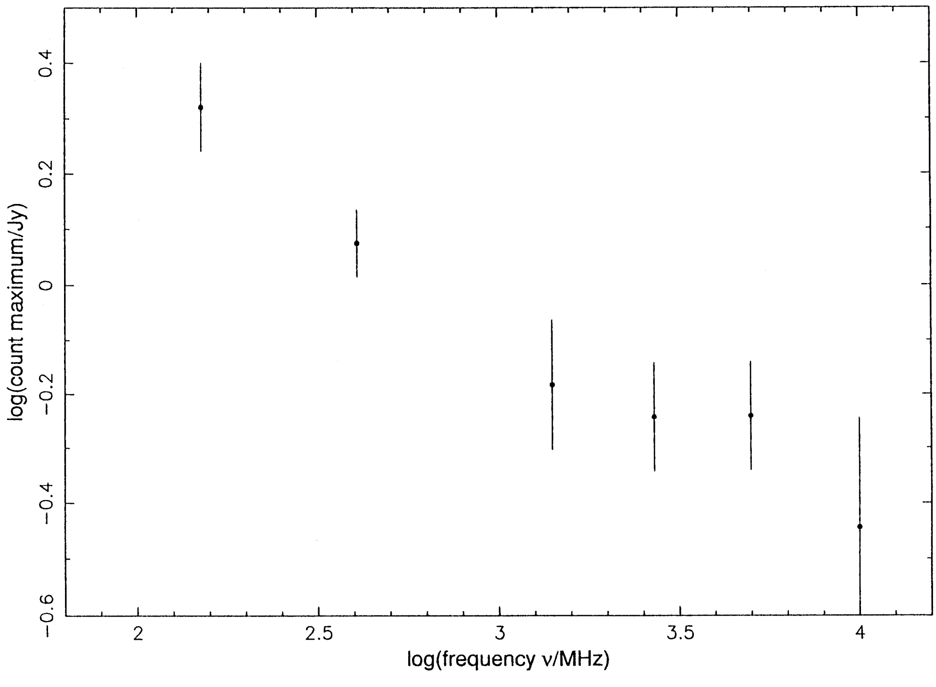

Fig. 3. Flux-densities of the relative differential source-count maxima, plotted as a function of survey frequency.

3.1 The Brightest Sources

The very brightest extragalactic sources are known in various degrees of intimacy to all of us. What is perhaps surprising is that despite their prominence, and despite the *N(S)* relation suggesting that they might constitute a class, they do not. The brightest 21 sources ($S_{2\cdot7\,\mathrm{GHz}} > 10$ Jy) are shown in Table 1. The list is split equally between objects at very low and high redshifts; the median redshift is 0·055. There are six QSOs in the list, five of which have the five highest redshifts, while the remaining object is 3C 273; the QSO redshift median is 0·6. The most distant galaxies have redshifts of 0·46 (3C 295) and 0·22, and are end-brightened (FRII) doubles; see Section 3·2. The source PKS 0521–36 was originally classed as an N-galaxy (nucleus-dominated) by Bolton *et al.* (1965); it became a BL Lac object (see Section 3·3·1) when the polarised optical spectrum and the lack of prominent emission lines were noted (Stein

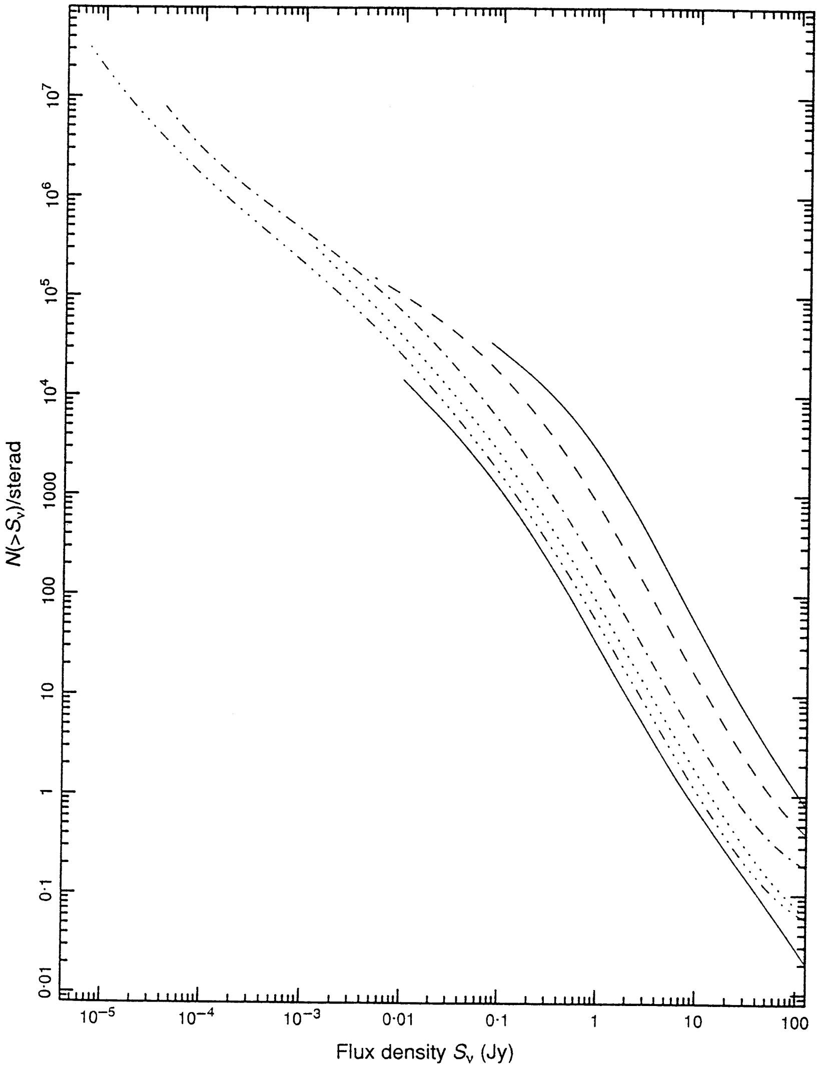

Fig. 4. Integral source counts at the six survey frequencies, obtained by integrating the polynomial fits shown in Fig. 1: upper solid curve, 0·151 GHz; dashed curve, 0·408 GHz; dot-dashed curve, 1·41 GHz; dotted curve, 2·70 GHz; triple-dot-dashed curve, 5·0 GHz; lower solid curve, 10·0 GHz.

et al. 1976), and reverted to a radio galaxy when broad emission lines flared into existence (Ulrich 1981). PKS 1934–63, whose discovery (Bolton *et al.* 1963) was crucial to the ideas of synchrotron self-absorption (Slysh 1963; Shklovskii 1965; Kellermann 1966*a*), is perhaps the prototypical GHz-peaked source (GPS; see Section 3·3·2), and is an interacting system (Fosbury *et al.* 1987). The remaining well-known objects approximate to FRI (Section 3·2) doubles. There is little homogeneity. The flatness (Euclidean behaviour) of this region of the count arises partly from the dilution of the evolving-bulge sources (following Section) with the nearby objects, and partly from the behaviour of the luminosity function at low redshifts and radio powers (Wall and Peacock 1985).

Table 1. The 21 brightest extragalactic sources at 2·7 GHz

IAU	Name	α (1950)	δ (1950)	$\pm$ ($''$)	$S_{2\cdot7}$	$\alpha_{2\cdot7}^{5}$	ID	V	z
0320−37	For A	03 20 46·80	−37 23 06·0	4·0	98·00	0·52	G	5·1	0·0057
0433+29	3C 123	04 33 55·21	+29 34 12·6	0·3	27·57	0·86	G	19·9	0·218
0518−45	Pic A	05 18 23·00	−45 49 44·0	6·0	29·00	1·07	G	16·0	0·035
0521−36		05 21 12·95	−36 30 16·0	0·6	12·50	0·49	G	15·0	0·055
0538+49	3C 147	05 38 43·53	+49 49 42·9	0·1	13·14	0·77	Q	16·9	0·545
0915−11	Hyd A	09 15 41·18	−11 53 04·4	0·4	23·50	0·90	G	14·7	0·054
1216+06	3C 270	12 16 51·20	+06 06 13·0	6·0	12·80	0·56	G	10·4	0·0069
1226+02	3C 273	12 26 33·25	+02 19 43·3	0·1	38·90	−0·05	Q	12·8	0·158
1228+12	Vir A	12 28 17·55	+12 40 01·8	0·1	120·00	0·93	G	8·7	0·0038
1253−05	3C 279	12 53 35·82	−05 31 07·6	0·1	11·20	−0·59	Q	17·8	0·538
1322−42	Cen A	13 22 32·23	−42 45 25·0	40·0	128·00	1·20	G	7·0	0·0008
1328+30	3C 286	13 28 49·65	+30 45 58·5	0·1	10·38	0·53	Q	17·3	0·849
1333−33	IC 4296	13 33 47·18	−33 42 39·8	0·9	10·06	0·79	G	11·1	0·013
1409+52	3C 295	14 09 33·44	+52 26 13·6	0·4	11·94	0·99	G	20·2	0·461
1648+05	Her A	16 48 40·10	+05 04 28·0	5·0	24·60	1·11	G	16·9	0·154
1717−00	3C 353	17 17 53·29	−00 55 49·5	0·4	33·80	0·84	G	15·8	0·031
1828+48	3C 380	18 28 13·51	−48 42 40·5	0·1	10·00	0·78	Q	16·8	0·691
1934−63		19 34 47·65	−63 49 34·7	1·6	11·10	0·88	G	18·4	0·183
2152−69		21 52 57·80	−69 55 40·2	0·5	19·27	0·71	G	14·0	0·027
2251+15	3C 454·3	22 51 29·53	+15 52 54·4	0·1	10·00	−1·37	Q	16·1	0·860
2356−61		23 56 29·47	−61 11 40·6	0·5	10·22	1·36	G	16·0	0·096

3.2 Evolution-bulge Sources

The evolution bulge is populated by the powerful radio sources, the sources of classical double structure with steep, smooth radio continua. Frequently there is a compact radio core, coincident with the nucleus of the optical counterpart, which is generally a faint galaxy, less frequently a QSO. This type of source dominates the low-frequency ($\nu < 1\cdot4$ GHz) surveys. But in a proportion of the sources, the central core is totally dominant; such radio-compact objects have spectra which do not obey simple power laws, and are usually identified with QSOs. The evolution bulge contains an increasing proportion of such objects as survey frequency is raised, as discussed below.

The cosmic evolution producing the bulge is violent (see e.g. Longair 1966; Wall *et al.* 1980, 1981; Condon 1989; Dunlop and Peacock 1990). The co-moving space density at $z \sim 1$ is factors of 1000 to 10,000 higher than that at the present epoch. Condon (1993) has emphasised that this evolution is such a dominant feature of the radio populations detected in sky surveys that the proportion of identifications with nearby objects is tiny; the median redshift is close to 0·8 for all samples of radio sources complete at virtually any level of intensity down to 1 mJy. Even amongst the very brightest samples it remains stubbornly high at 0·6 (Section 3·1), and is the reason for relativistic geometrical effects being so important in source-count interpretation at all intensities. As Condon puts it: 'Most extragalactic radio astronomers live in a distant part of the Universe ...' and their objects are powered by 'monsters', massive objects, black holes in all probability, with attendant phenomenology (Lynden-Bell 1969; Rees 1971; Blandford and Rees 1974), including gyroscopic effects providing the collimation axes.

With regard to the dominant double sources of low-frequency ($\nu \leq 1\cdot 4$ GHz) surveys, Fanaroff and Riley (1974) drew attention to a correlation between morphology and radio luminosity: doubles with end-brightened radio components (known as Fanaroff–Riley type II, FRII) were shown to require radio luminosities above $\log_{10}P_{1\cdot 4\,\mathrm{GHz}}(\mathrm{W\,Hz^{-1}}) = 25\cdot 5$, while those with their regions of highest surface brightness closer to the nucleus (FRI) are of lower radio power. The classic study by Laing *et al.* (1983; updated by R. A. Laing, personal communication) has near-complete identification and radio-structure data for the revised 3CR sample of 173 sources with $S_{178} \geq 10$ Jy. The sample contains 28 FRI, 132 FRII and 13 compact or core-dominated sources. Of the FRII sources, 30 are QSOs and 102 are galaxies; all 13 of the compact sources are QSOs. All of the 28 FRIs are galaxies. Most of the 3CR objects have so-called steep spectra (see Kellermann *et al.* 1969), in which the flux density obeys a power law $S_\nu \propto \nu^\alpha$, with the spectral index α generally in the range $-0\cdot 6$ to $-1\cdot 2$, the distribution peaking at about $-0\cdot 8$. These spectra frequently bend to steepen somewhat towards the higher frequencies. The interpretation is in terms of synchrotron radiation, with steepening due to the shorter lifetimes of the higher-energy electrons (Kellermann 1966*b*; Scheuer and Williams 1968).

All parent galaxies, hosts of either FRI or FRII radio sources, are very luminous and show a relatively narrow dispersion in absolute magnitude (Sandage 1972). The hosts of FRI objects are somewhat more luminous and occur in generally richer clustering environments than are those of the FRII objects of relatively low power (Owen and Laing 1989). It now appears that the FRI/FRII radio-morphology separation is a function of optical as well as radio luminosity (Owen and White 1991). This phenomenological summary of radio galaxies does not address the critical question of *what makes a radio galaxy*. Summaries of recent observations and ideas are given by Peacock (1993) and McCarthy (1993).

As survey frequency is raised, in flux-limited samples the proportion of sources with spectra that do not die away in steep and steepening power-laws decreases. In their place come increasing numbers of so-called 'flat-spectrum' sources. No description could be worse—'flat-spectrum' merely indicates 'non-steep-spectrum'. In fact the spectra of such objects in the frequency range $0\cdot 1$ to 10 GHz show wide variety, from low-frequency power laws inverting to rise towards the higher frequencies, to single or multiple 'humps' in the frequency range (e.g. Wall 1972*a*, 1972*b*; Kühr *et al.* 1981). Following the discovery of time-varying flux density in 3C 273 (Dent 1965), it was found that sources with steep-spectrum components *and* higher-frequency humps often show substantial time variations in flux density at frequencies close to or above the hump maxima. It was soon realised that the sources with humps in their spectra were compact, or 'core-dominated' (Kellermann *et al.* 1962); that the humps were due to synchrotron self-absorption in regions of very high surface brightness (Slysh 1963); that variations could be explained as expanding structures (Shklovskii 1965; van der Laan 1966); that sources with a region of radio spectrum in which the index was more positive than $-0\cdot 5$ showed self-absorption features (Wall 1972*b*); and that sources of such spectra were to be predominantly identified with QSOs (Bolton and Wall 1968). These points made the case for the extent of the PKS $2\cdot 7$-GHz survey, the

NRAO 5-GHz survey, and subsequent large-scale, cm-wavelength explorations of the sky.

The contrast in populations between low- and high-frequency surveys is shown by considering complete samples of the bright sources at 2·7 GHz (Peacock and Wall 1981, 1982; Wall and Peacock 1985), analogous to the 3CR (Laing *et al.* 1983) sample. Of the 117 steep-spectrum sources in the original complete sample of 168 sources with $S_\nu \geq 1{\cdot}5$ Jy at 2·7 GHz, Peacock and Wall (1982) found 20 to be FRI, 61 to be FRII and 36 to be unresolved. The remaining 51 sources are all core-dominated. The effect of changing frequency is not just the simplistic one of selecting more core-dominated sources; there is a complex interchange (Peacock and Wall 1982) which raises the number of FRIs, and the number of a still-mysterious class of objects, the 'compact steep-spectrum' (CSS) sources, discussed briefly below. It was at this stage that the view of radio-population botany as *'steep-spectrum'* = *extended* (with a radio-luminosity division into FRI and FRII) and *'flat-spectrum'* = *compact* was destroyed forever.

By 5 GHz, the proportion of core-dominated objects in bright samples has risen to well above 50% (e.g. Pauliny-Toth *et al.* 1978).

When sources are divided simply by integrated spectrum as an elementary way of separating extended and compact structures, the counts of the flat- and steep-spectrum objects differ substantially (Kellermann and Wall 1987). Each has a *separate* evolution bulge, the evolution bulge of the flat-spectrum objects occurring at a higher flux density than that of the steep-spectrum sources. The result has a major influence on the form of count as a function of frequency. As survey frequency is raised, the increasing proportion of flat-spectrum sources broadens the evolution bulge of the combined count into a plateau (Figs 1 and 2), while halting the march of the flux density of the peak towards lower flux densities (Fig. 3), which would be expected if all contributing sources had spectral indices near −1. The change in shape of count with frequency initially caused us to consider different evolutions and different space distributions for compact and extended objects (e.g. Schmidt 1976; Masson and Wall 1977; Wall *et al.* 1981), and substantial new databases and analyses had to be developed before the space distributions agreed (e.g. Dunlop and Peacock 1990). This apparent difference (and the subsequent reconciliation) had far more significant ramifications than we realised at the time.

These ramifications began to emerge with a startling discovery that appeared initially to have little to do with cosmology: superluminal radio sources. Between 1969 and 1971 (e.g. Moffet *et al.* 1972), repeated VLBI measurements of some flux-varying compact sources led to the realisation that their components had apparent relative velocities greater than *c*. Relativistic expansion had been established. (A brief and excellent summary of superluminal history is presented by Pearson and Zenzus 1987.) Rees (1966, 1967) had suggested relativistic bulk motion to alleviate the 'Compton catastrophe'—the self-destruction of radio sources by the relativistic electrons blasting the synchrotron-generated radio photons up into the X-ray spectral regime. This problem was serious: the alternative was to reject the cosmological nature of redshifts (Hoyle *et al.* 1966). Seminal papers by Blandford and Rees (1978), Blandford and Königl (1979), Scheuer and Readhead (1979), and Orr and Browne (1982) suggested a totally new view of radio-source populations. The most generally accepted model of superluminal sources is the *relativistic beaming model* (see Scheuer 1987) in which the observer is in a privileged position: the axis of ejection is pointed towards the observer; ejection is relativistic; and the apparent intensity of the source is 'Doppler-boosted', selectively amplified by immense factors. These papers pointed out that if the overwhelming majority of core-dominated sources were viewed by such observer-privilege, there must exist far greater numbers of 'less privileged' sources, the parent population, i.e. the beamed-but-badly-aimed objects. What did these objects look like; did they constitute a radio-source population known to us? The most commonly accepted answer is the 'Unified Scheme' of Orr and Browne (1982; see also Kapahi and Saikia 1982)—the extended steep-spectrum radio galaxies and QSOs are the side-on counterparts of the core-dominated, flat-spectrum, beamed superluminals. Orr and Browne calculated the higher-frequency source counts for beamed objects on the supposition that the standard steep-spectrum extended objects of the low-frequency count were the parent population, and a simple beaming model—and they showed how the flat-spectrum count, shifted to higher flux densities as described above, arises as a result. The requirement in such a model was that flat-spectrum, core-dominated sources had a similar space distribution and evolution behaviour to that of the steep-spectrum parent population.

Before considering fully unified models of flat- and steep-spectrum sources, QSOs and radio galaxies, a vital ingredient still had to be supplied, and it came from optical and X-ray investigations of nearby active galactic nuclei in Seyfert galaxies such as NGC 4151 and NGC 1068. The optical spectra of all of these show narrow lines of high excitation (e.g. [OII], [OIII]), while some show very broad lines of lower excitation, hydrogen in particular. The spectra of the latter class strongly resemble those of QSOs, and the objects have indeed been called mini-QSOs. Could the narrow-line and broad-line objects be unified? Was there a way in which the so-called broad-line region could be obscured in some objects, but never the narrow-line? The clue came from NGC 1068, in which broad lines are seen *in polarised light only*. Antonucci and Miller (1985) proposed the 'dusty torus': look head-on into the torus and see the blue continuum and the broad-line region produced by the monster, together with the narrow lines from the distributed gas outside the nuclear region; look side-on and see just the narrow-line emission in the cones outside the torus—no monster. Narrow-line objects in which polarised broad lines are seen constitute the side-on case in which the nuclear light can just be seen by scattering from dust or hot electrons in the cones. The realisation dawned that this could be the difference between QSOs and galaxies in the optical; looking down into the torus blinds the observer with perhaps 5 mag of extra blue continuum from the accretion disc around the monster at the nucleus, swamping the relatively low surface brightness of the galaxy's luckless stars, and making the object appear quasi-stellar. The elements were in place for unified models.

It was such considerations that led Robert Laing to take Charles Jenkins, Steve Unger and me into an extensive optical study, which has put a new perspective on one major aspect of the unified-model paradigm, namely that aspect that involves the powerful radio sources, the FRII radio galaxies and QSOs. Section 4 is a digression which presents our new results.

3.3 Additional Sub-populations of the Evolution Bulge

However, the evolution bulge population contains other sub-populations in addition to the FRI galaxies and the FRII radio-galaxy/QSO components.

3.3.1 BL Lac objects

In 1968 BL Lac, a 14-mag entry in the catalogue of variable 'stars', was identified with the flat-spectrum radio source VRO 42·22·01 (MacLeod and Andrew 1968; Schmitt 1968). Subsequently AP Lib (PKS 1514−24) joined this select group of extragalactic radio sources in the variable-star catalogue. But what distinguished them, and the numerous other such 'BL Lac objects' found subsequently, was not so much the error in classifying the objects as galactic or extragalactic, but the fact that the optical continua are virtually featureless, being devoid, in particular, of the emission lines which characterise other powerful radio sources. These optical continua are extremely blue, variable and polarised, synchrotron emission without a doubt and probably heavily beaming-enhanced. Several tens of such objects are known, many with redshifts now determined by careful searches for hints of absorption lines due to the underlying galaxy. Stein *et al.* (1976) present a review, while the conference volumes edited by Wolfe (1978) and Maraschi *et al.* (1989) collect current wisdom.

Are BL Lacs some kind of gas-poor QSO? Adoption of the term 'blazar' to encompass BL Lacs and highly polarised QSOs does not in itself force unity. The objects might be unusual isotropic radiators, gravitationally lensed QSOs (Ostriker and Vietri 1990), or relativistically beamed AGNs (Königl 1989) with the low-luminosity (FRI) radio galaxies as host population (Browne 1989). A comprehensive study by Morris *et al.* (1991) on an X-ray selected sample with near-complete redshift data provides considerable support for the latter scheme, from the point of view of luminosity functions, radio luminosities, and X-ray properties. Lensing (Ostriker and Vietri 1990) was shown by Morris *et al.* to be statistically unimportant; isotropic radiation is unlikely because of rapid variability and the requisite high luminosities. The BL Lacs are thus probably the counterparts of the core-dominated QSOs. The unification scheme (Browne 1989; Padovani and Urry 1990) operates at a lower radio power than the FRII–QSO scheme: the host (parent population) is the FRI galaxy (side-on) while the beamed (head-on) product is the BL Lac object.

3.3.2 Further compact populations: GPS and CSS

For surveys at cm-wavelengths, at the high flux densities, say $S_{2\cdot 7} > 2\cdot 0$ Jy, *all* flat-spectrum radio sources are identified with QSOs except for five or six radio galaxies and BL Lac objects. Towards the lower intensities, an increasing proportion of the flat-spectrum sources becomes identified with very faint ($m_b \geq 23$) galaxies. The apparent-magnitude distribution (see e.g. Savage *et al.* 1988) is bi-modal; these faint galaxies with compact radio structures are something quite different.

This component of the flat-spectrum population that is optically quiet consists of the *gigahertz-peak spectrum* (GPS) sources (e.g. O'Dea *et al.* 1991). The radio spectrum is distinctive; it does not show evidence for a low-frequency (presumably extended) component, but peaks near 1 GHz, and drops monotonically to the higher frequencies. The compact radio structure has low polarisation and this, together with the spectral decline, no detection of superluminal motion, and little variability, suggests that relativistic beaming plays no significant role in our view of the sources. A number of sources in the GPS class are identified with QSOs and, for these, VLBI observations show complex morphologies. These may well be intruders, part of the QSO–radio-galaxy paradigm. But for the majority (galaxies, optically quiet), the radio structure is double in form with the components separated by distances much less than the extent of the optical disk—typically 10–1000 pc (e.g. Phillips and Mutel 1980; Mutel and Phillips 1988; Pearson and Readhead 1988). The galaxies are very red, and the images show distortions suggestive of interaction.

Compact steep-spectrum (CSS) sources, on the other hand, are a product of low-frequency surveys, and were discovered (Kapahi 1981; Peacock and Wall 1982) when we thought that the simple correlation 'flat-spectrum = compact' and 'steep-spectrum = extended' categorised radio sources. The sources are unresolved, or barely resolved, by conventional interferometry. Although the high-frequency spectra are steep, many such objects show spectral maxima at frequencies above 100 MHz; and the analogy (or confusion) with GPS sources is obvious. Like the GPS sources, the QSOs amongst the CSS sources have complex morphologies, sometimes with triple structures showing the semblances of central cores or jets, sometimes with twisted or disrupted jets on intermediate scales, and sometimes impossible to categorise. The galaxies have simple double structures, some again showing weak jets and cores. All have radio structures with sub-Galactic dimensions and, statistically speaking, all are intrinsically small; the statistics do not support the hypothesis of projection effects producing the small sizes (Fanti *et al.* 1990).

In general, it appears that the CSS sources are basically larger versions of the GPS sources. It remains the subject of debate (Fanti *et al.* 1990; O'Dea *et al.* 1991; Fanti and Fanti 1994) as to whether this is an evolutionary situation ('youth'), in which the FRII sources are the end product, whether each manifestation represents frozen radio sources preserved in a dense and clumpy medium ('frustration') with jets trapped by dense gas and dissipating their energy there, or whether indeed there is a variation on this ('smothering'), with the energy flow to the outer lobes via the jets being stopped by a flood of gas from outside.

3.3.3 Ultra-steep-spectrum Populations

Two sets of objects are found at moderate-to-high flux densities, which have extremely steep spectra, i.e. in the optically thin regions of the spectra, the spectral indices α may be less than −1. The first of these is of relatively low luminosity [$\log_{10}P_{408}(\mathrm{W\,Hz^{-1}}) < 24$]; the second is of extremely high luminosity.

Slingo (1974*a*, 1974*b*) noted that bright sources with the steepest radio spectra are frequently located in galaxy clusters within $z = 0{\cdot}3$. The sources are amorphous in structure, clearly associated with the cluster *halo*s, i.e. the gravitational potential wells; they cannot be identified with any particular host galaxy within the cluster. The radio source in the Coma cluster (Willson 1970) is the archetypal *cluster-halo source*. The clusters involved are all in advanced evolutionary states, with low spiral contents, high velocity dispersions, and high X-ray luminosities (Burns *et al.* 1992). Evidence is accumulating to suggest that the halo sources are the results of mergers of gas-rich clusters (Briel *et al.* 1991; Tribble 1993).

This class of object is particularly noteworthy in being the *only* type of synchrotron-powered extragalactic source not obviously driven from a single nuclear engine. The existence of such sources must be borne in mind, particularly during the exercise of identifying samples of the next type of source described, the ultra-steep-spectrum radio galaxy at extreme redshifts.

The greater majority of ultra-steep-spectrum objects can be identified with extreme redshift radio galaxies. Following the discovery of eight galaxies out of a sample of 40 source identifications in the 4C catalogue with $\alpha_{0\cdot178}^{0\cdot5} < -1\cdot0$ for which redshifts are >2 (Chambers *et al.* 1988, 1990), the search for very-high-redshift radio galaxies amongst the steepest-spectrum objects has become a major industry (see the reviews by Miley and Chambers 1989; Chambers and Miley 1990; McCarthy 1993). The search must take place in the low-frequency catalogues, which preferentially select the steep-spectrum objects; large numbers of candidates must be searched, and radio spectra are thus needed for big samples. The growth in the industry is thus facilitated by the new large-area surveys at cm-wavelengths, i.e. the Greenbank and Parkes surveys at 5 GHz (e.g. Gregory and Condon 1991; Griffith and Wright 1993; Wright *et al.* 1994), which can find the ultra-steep spectrum sources from the large surveys at frequencies of 408 MHz and lower [e.g. 4C at 178 MHz (Pilkington and Scott 1965 *et seq.*); the Texas survey at 365 MHz (Douglas *et al.* 1980); the Bologna surveys at 408 MHz (e.g. Grueff 1988 and references therein); and the Molonglo reference survey at 408 MHz (Large *et al.* 1981)].

Of such objects, the three most distant known have redshifts of 3·6, 3·8 and 3·8 (= 4C 41·17, Chambers *et al.* 1990), comparable to the redshift of the most distant radio QSO ($z = 4\cdot3$, Hook and McMahon 1993). The discovery of the population of radio galaxies demonstrates unequivocally that star systems existed at such epochs, which correspond to when the universe was less than 10% of its present age. The objects show an *alignment effect*, i.e. ultraviolet, optical and infrared emission extended in the direction of the radio axes (McCarthy *et al.* 1987; Chambers *et al.* 1987). One picture is that star formation produced by powerful radio jets interacting with the interstellar medium provides aligned populations of stars only 10^8–10^9 years old, comparable in age to the radio structures themselves (De Young 1989; Rees 1989; Chambers and Charlot 1990). A second possibility is scattering of light from the highly luminous central source by an appropriate distribution of either electrons or dust, such models being supported by the detection of optical polarisation in distant galaxies (di Serego Alighieri *et al.* 1989). And a third is the production of extended emission by Compton scattering of microwave background photons (Daly 1992*a*, 1992*b*). The galaxies all show the strong, high-excitation emission-line spectra typical of powerful radio galaxies (see e.g. Fig. 5), and of course at such redshifts, Lyα is the most prominent line, with CIV 1549, HeII 1640 and [CIII] 1909 all in evidence as well. It is this array of emission lines of immense equivalent width that makes the redshifts measurable, and the galaxies thus useful as probes of the epochs of galaxy formation. The ultra-steep spectrum itself does not generally select

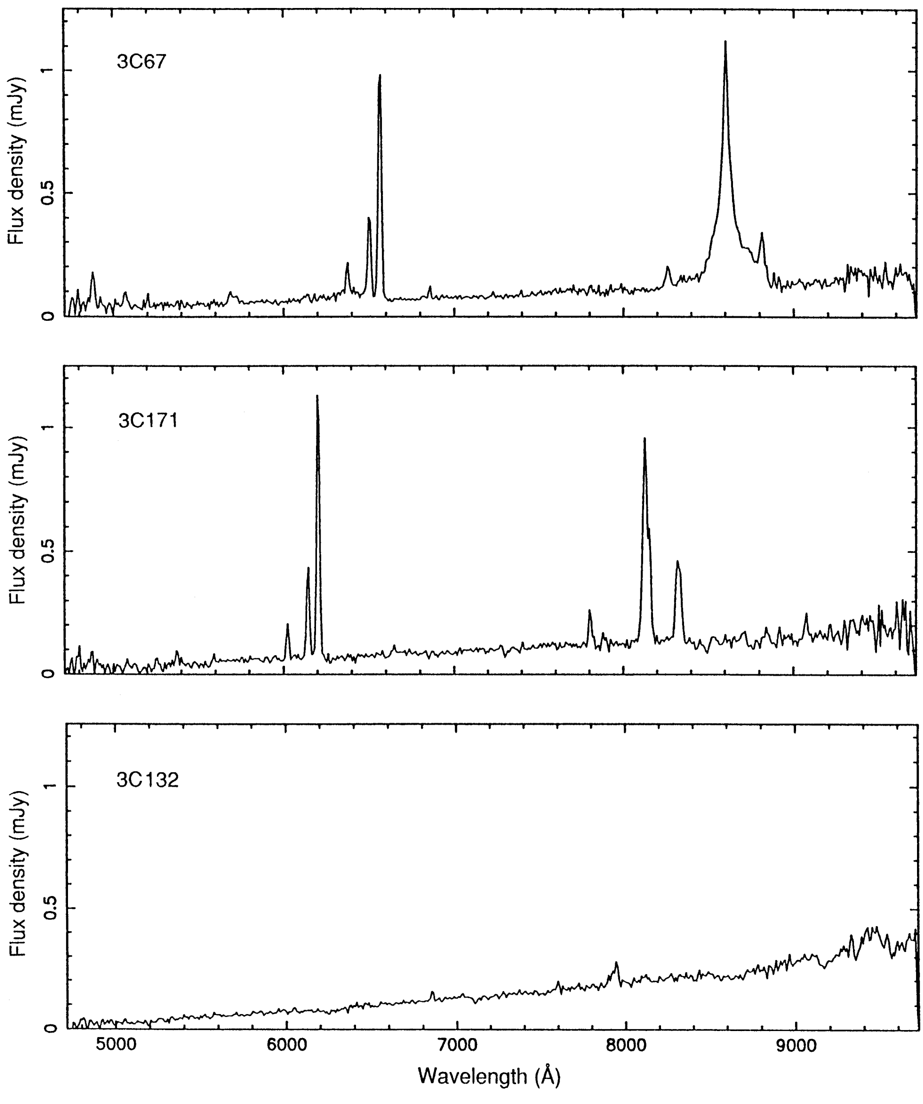

Fig. 5. Examples of the three different types of spectra in the 3CR sample of Laing *et al.*: 3C 67 (broad-line, $z = 0{\cdot}310$); 3C 171 (narrow-line, $z = 0{\cdot}238$); and 3C 132 (low-excitation, $z = 0{\cdot}214$).

objects of extreme power (and hence distance) by virtue of the P–α correlation (Heeschen 1960; Laing and Peacock 1980) because, while the galaxies found are very radio-luminous, they are not more luminous than the 3CR galaxies. The radio spectra of such objects curve to steepen at the highest frequencies due to synchrotron losses on time-scales very short relative to Hubble times; thus the very-high-redshift galaxies have apparently steep spectra because their redshift moves this steepest spectral region into the observer's frame.

3.4 Bottom of the Bulge: The milliJansky Sources (5C12)

Samples drawn at the flux density just faintwards of the peak of the evolution bulge (Fig. 1) are potent tools to estimate space densities at the largest observable redshifts. For example, Dunlop and Peacock (1990) have shown that the Parkes selected area sample ($S_{2\cdot 7} \geq 0\cdot 1$ Jy; Wall *et al.* 1971; Downes *et al.* 1986) provides the first clear indication of redshift cutoff in the space density of radio sources. The implication is that we have 'seen through' the luminosity function, and for the next decade or two towards the fainter flux densities, the range of the 'milliJansky sources,' the luminosity function produces radio sources which are still powerful, collimated, but at a lower power than the brightest sources found at either low or high frequencies. At yet lower (sub-milliJansky) flux densities, a new, nearer, lower-luminosity population takes over, as described in Section 3·5.

The mJy sources are thus at crossroads. They can provide substantially more information on the luminosity function and its epoch dependence; and they can provide data on extreme members of the sub-mJy population. The most detailed data set is from the 5C12 (the 12th synthesis region of the 5th Cambridge survey) program. Recently, my colleagues G. T. Rixon and C. R. Benn and I put together substantial optical data on 5C12 sources (Rixon *et al.* 1991; Wall *et al.* 1993) and here I summarise some of these results.

The 5C12 radio/optical survey of a 4°-diameter field near the NGP reaches $S_{408} = 10$ mJy and $m_v = 22\cdot 5$ mag; data for 300 sources include radio maps (Benn *et al.* 1982, 1988*a*), radio spectra (Benn *et al.* 1984), photographic photometry (Grueff *et al.* 1984) and IR photometry (Benn *et al.* 1988*b*). The original identification program (Benn *et al.* 1988*a*) yielded a sample of 73 complete and reliable identifications: 30 red galaxies (presumed ellipticals), 7 blue galaxies, 33 stellar (mostly blue) objects and 3 bright ($m_v < 15$) galaxies. We have now obtained low-dispersion spectra of many of these with the faint-object spectrograph of the William Herschel Telescope. In addition, we have obtained deep CCD images for a complete sample of previously unidentified 5C12 sources to search for optical counterparts below the limit of the photographic survey.

3.4.1 Optically passive sources: the red galaxies

Optical observations of the 11 brightest red-galaxy identifications were described by Rixon *et al.* (1991). The redshifts are in the range $0\cdot 12 < z < 0\cdot 31$, placing radio luminosities in the range $24\cdot 2 < \log_{10} P_{408}(\mathrm{W\,Hz^{-1}}) < 26\cdot 3$ ($H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$); the radio maps suggest that the majority are FRII in character. The galaxies are remarkably homogeneous in showing no evidence of nuclear activity or recent star formation, no significant change of rest-frame colour with redshift, and only small scatter in absolute magnitude, 0·4 mag about a median $M_v = -22\cdot 8$ mag, which does not differ significantly from that of the 3CR FRII sources whose radio powers are some two orders of magnitude greater.

3.4.2 Optically active sources: the blue galaxies and blue stellar objects

Two-thirds of the identifications with $m_v < 22\cdot 5$ mag have optical characteristics distinguishing them from the passive ellipticals. There is considerable variety, with the different kinds of object loosely separated by radio power. At

$\log_{10}P_{408}(\mathrm{W\,Hz^{-1}}) > 27$ there are a few 'classical' QSOs, with spectra dominated by non-thermal continua. At $26 < \log_{10}P_{408} < 27$, the blue stellar objects have radio-galaxy spectra (note that the resolution of the Schmidt plates is 2 arcsec): all have $M_v \sim -22{\cdot}8$ mag, most show narrow emission lines and a few show broad lines. At yet lower radio powers, there are Seyfert-type objects as well as two blue galaxies which appear to be starbursting systems. Two of the three brightest galaxies are interacting systems, and one of these two is an IRAS source. We appear to be seeing the start of the sub-mJy population (Section 3·5).

3.4.3 Deep identifications

Thirty new identifications were found in I-band CCD exposures at the positions of a complete sample of 64 previously unidentified 5C12 sources with $10 < S_{408} < 50$ mJy. The V and R magnitudes were obtained for a subset of these objects; these magnitudes suggest that most have redshifts between 0·7 and 1·0 [and hence $\log_{10}P_{408}(\mathrm{W\,Hz^{-1}}) < 26$] if they are no brighter than giant elliptical galaxies. One and perhaps two of the objects are variable, suggesting that they are AGNs. The faint identifications are bluer than local early-type galaxies, due either to young stars or to some non-thermal continuum. The magnitudes and colours are most successfully reproduced by a model of an AGN which adds a weak power-law component to a non-evolving elliptical galaxy. Calculations of space densities for these objects, based on the estimated redshifts, are consistent with the hypothesis of *no evolution* [$\log_{10}P_{408}(\mathrm{W\,Hz^{-1}}) \lesssim 26$] from $z = 0$ to the shell $0{\cdot}7 < z < 1{\cdot}0$.

3.4.4 Stratification of source type with radio power

The transition of the characteristic source type from optically passive galaxy through weak-cored AGN to classical QSO occurs in the same sequence, and at roughly the same powers, in bright-source surveys (e.g. 3CR, Laing *et al.* 1983; 2·7-GHz all-sky, Wall and Peacock 1985) and in 5C12 identifications with $m_v < 22$, despite the large difference in median redshifts. In particular, the lower limit in radio power of radio-loud QSOs (Kellermann *et al.* 1989; Dunlop *et al.* 1989) appears constant with redshift out to $z \sim 0{\cdot}7$. The deep 5C12 identifications are consistent with the continuation of a redshift-independent 'weak-AGN' stratum out to at least $z = 1$. Thus source type appears to be a function of radio power rather than redshift. This stratification in the P–z plane is important for models of luminosity evolution for radio sources: unless the optical appearance of sources is contrived to change in step with the radio power, such models cannot reproduce it. Detailed consideration of these data can thus provide further definition of the nature of the change of the space density of radio sources with epoch.

3.5 The Sub-milliJansky Sources

The flattening of the differential source counts at levels below $S_{1\cdot4} = 1$ mJy was discovered some ten years ago, when the deepest surveys with the VLA (Condon and Mitchell 1984), the Westerbork Synthesis Radio Telescope (Windhorst 1984) and the RATAN array (see Parijskij and Korol'kov 1987 for observational summary and references) pushed down below this level. The conclusion that a new population of radio sources had been encountered was quickly reached

(Condon 1984; Windhorst *et al.* 1985), although the point was made that a flattening of the counts in itself need not be due to a population differing from those encountered at higher flux densities (Subrahmanya and Kapahi 1983; Wall *et al.* 1986).

The existence of this new population is now well established as one that differs from that of the QSOs and radio galaxies whose beamed radio structures make up the evolution-bulge population at higher flux densities. To begin with, below 1 mJy the radio median angular size of sources suddenly shrinks to <3 arcsec (Coleman and Condon 1985; Oort 1987*b*; Fomalont *et al.* 1991). Moreover, the identifications of the faint sources are predominantly with blue galaxies (Windhorst *et al.* 1985; Oort 1987*a*, 1987*b*; Thuan and Condon 1987), which were quickly proposed (Danese *et al.* 1987; Franceschini *et al.* 1988) to be the starburst galaxies hosting the faint ($S_{60\,\mu\mathrm{m}} > 200$ mJy) IRAS sources. Detailed spectroscopy of the identifications from deep-survey samples (Benn *et al.* 1993) has now shown directly that the emission-line spectra of most of such blue-galaxy identifications are indeed indicative of strong bursts of star formation; a few AGNs and elliptical galaxies remain as the left-over intrusion of the AGN–elliptical galaxy population from the bottom of the evolution bulge, as described in the previous section. The tight correlation for starburst objects between the amount of dust present and the integrated synchrotron emission from supernova remnants implies that $S_{60\,\mu\mathrm{m}} \approx 100 S_{1\cdot 4\,\mathrm{GHz}}$ (Helou *et al.* 1985); this relation between the radio and far-IR properties is so close that the luminosity functions may be calculated in one waveband from data in the other (Condon 1990).

It further appears (Broadhurst *et al.* 1988; Lonsdale and Harmon 1990) that the starburst galaxy population is the blue-galaxy population encountered in the deepest optical surveys (e.g. Tyson 1988). The faint optical counts show a corresponding point of inflection as the population is encountered.*

The starburst galaxies are a relatively nearby population, the median redshift for objects about $S_{1\cdot 4\,\mathrm{GHz}} = 1$ mJy and with mean $m_v = 20\cdot 0$ mag being $0\cdot 25$ (Benn *et al.* 1993). Such galaxies have a mean absolute magnitude $M_v \approx -20\cdot 5$ mag, just slightly brighter than that of a typical Sbc galaxy (Pence 1976). The radio luminosities occupy the range $21 < \log_{10} P_{1\cdot 4\,\mathrm{GHz}}(\mathrm{W\,Hz^{-1}}) < 24$. Deep optical identification programs show that the median $m_v \approx 22\cdot 0$–$22\cdot 5$ mag, and the median redshift is in the range $0\cdot 6$ to $0\cdot 8$ (Windhorst *et al.* 1993).

Several authors (Condon 1984, 1989; Windhorst *et al.* 1987; Oort 1987*b*; Franceschini *et al.* 1988) have claimed that—as for the beamed radio galaxies and QSOs—evolution of the local radio luminosity function of the starburst objects is necessary to explain the shape of the faint source counts. The argument is the old one of a near-Euclidean count with objects at cosmological distances (see footnote, p. 629); the effects of relativistic geometry need to be overcome with substantial boosting of the local luminosity function at earlier epochs of the universe, in order to produce a count which does not fade rapidly and progressively below

* Confusingly, the encountering of the new blue population is described in the optical regime as a steepening of the optical count, and in the radio regime as a flattening of the radio count. If the overall differential count has a slope of index below $-2\cdot 5$ (the $-\frac{3}{2}$ power law of the integral count for a uniformly filled Euclidean universe), then a steepening in the differential plane used in the optical regime will appear as a flattening in the relative differential plane used in the radio regime.

Euclidean with decreasing flux density. With the close connection between radio and far-IR properties, an additional tool is available to sort out the form of this evolution, namely the constraint that such evolution must fit the detailed observations available for IRAS counts and redshift distributions (e.g. Saunders *et al.* 1990; Lonsdale and Harmon 1990; Oliver *et al.* 1992).

The deep surveys with the VLA have now pushed on down to microJansky levels (Fomalont *et al.* 1991, 5 GHz; Windhorst *et al.* 1993, 8·44 GHz). The latter survey, together with $P(D)$ (background-deflection) analysis, defines a source count down to 4 μJy. The following conclusions were reached about the populations found:

- At the brighter radio levels, the median redshift at $m_v \approx 23$ mag is 0·6 to 0·75. Model predictions indicate that the median redshift is only a weak function of flux density; the median angular size at μJy levels is found to be 2·6 arcsec, and the median linear size is thus 5–40 kpc (for a plausible range of H_0 and Ω).
- The median spectral index is surprisingly flat at $-0{\cdot}35{\pm}0{\cdot}15$, and very few sources show the high-frequency spectral steepening characteristic of ageing synchrotron electrons. Is the radio emission due to thermal bremsstrahlung from large-scale star formation in Galactic discs, or is there a steep-spectrum, non-thermal disc component with a flat-spectrum nuclear component, such as an optically thick AGN core or a free–free emission zone from the nuclear starburst?

It is thus not clear that the μJy surveys see the same blue starbursters that dominate source counts at the mJy level. It is not clear at all whether yet another radio population has been discovered, or whether the μJy observations are simply telling us more of the nature of the mJy sources.

It is curious to note that the groupings that originally gave rise to the concept of populations, namely flat-spectrum versus steep-spectrum, compact versus extended structure, QSOs versus radio galaxies, have (probably) become unified into one or two populations. At the same time, the survey and aperture-synthesis techniques, which were to discover how these objects were related, have now discovered one or more faint 'starburst-galaxy' populations which may be entirely unrelated to the powerful radio sources of the brighter surveys.

4. Digression 1: Unified Models and Spectrophotometry of 3CR Radio Sources

4.1 Unified Models for Powerful Radio Sources

The particular aspect of unified models with which we (Robert Laing, Charles Jenkins, Steve Unger and JVW) were concerned was the suggestion that powerful radio galaxies and QSOs are the same type of object seen from different directions (Scheuer 1987; Barthel 1989; review by Antonucci 1993). In the simplest version of this model, the central continuum source and broad-line region are surrounded by an opaque torus whose axis coincides with that of the radio source. If the object is viewed from a direction within some angle $\theta_c \approx 50°$ of this axis, then the broad-line region can be seen, and the object is classified as a broad-line radio galaxy or QSO. From other directions, it appears to be a narrow-line radio galaxy. The broad-line objects are expected to have stronger radio cores and one-sided radio jets as a result of Doppler favouritism.

Whilst this simple hypothesis works reasonably well for a sample of 3CR radio sources with $0{\cdot}5 < z < 1{\cdot}0$ (Barthel 1989), Browne (1987) had already shown that there were problems in extending it to lower redshifts, even within the same radio sample. Modifications to, and difficulties with, the idea were discussed by Singal (1993), Browne and Jackson (1992), Lawrence (1991) and Kapahi (1990). Most of these discussions were based on heterogeneous optical spectra, some of considerable antiquity, the criteria for recognising broad-line radio galaxies being especially dubious. We therefore decided to obtain spectrophotometry for a well-defined sample of radio sources, with the aim of testing Barthel's hypothesis.

4.2 Observations

The objects were selected from the 3CR radio sample defined by Laing *et al*. (1983), which imposes the criterion $S_{178} \geq 10{\cdot}0$ Jy; our sample included all objects with $0^h <$ RA $< 13^h$, redshift $z < 0{\cdot}88$ and $m_v <$ 20. The observations were made with the FOS-2 spectrograph on the William Herschel Telescope at La Palma. Some 400 spectra of 88 objects were obtained over a 3-week period, using a slit of $2{\times}20$ arcsec^2. All of the data were tied to short exposures taken under photometric conditions. The key features of this study are that the sample is complete, the data are homogeneous and accurately calibrated and that the wavelength range extends to 1 μm.

4.3 Results

We detected four new broad-line radio galaxies with $z < 0{\cdot}4$. Broad wings are clearly visible at Hα, but are difficult to see at Hβ (almost certainly explaining why they were missed in earlier surveys). Two of the new detections are CSS sources (3C 67 and 268·3); the other two are classical doubles with one-sided jets (3C 33·1 and 219).

Our spectra show clearly that *some FRII radio sources have low-excitation spectra*, by which we mean that lines such as [OIII] are very weak or undetectable. These objects have been known for a considerable time (Hine and Longair 1979), but their existence has tended to be ignored in discussions of unified schemes. They are important, since they are nearly as common as broad-line objects in our sample. Indeed a plot of [OIII]/Hα flux against equivalent width of [OIII] for objects without detectable broad Hα shows a very clean distinction between narrow-line objects of high and low excitation. The distinctive nature of the three spectral classes, (1) broad-line, (2) narrow-line and (3) low-excitation, is shown in Fig. 5, which also serves to illustrate the quality and extent of the spectral coverage.

Classifying the optical spectra into three rather than two classes, together with our discovery of new broad-line galaxies at low redshifts, makes a very significant change to the redshift-distribution test for unified models. In this test we have considered only FRII radio sources; it is clear that the low-excitation objects cannot be members of either of the other two classes seen at different orientations, since their narrow-line spectra are totally different. The test is whether the redshift distributions of the narrow- and broad-line objects are identical for FRII radio sources in our sample. The result is that they are statistically identical in the present sample, fully consistent with the idea that the fractions of broad-and narrow-line objects are independent of redshift, and that the half-angle of the putative obscuring cone is 50° (from the sky-coverage ratio yielded by the ratio of the 16 broad-line to the 29 narrow-line members of our reduced sample).

This is the major result from the data; but other aspects follow:

- *Narrow-line luminosities.* In the simplest version of the unified model, the luminosity from narrow forbidden lines should be independent of orientation, but Jackson and Browne (1990) showed that there was a significant tendency for the broad-line objects to have higher [OIII] powers at a given redshift. In our case, the distributions largely overlap and the tendency is greatly reduced, due to our having excised the low-excitation objects. It may be that a slightly different excitation criterion or some orientation dependence of [OIII] luminosity (Hes *et al.* 1993) would eliminate the difference; but in any event the effect is no longer a serious problem for the unified model.
- If the narrow- and broad-line objects together form an isotropic sample, then we would expect that the narrow-line objects would be larger, the radio structure being viewed essentially side-on. Against a calculated mean ratio of sizes of $1 \cdot 74$, we measure the mean ratio to be $1 \cdot 4$, with weak evidence for an increase with redshift. The test is marginally consistent with the predictions of the simple unified model, but is a great step forward from the results of Kapahi (1990), who found that the broad-line objects were *larger* at low redshift. The difference is again due to our using a complete sample together with the omission of the low-excitation objects.
- *Incidence of radio jets.* Bridle and Perley (1984) showed that jets are significantly more common in FRII QSOs than in galaxies of comparable luminosity. This is as expected in the unified models if radio jets are two-sided and relativistic, since Doppler beaming makes the approaching jet brighter as the angle to the line of sight decreases. This result may be made more precise and extended to larger ranges of power and redshift using the present data. A comparison between the broad-line and high-excitation narrow-line classes shows that 11/16 of the broad-line objects show one-sided jets (by the Bridle and Perley criteria) compared with 1/29 of the narrow-line objects.
- *Radio cores.* The distributions of R (the ratio of core to extended luminosity at a fixed emitted frequency of 5 GHz) for the broad- and narrow-line objects are very different in the sense that the broad-line objects have relatively brighter cores at all redshifts. The difference between the two classes is in the sense expected from Doppler favouritism in the unified model, confirming the result of Barthel (1989) for a larger redshift range. The median values of R for the two classes differ by a factor $\approx$10. The unified model predicts that the median angles to the line of sight are 35° and 71°. If we adopt a simple beaming model with a spectral index of 0 and a Lorentz factor of 5 for the flow, we predict that the ratio of medians should be $\approx$12, in good agreement with observation considering the crudity of the assumptions.

Finally, what are the low-excitation FRII galaxies? They are heterogeneous in their properties. A few of them (mostly with $z < 0 \cdot 2$) have radio morphologies intermediate between those of the FRI and FRII classes. The remainder are *bona fide* FRIIs with secure identifications established by precise coincidence between the radio core and optical positions. The two largest objects in the sample, 3C 236 and DA 240, have spectra of this low-excitation type, but the higher-redshift examples are mostly quite small. We suspect that some of the latter are bright central-cluster galaxies similar to 3C 295 (not observed by us, but satisfying our selection criteria). It seems likely that these objects form an isotropic sample, albeit a heterogeneous one, and it is quite possible that they form part of the parent population of BL Lac objects. It was supposed until recently that this population consisted entirely of FRI radio galaxies, but recent evidence (e.g. Murphy *et al.* 1993) suggests that some BL Lac objects have extended radio emission with powers and structures more characteristic of FRIIs. The parent population could, therefore, consist of a mixture of FRIs and a few FRIIs with low-excitation spectra.

4.4 Conclusions

The present study generally supports the unified scheme for high-luminosity radio sources. The most important new results are that we have detected a number of previously unknown broad-line radio galaxies, and have drawn attention to a significant population of FRII radio galaxies with low-excitation spectra. Once the latter are excluded, the simple hypothesis that the fraction of broad-line objects is independent of redshift is consistent with our data. Whilst slight discrepancies remain in the comparison of [OIII] powers and linear sizes, they are much smaller than in previous studies. The radio core and jet properties are in good agreement with expectations. The low-excitation class contains a mixed bag of radio sources; we expect it to be an isotropic sample and speculate that it could form part of the parent population of BL Lac objects. In determining uniform and wide-range spectra for the sample, the study has succeeded in establishing a major aspect of the unified-model paradigm, namely that *the parent population of high-power broad-lined objects (galaxies and QSOs) can be the narrow-line FRII galaxies*.

JGB's intuition was that QSOs were utterly different from radio galaxies. On the current picture he remains *technically* correct in a sense—they do differ. QSOs are the accretion discs and the core–jet energy sources, housed in a fire-brick torus; radio galaxies are the systems of stars (and gas) housing the monster with its firewall. Without JGB's push to survey the sky at higher frequencies, to identify the sources, and to determine their nature, would we have the balanced picture of the radio sky that enables us to consider this unified picture? *We never realised that raising the survey frequency to select compact flat-spectrum radio sources was equivalent to walking around radio galaxies to gaze down into the heart of the monster.*

5. Digression 2: Radio Sources and the Shape of the Universe

If JGB's intuition did not lead him quite as far as unified models, in one other sense it was very accurate. He firmly believed in the anisotropy of the sky for bright radio sources. Together we spent many hours in naive statistical searches of the bright-source statistics to try to establish the anisotropies which he knew were there. The statistics which we used said that they were not.

But they were. JGB was right. The inconsistencies which we noted in the early 1970s (e.g. Wall 1977; Pauliny-Toth 1977) were real enough; what we had not appreciated was large-scale structure, and the local supercluster in particular. It took Shaver and Pierre (1989) and Shaver (1991) to show how the brightest sources, in particular those within $z < 0{\cdot}02$, are strongly influenced in their sky distribution by the three-dimensional structure of the local supercluster, sufficiently so to explain discrepancies in sky distribution between different parts of the 2·7-GHz survey (Wall 1990), and between different Galactic hemispheres (Pauliny-Toth 1977).

The deep pencil-beam surveys have also revealed non-uniformities both in the sky distribution and in the three-dimensional distribution of radio sources (Windhorst *et al.* 1990; Wall *et al.* 1993; Windhorst *et al.* 1993). At intermediate flux densities, the new large-area surveys of the NRAO and Parkes (e.g. Gregory and Condon 1991; Griffith and Wright 1993; Wright *et al.* 1994) provide unparalleled opportunities for such statistical studies. The first indications are that real structure is revealed; significant non-uniformities are shown up by two-point correlation function analyses (Wall *et al.* 1993; Kooiman *et al.* 1994).

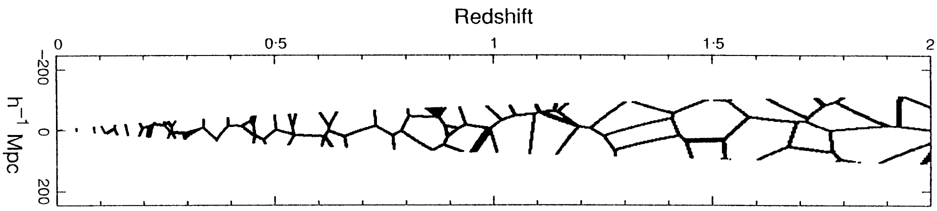

Fig. 6. A slice through a Voronoi foam simulation of the cellular universal structure, with density of superclustering $(100\ \mathrm{Mpc})^{-3}$ and opening angle (or survey area) of 5°.

To examine the significance of these effects, Benn and Wall (1994) have reversed the approach, constructing universes of realistic sponge-like topology via Voronoi tessellations, and sprinkling the resulting cellular structure with appropriate numbers of radio sources at different epochs, with big enough samples at different intensity levels to predict what effects might be seen. An example of the foamy topology that results from these models is shown in Fig. 6. The results of the exercise provide new and significant information about the largest-scale structures present in the universe; the following is a summary.

(i) The well-established isotropy of the radio sky for bright sources, at first sight surprising given the inhomogeneity of galaxy distribution on scales ~100 Mpc ($H_0 = 100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$), is reproduced if the superclustering scale is less than 250 Mpc. This is a consequence of the small mean number of bright sources detected per supercluster volume.

(ii) If the density of superclustering (cell density) is $\sim(100\ \mathrm{Mpc})^{-3}$, the region-to-region fluctuations for 5°- diameter zones are predicted to exceed those for the random-distribution model at flux densities $S_{1\ \mathrm{GHz}} < 3$ mJy, while for 0·5°-diameter surveys, the corresponding flux density is ~0·1 mJy. *These are approximately the flux-density limits of the deepest radio sources to date.* Moreover, this result highlights the need for caution in compiling supposedly representative samples of sources from deep pencil-beam syntheses.

(iii) Area-to-area fluctuations in the source counts provide a more sensitive test of large-scale structure than two-point correlation analyses within individual fields. This is because each pencil-beam survey pierces a different series of cells, while different lines of sight within an individual survey may pierce the same series of cells.

(iv) At a given value of superclustering density, for area-to-area counts there is a maximum angular diameter beyond which the number of detected sources per supercluster cell, and thus the sensitivity to large-scale structure, does not increase.

(v) Imposing a redshift limit has surprisingly little effect on sensitivity to large-scale structure. With a cutoff, the surveys pierce fewer cells, so that the anisotropy is less washed out, but this gain is offset by an increase in Poisson noise, which happens to be of the same order.

On the basis of this analysis, we re-examined the radio-source anisotropy analyses which the modelling indicated as providing strong constraints on large-scale structure. The 5C surveys and the deep Westerbork and VLA surveys all have the potential to reveal large-scale structure. The current marginal detections set a strong constraint on the mean diameter of the cells of the Voronoi foam to be $\leq$100 Mpc. This constraint is compared with results from redshift surveys, optical two-point correlation functions and COBE data in Fig. 7.

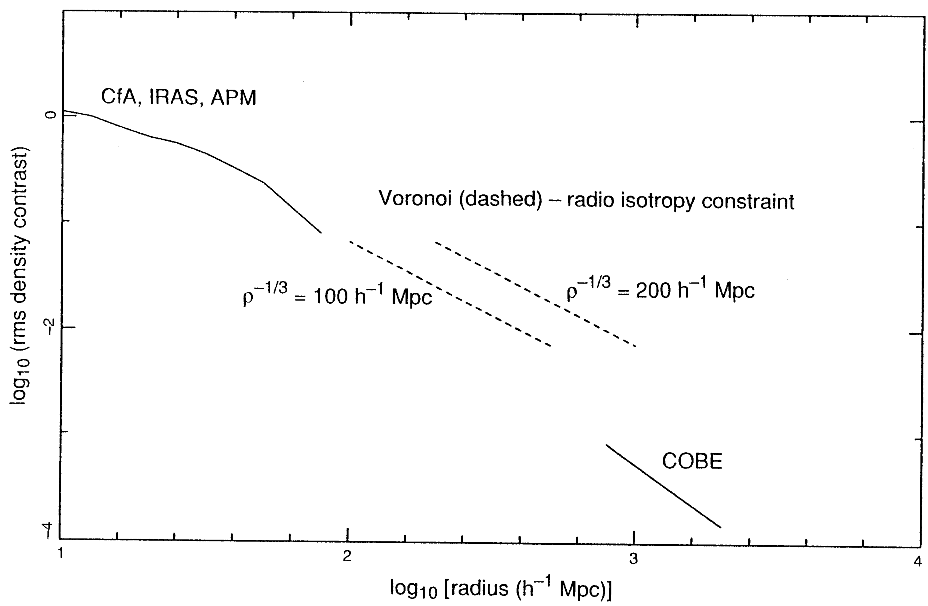

Fig. 7. Density contrast as a function of sampling radius, showing values inferred from CfA and IRAS redshift surveys and APM two-point correlation analyses (solid curve), from COBE data (solid curve), and values corresponding to Voronoi tessellations with densities of superclustering (100 Mpc)$^{-3}$ and (200 Mpc)$^{-3}$ (dashed curves), these being the approximate limits supplied by the Benn and Wall (1994) analysis of radio-source anisotropy.

Given the sizes of structures already known from optical studies, we must now be on the threshold of detecting their influence on the isotropy of the radio sky. Radio sources, detectable without obscuration as far as the most distant objects yet observed, may thus reveal considerable detail of the real skeleton structure of our universe.

The populations of radio sources thus provide us with astrophysical challenges in abundance: black holes and accretion disks, energy transport via collimated beaming in both relativistic and non-relativistic regimes, galaxies dominated by star formation and by central monsters, evolution which must trace environment and fuel supply, and the achievement by the universe in making gas, dust and full-scale galaxies at epochs as early as 10% of its lifetime. *It may be that the populations also yield for us an unobscured view of the overall arrangement of the matter in the universe as well.* If so, JGB's intuition will again have served us soundly, and an essential ingredient will be available to assist in the attack on our greatest challenge—how galaxies got there in the first place.

Acknowledgment

I wrote an obituary for *The Times* of 17 July 1993. Under the exercise of editorial prerogative, the last paragraph was brutally truncated, ruining the balance I sought. With the indulgence of the present editors, perhaps I can redress the matter by including the paragraph here.

> 'John Bolton was a competitive man, fiercely so, but fair. He aimed to be best. When he grew roses in the dry and dusty hinterland of New South Wales, they were beautiful. His lawn was the greenest. In his earlier years a fine sportsman, cricketer, swimmer and long-distance cyclist, he took up golf late in life as a most unlikely player, an arthritic swing limiting his long game. But a deadly short game and his fierce concentration made him very hard to beat. The intense and powerful personality did not endear him to everyone—there was little tolerance for mediocrity, poor judgement, or lack of commitment. However, his enthusiasm for quality and for dedication, together with his own dedication to active leadership and participation in each and every endeavour, resulted in a team around him who were loyal in the extreme. He expected commitment, and in his dedication to science he taxed himself and those close to him heavily. His graduate students received outstanding supervision as well as pastoral care. He was superbly egalitarian; he showed the deepest respect for those who were best in their field, at carpentry, at astronomy or whatever; it was the same to him, and all such 'Bolton experts' were treated with openness and generosity as his friends ...'

JGB made you stick to your guns. He did not believe in a complicated, difficult universe. If something simple didn't work and there was a complicated reason why it didn't work, there was trouble. If you wanted to complicate the simple scheme with elegant physics or that kind of junk, you'd better know what you were talking about. Much better that there be a *simple* reason why it didn't work. At the telescope, during data analysis, or even on the golf course, he made you have a clear picture, he made you think in the simplest terms of what to do. And he then couldn't understand if you didn't go ahead and do it.

I thank Robert Laing for his knowledgeable and perceptive criticism of a draft of this paper.

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Manuscript received 11 May, accepted 1 July 1994