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Radio Surveys and Large Scale Structure*

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Abstract

An analysis of the Molonglo Reference Catalogue indicates that significant departures from isotropy are present in the sky distribution of strong extragalactic radio sources. This has been shown to be due to local large scale structure, specifically a concentration to the supergalactic plane, which also influences the slope of the source counts. A study of the three-dimensional distribution of local radio galaxies shows that they are more strongly concentrated to the supergalactic plane than are optically-selected galaxies, and that the supergalactic concentration is more extensive than hitherto believed. It appears that radio galaxies (and clusters of galaxies) trace the 'skeleton' of large scale structure, about which normal galaxies are more loosely distributed. Thus, while large scale structure evidently complicates the interpretation of radio source counts, it appears that radio surveys can be of value in exploring structures on the largest scales.

1. Introduction

It has been widely believed, since the early days of radio astronomy, that the sky distribution of extragalactic radio sources should be essentially isotropic. This follows from the broad luminosity function of extragalactic radio sources — at any limiting flux density a sample contains objects over an enormous range of redshifts, and even though radio galaxies and quasars are known to occur in high density environments (e.g. Prestage and Peacock 1988; Yee and Green 1987) any irregularities due to the expected large scale structures would still be expected to be insignificant. Nevertheless, in view of their potential importance, many attempts to detect departures from isotropy on all scales have been made over the years. Perhaps the strongest evidence for large scale anisotropies was that presented by Pauliny-Toth (1977) and Wall (1977) in the form of variations in the slope of the source counts over very large angular scales. Even these, however, were regarded as marginal; the general consensus remained that the extragalactic radio sources are randomly distributed over the sky (e.g. Webster 1977; Longair 1978; Condon 1988), although dissenting voices were still heard [e.g. Mills (1977): '... the present results do suggest that radio sources are not randomly distributed throughout the Universe. If

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this is so, the source counts at high flux densities may provide little or no information about source evolution ...'].

Some early work had focussed on the possibility of radio emission associated with the supergalactic plane, as it is the most obvious local feature in the large scale distribution of galaxies. Hanbury Brown and Hazard (1953) and Kraus and Ko (1953) reported possible background radio emission along the supergalactic plane, although this was later shown to be galactic in origin (Hill 1958; Shakeshaft and Baldwin 1959). Mills *et al.* (1958) argued that radio sources could be formed preferentially in clusters or superclusters such as the Local Supergalaxy due to collisions or interactions of galaxies, thus affecting the counts of discrete sources. Hanbury Brown (1962) showed that the Local Supergalaxy as defined by de Vaucouleurs (1953, 1956) could indeed affect the source counts, but Clarke *et al.* (1963) argued that the effect would still be small. From that time until very recently the supergalactic plane was again forgotten, at least with regard to the distribution of radio sources.

2. Sky Distribution of Extragalactic Radio Sources

Recently the Molonglo Reference Catalogue (Large *et al.* 1981) was used in a new study of the sky distribution of extragalactic radio sources by Shaver and Pierre (1989), with emphasis on the concentration of sources to the supergalactic plane. The Molonglo Catalogue is particularly well suited to such a study, for several reasons. It uniformly covers a large area ($7\cdot85$ sr) with a high surface density ($930\ \mathrm{sr}^{-1}$) and $99\cdot9\%$ completeness. The low survey frequency (408 MHz) discriminates in favour of local objects (steep-spectrum radio galaxies) and against distant objects (flat-spectrum quasars). And the limiting flux density (1 Jy, approximately where the counts steepen) is an ideal compromise — a higher limit would give too few sources for good statistics and a lower limit could give too much contamination from more distant sources.

Fig. 1 shows the distribution of these sources over the sky. There is no significant variation in surface density as a function either of declination or galactic latitude, indicating that both calibration effects (which are declination-dependent) and galactic contamination are negligible. However, from the smoothed distribution it appears that some anisotropies on very large scales may be present. This is confirmed in Fig. 2, which shows the source counts at low ($< 10°$) and high ($> 10°$) supergalactic latitudes. Along the supergalactic plane the surface density is higher ($1030\ \mathrm{sr}^{-1}$ compared with $910\ \mathrm{sr}^{-1}$, a $3\cdot7\sigma$ excess over random expectation), the slope of the source counts is flatter ($-1\cdot54\pm0\cdot11$ compared with $-1\cdot91\pm0\cdot06$), and the amplitude of the angular two-point correlation function may also be greater ($1\cdot40\pm0\cdot50$ compared with $0\cdot46\pm0\cdot21$ for $\theta < 7\cdot5'$).

Shaver and Pierre showed that a simple model of local large scale structure could be constructed to account for these results, in which all the objects out to a given radius have been collapsed onto the supergalactic plane, and beyond that radius are distributed homogeneously (Fig. 3). Using the standard radio luminosity function they showed that a radius of $0\cdot02$ in redshift was consistent with the above results. This size, already several times bigger than the traditional Local Supergalaxy, is only a lower limit, as there could of course be some radio sources within the sphere above or below the plane.

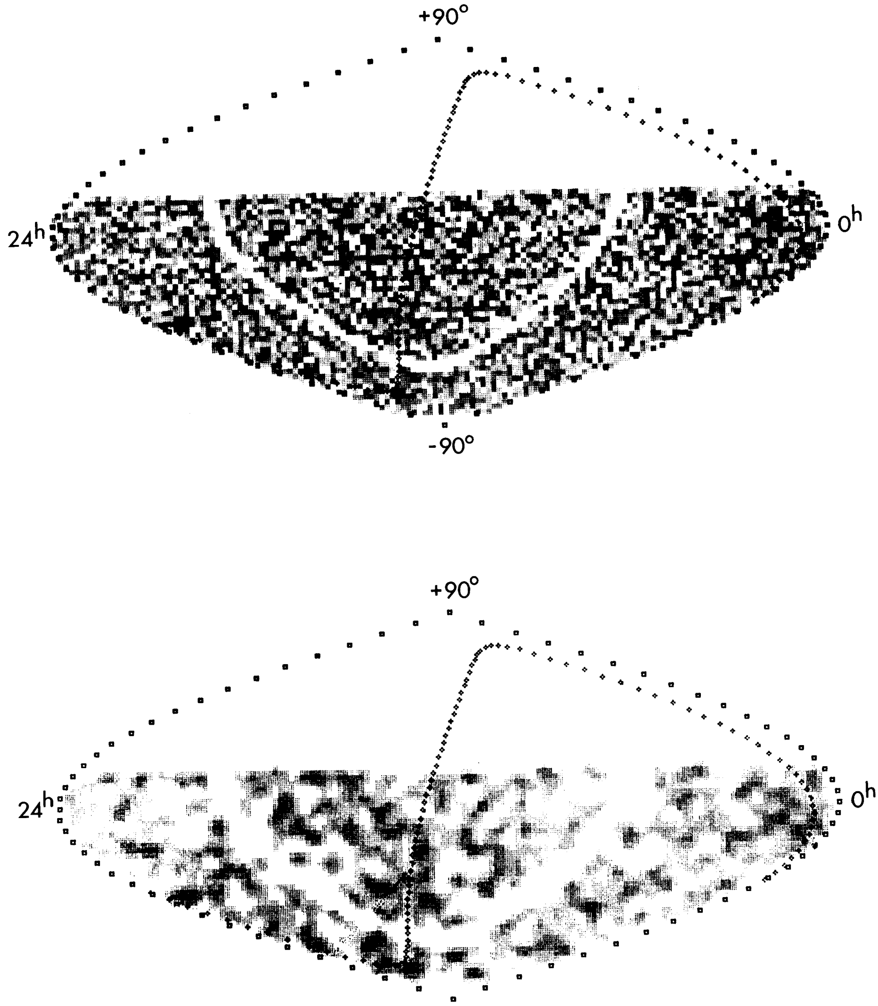

Fig. 1. Sky distribution of Molonglo radio sources with $S_{408} > 1$ Jy in equatorial coordinates, binned in 2·5° bins (top) and smoothed with a truncated Gaussian of FWHM 8° (bottom). The supergalactic plane is indicated by the crosses, and the galactic plane is the empty 6° band which was excluded from the Molonglo Reference Catalogue.

It therefore became clear that both the sky distribution of extragalactic radio sources and the slope of the source counts are affected by local large scale structure. The next step was obviously to use redshift information, to map out the actual three-dimensional distribution of local radio galaxies and compare it with the above model.

3. Space Distribution of Local Radio Galaxies

(a) The Samples

In any study of local large scale structure, especially using sparsely distributed objects, it is clearly desirable to have all-sky samples. It is also important, if the distributions of different types of objects are to be compared, that any

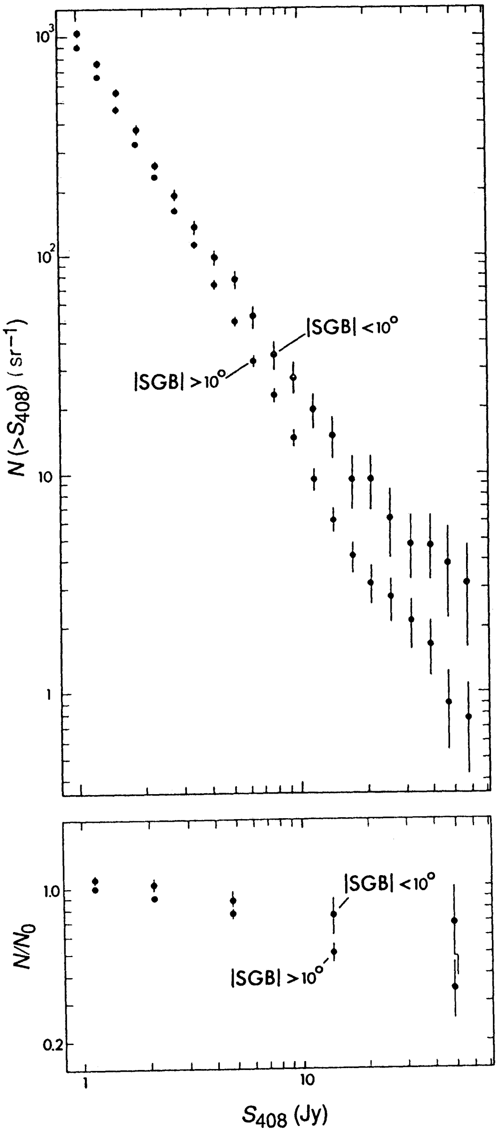

Fig. 2. Integral (top) and differential (bottom) source counts at low (|SGB| < 10°) and high (|SGB| > 10°) supergalactic latitudes. Error bars are $\pm\sqrt{N}$. The differential counts are normalised to N_0 (>S) = 1000 $S^{-1\cdot5}$ sr^{-1}.

selection effects be identical for the different samples. The starting point in this study was to assemble an all-sky (except for the zone obscured by our own Galaxy) sample of optically bright galaxies from the ESO, MCG and Zwicky catalogues. This sample, comprising some 8300 galaxies with $m_B \leq 14\cdot5$, formed the parent sample from which sub-samples of radio, infrared and optical galaxies were made, all with essentially the same selection effects (those of the parent sample). The details of these samples will be presented in a forthcoming paper, and only a brief summary is given below.

The radio sub-sample consists of galaxies with 408 MHz flux density $S_{408} > 1$ Jy. It was produced by cross-correlating several radio catalogues with the parent sample. The most important of these radio catalogues was again the Molonglo catalogue, because of its completeness and large sky coverage, but several other catalogues also had to be used (Parkes, Bologna, Green Bank, 3C, 4C, 6C and Jodrell) to cover other regions of the sky, particularly in the north. Supplementary information was obtained from various other sources (e.g. Colla *et al.* 1975; Burbidge and Crowne 1979; Véron-Cetty and Véron 1983; Wall and Peacock 1985) to maximise completeness. Complications arose inevitably from different survey frequencies and angular resolutions, but the sample of 92 local radio galaxies is thought to be virtually complete; 91 of them have measured redshifts, and 63 of those are at $z < 0 \cdot 02$.

The infrared sub-sample was obtained by cross-correlating the Strauss *et al.* (1990) sample of IRAS galaxies with 60 μm flux $S_{60} > 1 \cdot 6$ Jy (restricted to $z < 0 \cdot 02$) with the parent sample, to obtain 1227 IRAS galaxies with the same selection criteria as the parent sample.

The optical sub-sample was obtained by randomly taking one galaxy in eight from the parent sample. This resulted in 1038 galaxies, for which, thanks to data kindly provided by J. Huchra and more recent observations, 948 now have measured redshifts, and of those, 740 are at $z < 0 \cdot 02$.

Other all-sky samples which have been used in this study are as follows: (i) the Wall and Peacock (1985) complete sample of strong extragalactic radio sources with $|b| > 10°$ and $S_{2700} > 2$ Jy (corresponding roughly to $S_{408} > 8$ Jy); there are 16 with $z < 0 \cdot 02$, and there is no optical magnitude limit, hence no optical selection effects; (ii) the Piccinotti *et al.* (1982) sample of X-ray galaxies (17 at $z < 0 \cdot 02$); (iii) the Lahav *et al.* (1989) sample of X-ray clusters (6 at $z < 0 \cdot 02$); and (iv) the Abell *et al.* (1989) catalogue of clusters, which is unfortunately incomplete at low redshifts but still contains 16 clusters at $z < 0 \cdot 02$.

(b) Results

Fig. 4 shows two projections of the space distribution of the powerful radio galaxies from the Wall and Peacock (1985) sample. The concentration to the supergalactic plane is immediately obvious, and the similarity of Fig. 4*b* to Fig. 3 is striking. These are *all* the radio galaxies with $S_{2700} > 2$ Jy and $|b| > 10°$ out to $z = 0 \cdot 02$ (there is no optical magnitude limit), so it appears that the regions above and below the plane out to at least $z = 0 \cdot 02$ are indeed essentially devoid of such objects.

In Fig. 5, similar projections are shown for the radio galaxies from the 1 Jy sample (Figs 5*a* and 5*b*) and the optical sub-sample (Fig. 5*c*). These samples can be directly compared with each other, as the selection effects are identical, and one has the impression that the more powerful radio galaxies are more concentrated to the plane than the less powerful radio galaxies, which in turn appear to be more concentrated than the optical galaxies. This impression is confirmed in Fig. 6, which shows the integral distributions in supergalactic latitude for a variety of populations at $z < 0 \cdot 02$. Preliminary analysis using a Kolmogorov–Smirnov test indicates a $4 \cdot 7\sigma$ difference between the concentrations of the radio and optical galaxies, and a $2 \cdot 7\sigma$ difference between the stronger ($S_{408} > 4$ Jy) and weaker ($1 < S_{408} < 4$ Jy) radio galaxies. Amongst the optical galaxies themselves there is no striking dependence of supergalactic concentration on either galaxy type or luminosity, but this remains to be further explored.

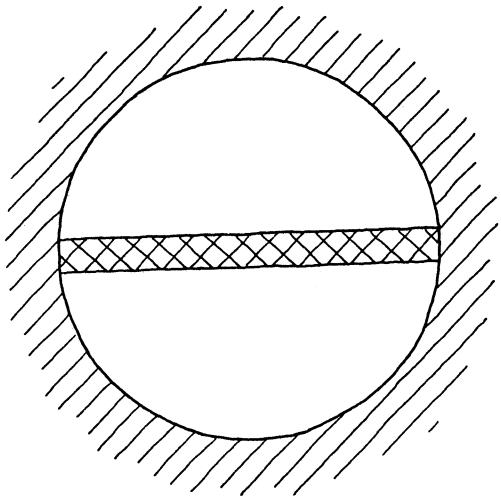

Fig. 3. Model of the possible space distribution of local radio galaxies, to account for the concentration of Molonglo sources to the supergalactic plane. All objects out to $z = 0 \cdot 02$ have been collapsed onto the supergalactic plane (shown edge-on), and outside this sphere the objects are distributed at random.

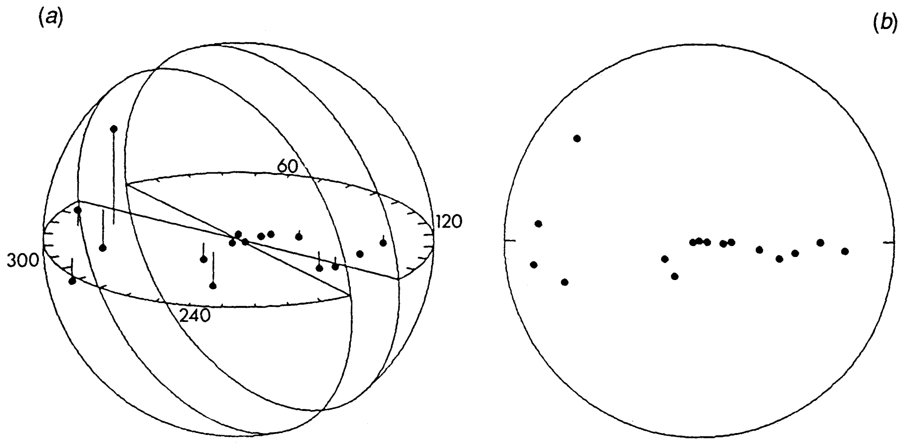

Fig. 4. Projections of the three-dimensional distribution of all the radio galaxies from the Wall and Peacock (1985) complete sample out to $z = 0 \cdot 02$. On the left (*a*), the supergalactic plane is the horizontal disc calibrated in 10° intervals of supergalactic longitude, and the thin vertical lines show the projections of the objects onto the supergalactic plane. The sectors missing are the zones of low galactic latitude. On the right (*b*), the distribution is viewed edge-on to the supergalactic plane.

It is noteworthy that the Abell clusters are very similar to the radio galaxies in their concentration to the plane, and different from the optical galaxies (although it should be cautioned that the clusters and galaxies have different selection effects); furthermore the few clusters of richness class >1 out to $z \sim 0 \cdot 02$ are all very close to the plane, suggesting that supergalactic concentration may be a function of cluster richness. Even the IRAS galaxies may be somewhat more concentrated to the plane than the optical galaxies. This appears at first surprising, as IRAS galaxies are almost all spirals which are less clustered than ellipticals, but the present sample is one of high infrared flux, and if the high luminosity derives from interactions between galaxies (e.g. Lawrence *et al.* 1989) then they may also be located preferentially

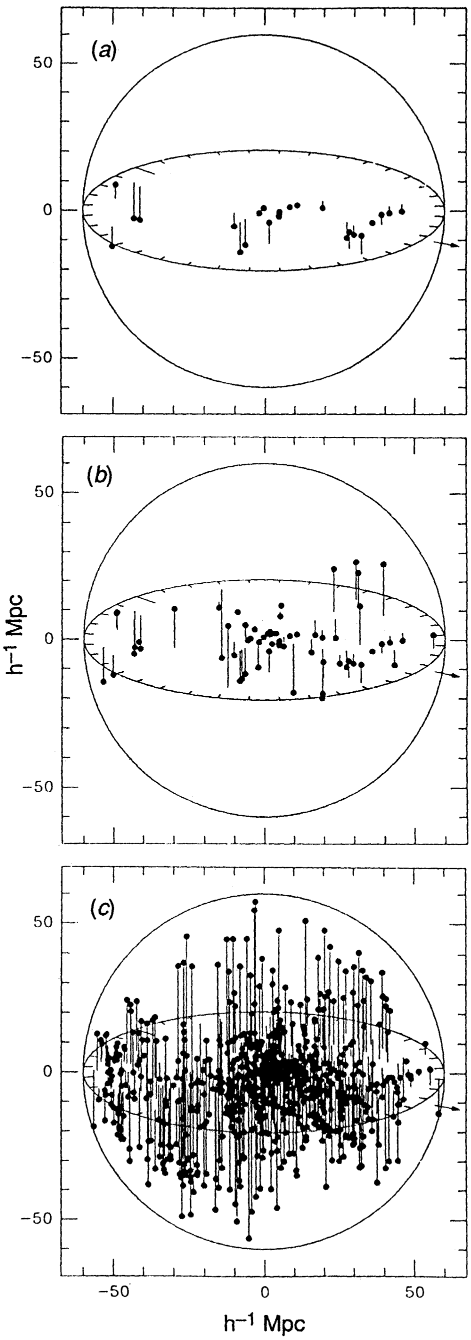

Fig. 5. Space distributions of the complete radio and optical galaxy samples out to $z = 0\cdot02$: (*a*) radio galaxies with $S_{408} > 4$ Jy, (*b*) radio galaxies with $S_{408} > 1$ Jy, and (*c*) the optical galaxies. Orientation and symbols as in Fig. 4*a*. The arrows show the 'Great Attractor' direction.

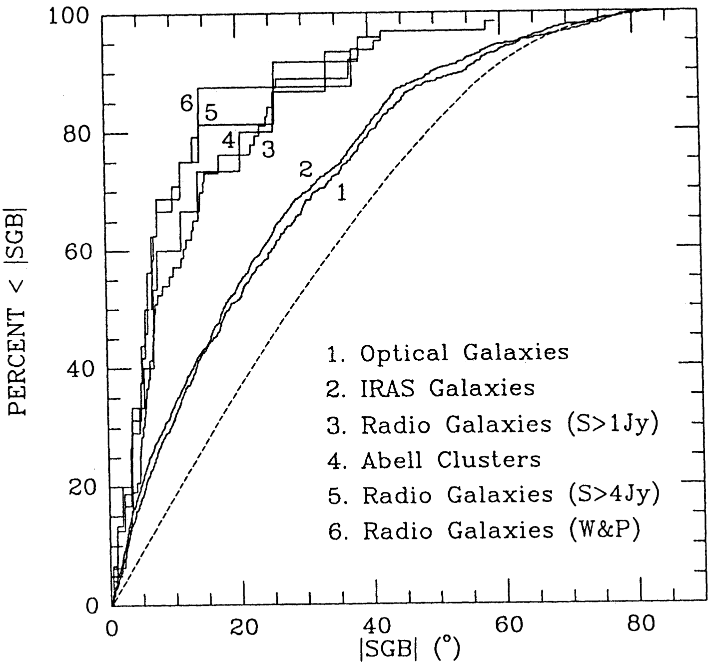

Fig. 6. Integral distributions in supergalactic latitude for several samples as indicated, for $z < 0 \cdot 02$. The dashed curve represents a random distribution with $|b| > 10°$.

in regions of enhanced density. The X-ray galaxies and clusters also appear to be more concentrated to the supergalactic plane than the optical galaxies, although the numbers are small and the selection effects different.

The arrows in Fig. 5 indicate the direction of the so-called 'Great Attractor', the cause of the local large scale streaming motions (Burstein 1990). Clearly, given the local dominance of the supergalactic concentration, it is hardly surprising that the Great Attractor direction lies near the supergalactic plane. Furthermore, there appears (from both Figs 4 and 5) to be a longitudinal asymmetry in the distribution of objects in the plane itself, with a predominance of galaxies in the Great Attractor direction. This would be consistent with the Great Attractor being just an asymmetry in the supergalactic concentration.

The size of the 'supergalactic zone', i.e. the region within which there is an excess of objects on the supergalactic plane, can be estimated by determining at what redshift the supergalactic latitude distribution of the radio galaxies appears random, or at least similar to that of the optical galaxies, and a radius corresponding to $z \sim 0 \cdot 024$ is obtained. This is illustrated in Fig. 7, which shows that the space distributions of the most powerful and luminous radio galaxies in the sphere within $z = 0 \cdot 024$ and the surrounding shell ($0 \cdot 024 < z < 0 \cdot 035$) are completely different, even though the selection effects are identical. The fact that the range $0 \cdot 024 < z < 0 \cdot 035$ is approximately where the 'Great Wall' is found (Geller and Huchra 1989; see also Djorgovski *et al.* 1990) suggests that the latter may be part of a still larger structure which encompasses the supergalactic zone, again reminiscent of Fig. 3.

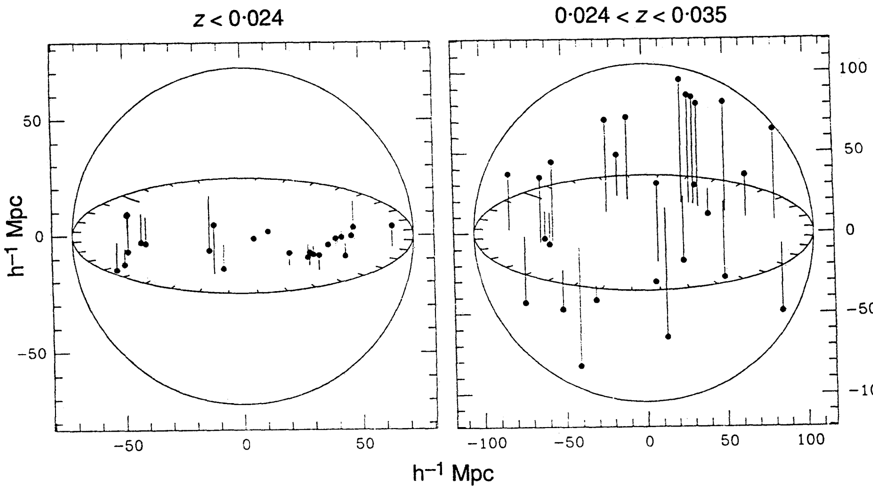

Fig. 7. Space distributions, in two redshift ranges, of powerful ($\log P > 22{\cdot}5$ in units of W Hz^{-1} sr^{-1}) and luminous ($M_B < -20$) radio galaxies from the 1 Jy sample extended to $m_B < 15$. Orientation and symbols as in Fig. 4*a*.

4. Discussion

It is clear from the above analysis that radio galaxies are powerful probes of large scale structure. The principal results concerning local large scale structure can be summarised as follows:

(a) The supergalactic plane, conveniently edge-on, is evidently a unique 'laboratory' for the study of the large scale segregation of extragalactic populations. Radio galaxies and clusters are more concentrated to the supergalactic plane than are normal galaxies. There is thus a large scale spatial segregation of populations: the radio galaxies and clusters appear to define the 'skeleton' of large scale structure, which is 'fleshed out' by normal galaxies. This is consistent with the well-known fact that radio galaxies (particularly of Fanaroff–Riley type I) are found in rich environments. The degree of concentration appears to be greatest for the strongest radio galaxies and richest clusters. The dependence on radio power could be due either to a greater efficiency in accumulating fuel in the denser supergalactic environment, or to greater containment of the radio lobes in the (presumably) denser intergalactic medium of the supergalactic structure.

(b) This spatial segregation presumably explains why the amplitude of the spatial two-point correlation function is greater for radio galaxies and clusters than for normal galaxies, and why it is a function of cluster richness (Bahcall and Soneira 1983; Bahcall and Burgett 1986; Peacock *et al.* 1988): the radio galaxies and clusters (particularly the strongest and richest) are spatially concentrated in large structures, whereas normal galaxies are more widely and loosely scattered.

(c) The supergalactic concentration is the dominant structure out to $z \sim 0{\cdot}024$ (although whether it is comprised of one coherent structure or several smaller concentrations which happen by chance to lie on the plane defined by the Local Supergalaxy is unclear). The regions above and below the plane are essentially devoid of strong radio galaxies out to that redshift. The Great Attractor may be just an asymmetry in the supergalactic concentration. More distant radio galaxies appear to be much more isotropically distributed over the sky, indicating that this redshift may define the limit of the supergalactic zone. The Great Wall may be a part of this boundary. This supergalactic structure therefore appears to extend over some 140–150 h^{-1} Mpc. It is remarkable that the supergalactic plane, a feature in the sky known since the work of the Herschels almost 200 years ago, turns out to be one of the largest structures so far known in the Universe. With such pronounced structure on such a scale, it is clear that a 'fair sample' of the Universe must extend over a volume several times larger.

(d) Evidently both the surface density of extragalactic radio sources and the slope of the source counts are indeed affected by local large scale structure (the simple model derived to explain these effects is in fact remarkably similar to the observed three-dimensional distribution of local radio galaxies); large scale structure can apparently not be neglected in the analysis of radio surveys. Conversely, as radio galaxies seem to economically trace out the 'skeleton' of large scale structure, and even quasars (particularly radio-loud quasars) also appear to be strongly clustered with each other and with galaxies (e.g. Shanks *et al.* 1987; Iovino and Shaver 1988; Yee and Green 1987), it appears that radio surveys can provide a powerful and efficient means of tracing out structure on the largest scales.

A more detailed account of this work will appear in a forthcoming paper in *Astronomy & Astrophysics.*

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