CHAPTER IX

THE DISTRIBUTION OF RADIO SOURCES

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RADIO SOURCE COUNTS AND THEIR INTERPRETATION

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ABSTRACT. Radio source counts at several wavelengths are shown and discussed in terms of evolving populations. The deepest counts now reach a surface density close to a million sources per steradian. At this level essentially all of the luminous radio galaxies and quasars appear to be included, and the weaker sources apparently reflect a relatively nearby population of less luminous radio sources.

1. HISTORICAL BACKGROUND

Since the early years of radio astronomy, counts of radio sources as a function of flux density have been used together with optical identifications and measured redshifts to explore the distribution of radio galaxies and quasars as a function of luminosity and cosmic epoch. At optical wavelengths complete surveys of quasars and galaxies are difficult, due to a variety of selection effects which can lead to incompleteness or unreliability. Flux density-limited samples are affected by varying degrees of obscuration and sky brightness, as well as by the presence of bright spectral features. Color-selected samples are also influenced by bright emission lines within the filter bandpass as well as by the large and uncertain K correction. Moreover, morphological distinctions between galaxies and quasars are distance dependent, and for faint objects, quasar surveys may be contaminated by galactic stars.

At radio wavelengths, the sky is cold, absorbtion is negligible, and even for very distant sources, measurements of flux density and position are now routinely made to an accuracy of a few percent and a second of arc, respectively.

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The extended radio sources which dominate the counts at low frequencies are optically thin, so that unlike many galaxies at optical wavelengths, the apparent radio luminosity is not orientation dependent. Except very close to the galactic plane, essentially all discrete radio sources appear to be extragalactic and there is a negligible galactic contribution.

The radio surveys, on the other hand, are affected by noise, confusion, and resolution which lead to systematic errors in determining the source count. However, these biases are well understood, and corrections to the observed count are readily determined (e.g., Murdoch et al. 1973, Windhorst et al. 1984). A more serious problem is that it is not possible from radio measurements alone to determine redshifts or even to distinguish between quasars and qalaxies. Despite dramatic improvements in the sensitivity of optical telescopes, the identification and spectroscopic analysis, especially for optically faint counterparts of radio sources is, however, still time consuming. Even for the 3CR catalogue of the strongest sources, the identification and redshift measurements only now approach completeness (Laing et al. 1983, Spinrad et al. 1985).

With complete optical identifications of selected radio samples, the radio luminosity function and its dependence on redshift may be derived in a straightforward way, provided that the geometry of the universe is assumed. However, since there are only a limited number of optical identifications, the determination of the radio luminosity function and its evolution has centered on the analysis of radio source counts, which may include thousands of objects distributed over a wide range of luminosity and redshift and supplemented by optical identifications and redshifts for restricted samples, primarily selected from strong source surveys. For the strong radio sources selected from low frequency surveys, about 80 percent are identified with bright elliptical or N galaxies of absolute magnitude near -23 (H_o = 50 km/sec/Mpc) and about 20 percent with quasars and BL Lacs (Spinrad et al. 1985). At high frequencies, the strong sources are approximately equally divided between quasars and galaxies. At low flux densities, essentially all quasars have already been counted and the counts at both high and low frequencies are dominated by galaxies (e.g., Windhorst et al. 1986).

Although the radio measurements are now routinely made with high precision and cover a wide range of flux density, this was not always the case. Until the development, in the 1960's, of synthesis arrays and large steerable dishes operating at short wavelengths, the poor sensitivity and

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angular resolution of radio surveys led to large errors due to noise and especially confusion between nearby unresolved sources. In particular, the first extensive radio source surveys made at Cambridge gave a slope of the log N-log S relation apparently well in excess of the value of -3/2 expected from a uniformly filled static Euclidean universe. At the same time, however, surveys made in Australia indicated a slope much closer to the Euclidean value. Moreover, in the limited region of the sky where the two surveys overlapped, except for the brightest sources, there was little agreement on individual sources. It is now recognized, however, that the effect of large experimental errors in these early surveys were exaggerated by the use of integral counts, which suppresses features in the source count as well as underestimates the uncertainty due to non independent data points (Jauncey 1967, Crawford et al. 1970). Radio surveys now have sufficient resolution to avoid these difficulties. Even more important, however, due to the very large range in flux density (over 10^6 sources per ster) over which counts are now compiled, the slope of the very strongest sources is no longer a crucial part of the general interpretation.

In this review we summarize in Section 2 the modern radio source counts, with particular emphasis on the 5 GHz (6 cm) count which now reaches sources as faint as 25 micro Janskies. In Section 3 we discuss the interpretation in terms of cosmological evolution, and in Section 4 the analysis is extended to distinguish between the compact flat spectrum sources and the extended steep spectrum sources. In Section 5, we discuss alternate interpretations of the source counts, and in Section 6, we speculate on what might be learned from future measurements made with radio telescopes of improved sensitivity and resolution.

2. THE RADIO SOURCE COUNTS.

When presented in differential form, the steep slope of radio source counts makes them inconvenient for graphical presentation. It has become customary to show the differential source count normalized to the static Euclidean slope of -5/2 corresponding to a slope of -3/2 for the integral count. Alternately, some authors choose to show the unnormalized differential count multiplied by $S^{5/2}$. This has the advantage of not requiring the introduction of an arbitrary normalization factor which is usually taken as the number density of sources with flux density above 1 Jy.

In Figures 1 through 4 we show the normalized radio source counts at 408 MHz (74 cm), 1.4 GHz (21 cm), 2.7 GHz

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TABLE I

5 GHz Source Surveys

Survey	Instr.	S_{lim}	n	Ω	References
S1[1]	140	800	23	0.27	Kellermann et al. 1968, Astrophys. Lett. 2, 10.
S2[1]	140	600	136	0.97	Pauliny-Toth et al. 1972, A. J. 77, 265.
S3[1]	140	600	123	1.06	Pauliny-Toth and Kellermann 1972, A. J. 77, 797.
S4[1]	300/100	500	269	1.71	Pauliny-Toth et al. 1978a, A. J. 83, 451.
NPS[1]	100	14	82	0.0046	Pauliny-Toth et al. 1978b, A & A Suppl. 34, 253.
S5[1]	100	250	185	0.37	Kuhr et al. 1981, A. J. 86, 854.
	100	10–18	118	0.0071	Pauliny-Toth et al. 1980, A & A 85, 329.
5C6[1]	100	20	96	0.0066	Maslowski et al. 1980, A & A 95, 285.
	300	15	186	0.0096	Leddon et al. 1980, A. J. 85, 780.
	210	32	53	0.0082	Wall et al. 1982, MNRAS 200, 1123.
	VLA	0.54	14	0.00016	Bennett et al. 1983, Nature 301, 686.
	300	35	480	0.069	Owen et al. 1983, A. J. 88, 1.
	VLA	0.35	25	5.9×10^{-5}	Fomalont et al. 1984, Science 225, 23.
	VLA	0.06	9	7.3×10^{-6}	Fomalont et al. 1984, Science 225, 23.
5C2[1]	100	17	106	0.0066	Maslowski et al. 1984, A & A 139, 85.
GB[1]	100	30	99	0.0092	Maslowski et al. 1984, A & A 141, 376.
MG	300	53–106	5974	1.87	Bennett et al. 1986, Ap. J. Suppl. 61, 1.
	300	20	625	0.035	Altschuler 1986, A & A Suppl. 65, 267.

[1] Included in compilation of Maslowski et al. 1984, A & A 141, 376.

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(11 cm), and 5 GHz (6 cm), based on the best available data. Exploratory observations have also been made at frequencies as high as 10.7 GHz (2.8 cm) (Aizu 1987). The data at 408 MHz are discussed by Wall et al. (1980); the 1.4 GHz data by Windhorst et al. (1984), Windhorst et al. (1985), and Windhorst (1986); the 2.7 GHz data by Wall et al. (1981), Peacock and Wall (1981), Wall and Peacock (1985) and Wall et al. (1986). The 5 GHz data are summarized in Table I and discussed further in this paper.

Because of the wide range of flux density and source density involved, no single instrument can provide a complete count, even at a single frequency. Pencil beam instruments, large steerable dishes, and phased arrays are typically used to survey large regions of the sky to obtain statistically significant counts for the stronger sources with a relatively low surface density. Separate surveys made from the northern and southern hemispheres are necessary to cover the whole sky, and in Table II we list the major all sky catalogues which have been compiled from large scale radio surveys.

TABLE II

All Sky Catalogues

Freq. (MHz)	S_{min} (Jy)	n	Ω	References
178	10	173	4.05	Laing et al. 1983, MNRAS 204, 151.
408	10	160	10.1	Robertson 1973, Astr. J. Phys. 26, 403.
2700	2	233	9.81	Wall and Peacock 1985, MNRAS 216, 173.
1400	2	234	4.30	Bridle et al. 1972, A. J. 77, 405.
5000	1	518	9.81	Kuhr et al. 1981, A & A Suppl. 45, 367.

Synthesis instruments provide the most sensitive surveys, but only over very small regions of the sky typically covering 10^{-5} to 10^{-4} ster. Counts of very faint sources based on only a few such small fields may be subject to error if there is significant clustering. Nevertheless, in contrast to the early radio source surveys, modern data obtained by different authors using very different kinds of radio telescopes are in good agreement with respect to individual source position and flux density as well as in surface density.

Examination of Figures 1 through 4 shows five regions of the source count as follows:

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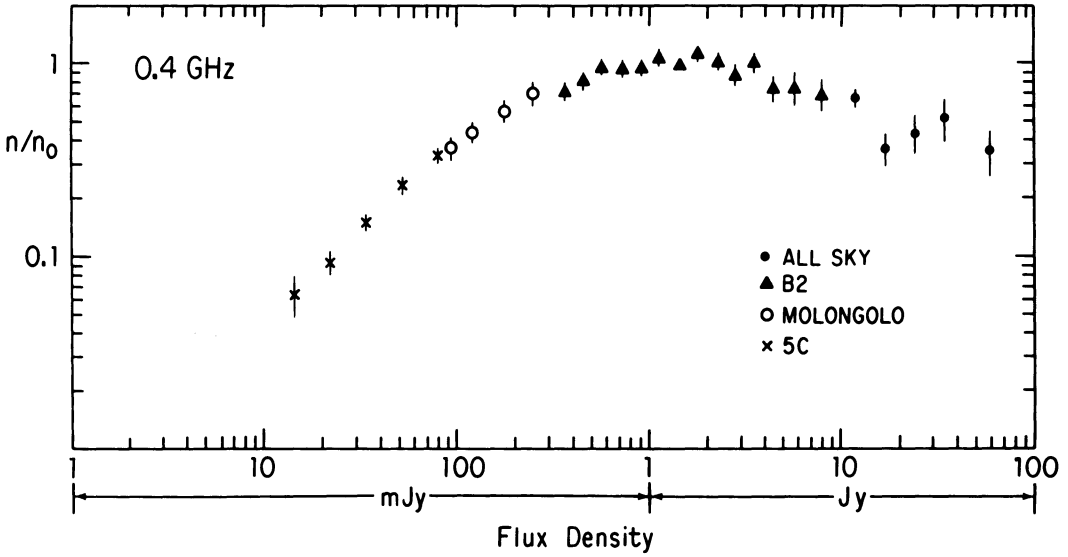

Fig. 1. Source count at 0.4 GHz normalized to a uniformly filled static Euclidean uviverse with a differential number count $n_o = 1125S^{-5/2}$. Data are taken from the all sky catalogue of Robertson (1973), from the Bologna B2 Survey (Colla et al. 1973, A&A Suppl. 11, 291), from the Molongolo Deep Survey (Robertson 1977, Austr. J. Phys. 1977, 30, 241), and from Pearson and Kus (1978, MNRAS 182, 273), all as complilied by Condon (1984).

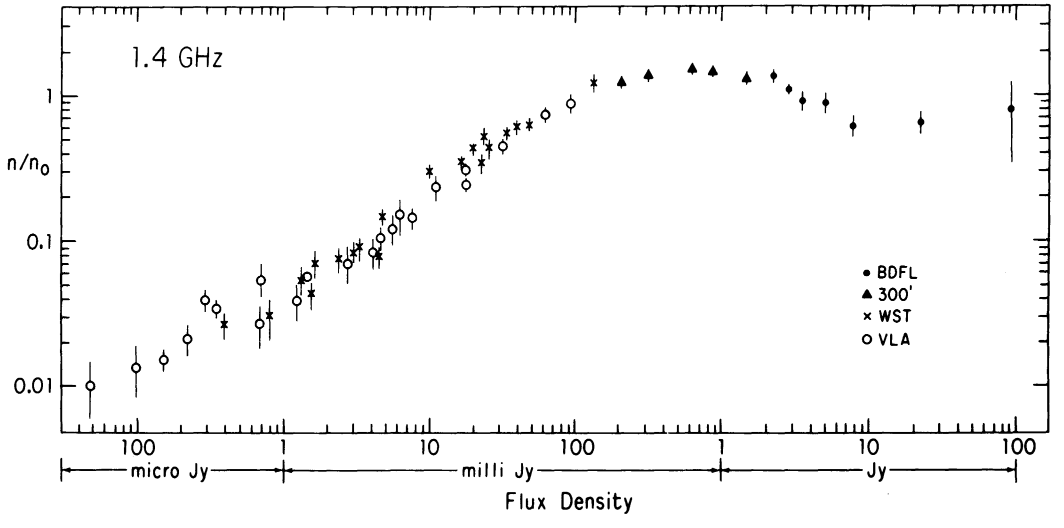

Fig. 2. Source count at 1.4 GHz normalized to a uniformly filled static Euclidean universe with a differential number count $n_o = 225S^{-5/2}$. Data are from the BDFL compilation (Bridle et al. 1972), the 300 foot GB and GB2 surveys (Machalski 1978, A&A Suppl. 65, 157), various Westerbork surveys as compiled by Windhorst et al. (1984, A&A Suppl. 58, 1), Oort and Windhorst (1985, A&A 145, 405) and Condon (1984).

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1) Euclidean Region. At the highest flux densities corresponding to source densities of only a few tens of sources per ster, the source count is close to the Euclidean value reflecting the fact that the very bright sources contain many nearby objects (Wall and Peacock 1985).

2) Steep Rise. Between source densities of about 20 to 50 sources per ster, the observed number of sources appears to increase rapidly, with a slope which is in excess of the Euclidean value. But over the whole sky there are only about 500 sources that contribute to this part of the count, and so the statistics are limited. It is this rapid rise in source density which occurs only over a limited range of flux density, that led to the earlier claims of a "huge excess of weak sources." The best fitting slope in this region of the source count is significantly steeper than the Euclidean value, but only over a limited range of perhaps three to one in flux density.

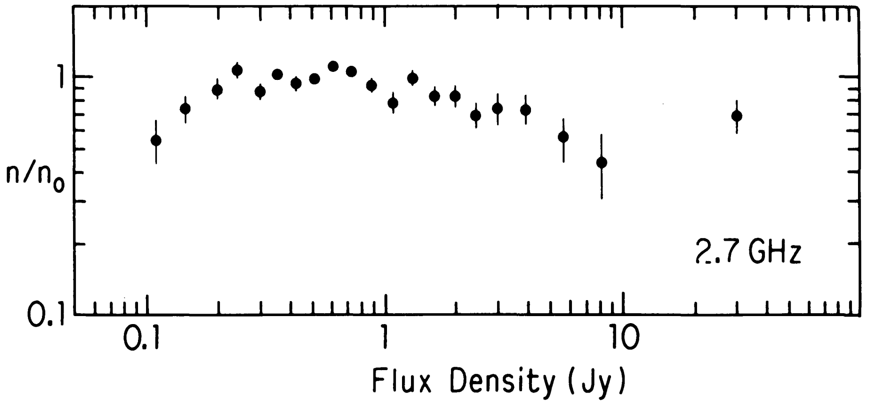

Fig. 3. Source count at 2.7 GHz normalized to a uniformly filled static Euclidean universe with a differential number count $n_o = 150 S^{-5/2}$. Data are from surveys made with the Parkes 210 ft radio telescope as compiled by Wall and Peacock (1985).

3. Euclidean Region. Particularly at the shorter wavelengths there is a plateau region that has a Euclidean slope over a range of flux density of up to 100 to 1, which extends up to a surface density of 2000 sources per ster.

4. Convergence. Below the plateau region the counts at all wavelengths drop relative to the Euclidean value for another two orders of magnitude in flux density. In this region the differential slope is about -3/2.

5. Euclidean Region. At the very lowest flux densities of less than about one mJy the count again steepens (flattens in the normalized presentation) to approximate the Euclidean slope.

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3. INTERPRETATION OF THE COUNTS

There are too few very luminous sources at low redshifts to define the high luminosity end of the local luminosity function and so it must be derived from the data at intermediate or high redshift along with the evolution function. The broad range of the radio luminosity function

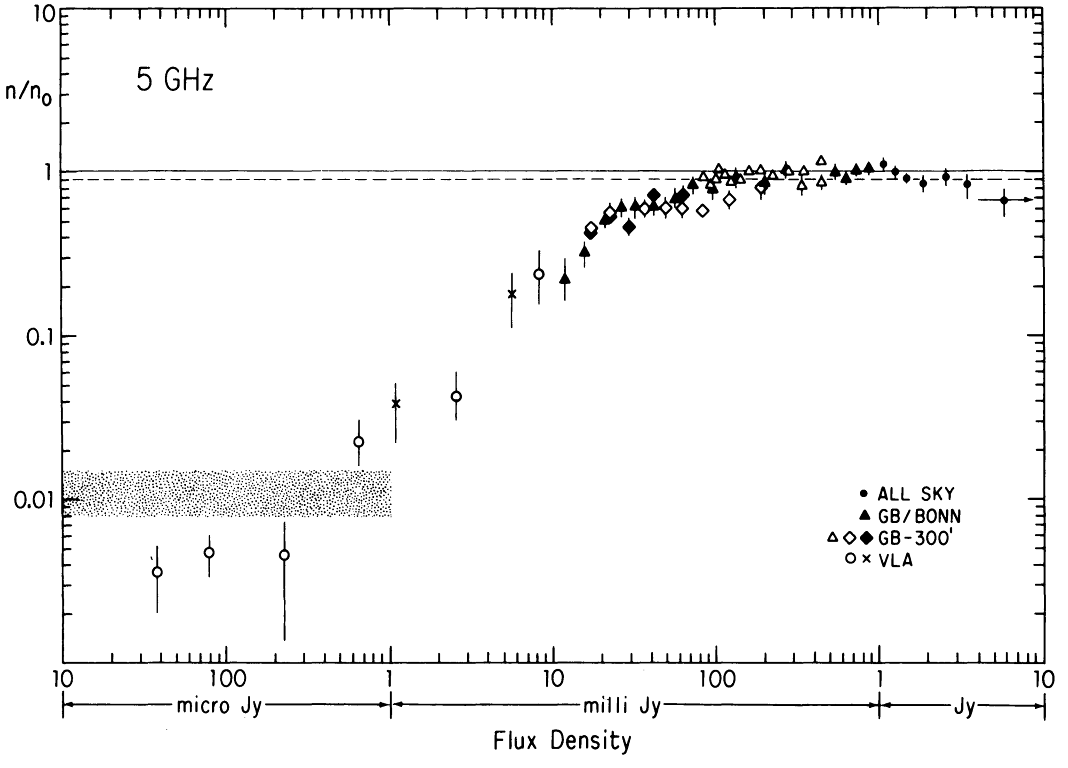

Fig 4. Source count at 5 GHz normalized to a uniformly filled static Euclidean universe with a differential number count $n_o = 90S^{-5/2}$ as indicated by a solid horizontal line. The dashed horizontal line is drawn at $n_o = 80S^{-5/2}$ and represents a somewhat better fit to the data above 100 mJy. Data are taken from the All Sky compilation of Kuhr (1981), the Green Bank-Bonn surveys made with the 140 foot, 300 foot, and 100 meter telescopes as compiled by Maslowski (1984), the MG Survey (Bennett et al. 1986), the 300 foot surveys of Owen et al. (1983) and Leddon et al. (1980), and Altschuler et al. (1986), as well as the VLA surveys of Fomalont et al. (1984) and Bennett et al. 1983. The points at the three lowest flux density intervals are preliminary values from a new deep VLA survey (Kellermann et al. 1986, Highlights of Astronomy, pg 367). The horizontal stipled area at the lower left represents the predicted counts based on an extrapolation of IRAS observations and measured ratios of 6cm to 60 micron flux density (Biermann et al. 1985).

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compared with the range of flux density covered by the counts makes it difficult to untangle the geometry, the form of the luminosity function, and the way it changes with redshift. If the luminosity function is flat, i.e., dominated by strong sources, then flux density-limited samples are dominated by the most luminous sources and there is a well defined Hubble type relation between flux density and redshift. On the other hand, if the luminosity function is steep, then there is an inverse Hubble law, and the weaker sources are relatively nearby low luminosity objects and not distant powerful sources. Clearly in this case the interpretation of the source counts is not obvious, particularly in the absence of independent distance information. Indeed, the so-called "local hole" interpretation of the strong source count becomes a "distant hole" interpretation. Finally, there is a "critical luminosity function" in which each luminosity contributes equally at all flux densities. In this case, there is no Hubble relation at all, and each flux density range contains the same distribution of redshifts.

In the uniformly filled static Euclidean universe, with a differential source count slope of -5/2, the critical luminosity function is a power law with differential slope also equal to -5/2 (von Hoerner 1973). Derivations of the radio source luminosity function show that it is more complex than a simple power law and has a marked change in slope near 10^{25} W/Hz (e.g., Auriemma et al. 1977, Windhorst 1984, Meurs and Wilson 1984, Peacock 1985). For the more luminous sources, the slope is steeper than the critical value, while at lower luminosity the slope is flatter. Although in a relativistic universe, geometric effects and the K correction make the critical slope less steep than -5/2, the actual luminosity function appears to be close to the critical slope over a wide range of luminosity. Thus radio source counts show little relation between observed flux density and redshift. This conspiracy of nature has made the interpretation of radio source counts difficult, and at least in the past, a source of great controversy.

Although there is no radio equivalent of Hubble diagram for radio galaxies and quasars, it has long been known that galaxies selected as the result of the identification of radio sources have a remarkable narrow range of absolute magnitude which makes them ideally suited for studying the optical Hubble diagram (e.g., Sandage 1972). Although there is a much bigger dispersion in the optical magnitude of quasars, as pointed out by Wall and Peacock (1985) and shown in Figure 5, there is some evidence that quasars selected from radio identifications do loosely follow a Hubble relation.

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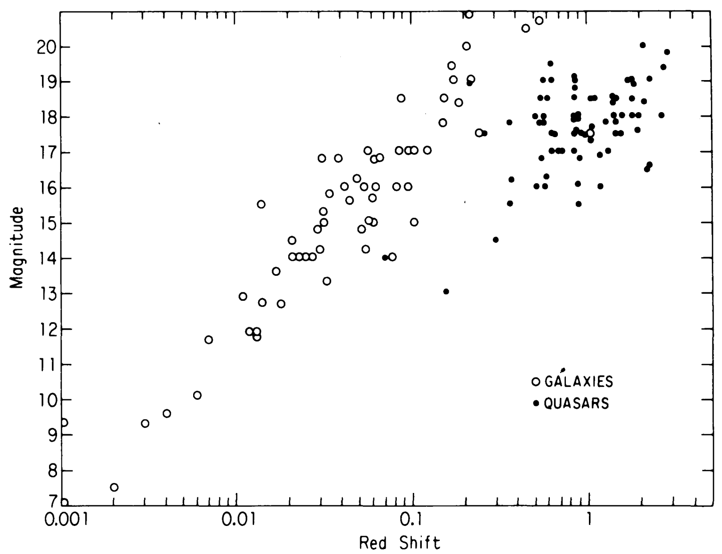

Fig. 5. Red shift magnitude diagram for all identified sources with 6 cm flux density greater than 2 Jy.

3.1 Evolution

Many authors, (e.g., Robertson 1980, Wall et al. 1980, Peacock and Gull 1981, Peacock 1985) have attempted to interpret the observed source counts constrained by the identification content and measured redshifts of flux density limited samples, but the number of unknowns is still too large to define uniquely the geometry, the local luminosity function, the evolution function, and possible redshift cutoff. Because of the relatively narrow peak in the count, particularly at long wavelengths, and in view of the relatively broad radio luminosity function, essentially all recent workers agree with the conclusions of Longair (1966) that pure luminosity or pure density evolution, corresponding to a horizontal and vertical translation of the luminosity function respectively) does not work. It is generally agreed that some sort of luminosity-dependent density evolution, in the sense that only the most luminous sources evolve, is necessary to reproduce the sharp peak in the normalized source count.

For the strongest few hundred sources in the low frequency 3CR catalogue, identifications and redshifts are nearly complete (Spinrad et al. 1985). For these sources, which constitute the steep part of the source count, the luminosity-volume test has shown that the evolution is confined to quasars and the most powerful radio galaxies, and that the lower luminosity sources appear to be more uniformly distributed (e.g., Laing et al. 1983).

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It has been customary to describe the evolution function as a power law of the form $(1+z)^p$, an exponential law of the form $e^{t/\tau}$, or with a free form fit to the data, (e.g., Robertson 1980, Peacock and Gull 1981, Peacock 1985). The power law is mathematically convenient, but requires a cutoff at large redshift ($z \sim 2.5$) to obtain the observed convergence of the counts at low flux density. The exponential law has a straightforward interpretation in terms of cosmic look back time. The free form approach provides a tool for including all of the available data, but it is sometimes claimed that a physical understanding of the evolution is obscured. However, the assumed analytical forms, power-laws and exponential functions offer no real physics either.

The analysis of source counts, and of the free form approach in particular, uses the counts, identifications, and redshifts - incomplete as they are - to provide the best numerical description of space density and its epoch dependence. In view of the non physical basis, denoting such descriptions as "models" is misleading. Nevertheless, the results do have substantial significance:

i) the degree of evolution, and its dependence on epoch and radio luminosity are delineated, time scales are established, and the possibility of a redshift cutoff is explored;

ii) the derived luminosity functions may be compared with true physical models or used to predict such quantities as the angular size-flux density and the angular size-redshift relations, or the integrated radio background due to discrete sources:

iii) the overall statistical agreement between data sets and the ability of the conventional framework (e.g., geometry and Doppler redshifts) to account for the data is checked;

iv) the differential evolution of different radio source populations may be investigated (see Section 4);

v) the needed areas for further work are elucidated.

Condon (1984) has noted that because the local luminosity function has a rather well defined knee, simple luminosity evolution (horizontal translation of the luminosity function) will give an apparent luminosity dependent change in the space density in the required sense that the evolution appears to mostly affect the more luminous sources. Condon was able to fit the observed source counts at a number of wavelengths with a combination of simple luminosity and simple density evolution. He points out that more complex types of evolution, such as described by Wall, Pearson, and Longair (1980) or by Peacock and Gull (1981) are not excluded, but Condon's approach is attractive since it treats all sources in the same way and does not require that the strong sources behave differently from the weaker ones. A similar approach to Condon's has been used by Green (1986) to describe the evolution of the quasar optical luminosity function, without the need to postulate a different z dependence for the strong and weak sources.

Somewhat paradoxically, however, the counts of optically selected quasars and the results of the luminosity volume (V/V_{max}) test on optically selected quasars indicate an even more dramatic evolution than for radio sources (e.g., Green 1986). Taken literally, this leads to the surprising conclusion that there is a net negative evolution for radio quasars in the sense that a quasar at large redshift is less likely to become a strong radio source than a nearby quasar. This is in contrast to galaxies, where the probability of a bright elliptical galaxy becoming a strong radio source appears to increase dramatically with increasing redshift.

3.2 Faint Radio Sources

As shown in Figures 2 and 4, near a level of 1 mJy the slope of the source counts change, suggesting the emergence of a new population of sources. This change in the slope of the source count is seen both at 1.4 GHz (e.g., Windhorst et al. 1986) and 5 GHz (e.g., Kellermann et al. 1986) in a number of survey fields, and, is therefore, unlikely to be the result of an unusual clustering in one particular region of the sky. Van der Laan (1983) and Windhorst (1986) suggest that the observed increase in source density at sub mJy levels is due to a population of blue peculiar, interacting and merging galaxies. Wall et al. (1986) and Weistrop et al. (1987) find no evidence for any new population, and suggest that the sub mJy sources are relatively low luminosity radio galaxies at moderate distance. Normal spiral galaxies such as those found locally cannot account for the weak source population without evolution (Condon, 1984). However, radio observations of IRAS sources (e.g., Condon et al. 1982, de Jong et al. 1985) suggest that the sub mJy source count can be reproduced by a simple extrapolation of the -5/2 power law which describes the IRAS counts of moderately active (e.g., starburst) and relatively nearby ($z < 0.3$) galaxies (Biermann et al. 1985). Thus the faint radio sources which constitute the low end of the source count may not give us information on the evolution of quasars and radio galaxies, but may provide substantial information on the local radio luminosity function of certain types of active galaxies.

4. SOURCE POPULATIONS

The interpretation of radio source counts is complicated by the fact that extragalactic radio sources are an inhomogeneous collection of quasars, radio galaxies, compact, and extended sources, all of which may have a different local radio luminosity function which may have different individual lifetimes and which may show different cosmic evolution. For the most part, compact sources are identified with quasars and extended sources with radio galaxies, but the correlation is far from perfect. Some radio galaxies are dominated by a compact core while many quasars, such as most of those found in low frequency surveys like the 3CR survey, host extended radio sources.

The compact radio sources are most easily distinguished by their flat radio spectra, and are, therefore, most commonly detected at short wavelengths, where they represent about half of the strong source population. At long wavelengths, the source count is dominated by the steep-spectrum extended sources. Since there is only one population at low frequencies, the interpretation of the source counts are more straightforward than at high frequencies.

In Figure 6, we show the 6 cm source count separated into the two classes of flat spectrum (compact) and steep spectrum (extended) sources. The individual sub counts each peak more sharply than the combined count and at different flux densities, so that the near-Euclidean slope observed above 30 mJy for the combined 6 cm count results from combining the two sub counts. It is curious that the effect of evolution, the relativistic effect of the redshift on the observed flux density, the change in the volume element with redshift, and the combination of the two subcounts combine to mimic a uniformly filled static Euclidean universe over a wide range of flux density.

As shown in Figure 6, the strongest sources are roughly equally divided between the two classes. The steep-spectrum subcount peaks near a few hundred mJy while the flat specrum sources peak near 1 Jy and drops rapidly at lower flux densities, where they contribute only about 1/3 of the total count. However, below 1 mJy, the flat spectrum population again contributes more than half of the total. Thus, independent of the indicated upturn in the count, the change in spectral distribution at sub mJy levels suggests a change in source population.

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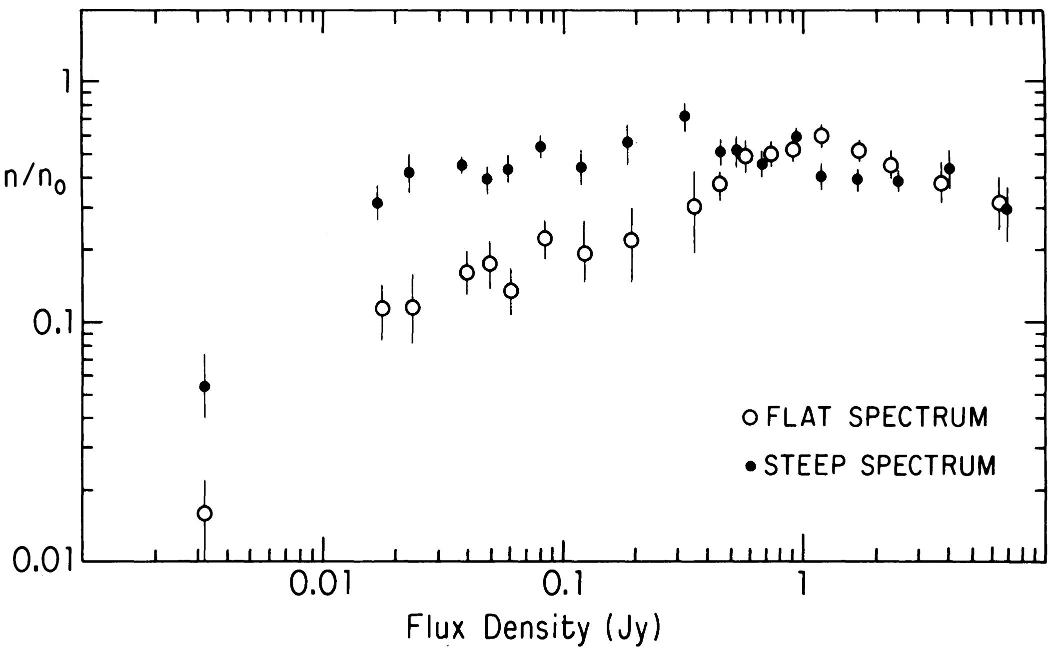

Fig. 6. Differential source counts for flat (α > -0.5) and steep (α <-0.5) spectrum souces normalized as in Fig. 4. Data are taken from the compilations of Pauliny-Toth et al. (1978a) and Condon (1984) and for the point at 3 mJy from Fomalont et al. (1984).

The early interpretations of the separate sub counts or of the corresponding luminosity-volume (V/V_m) test suggested that the flat spectrum population is distributed more uniformly than the steep spectrum sources (e.g., Schmidt 1976, Masson and Wall 1977). However, the data used in these investigations covered that part of the source count where the slope is not so steep and includes the relatively low power sources which have a more uniform space distribution, (e.g., Kellermann 1980). More recent analyses of the much more extensive material now available indicates that for both populations, the powerful sources evolve more strongly than the those of low luminosity, (e.g., Laing et al. 1983, Wall and Peacock 1985, Peacock 1985, Zawislak-Raczka and Kumor-Obyrk 1986).

5. ALTERNATIVE INTERPRETATIONS

For strong radio sources, modern surveys give source counts which are very close to that obtained 25 years ago by Australian workers and which have an initial slope not grossly different from that of a uniform distribution of sources in a static Euclidean universe. The earliest interpretation in terms of dramatic cosmic evolution was based on an inappropriate analysis of poorly understood data. Later, a more sophisticated analysis of the so-called P(D) statistics of the confusion limited surveys reinforced the need for a radio source population which has changed dramatically with cosmic epoch, an interpretation which in general terms is still widely accepted. However, the data and consequently the arguments, have changed, and although much more detailed and subtle, the general conclusions remain essentially unchanged.

Except for the strongest sources, the observed counts are characteristic of a homogeneous distribution of sources in a relativistic universe where the effect of the redshift on the volume element and flux density suppress the count at low flux densities below the -3/2 Euclidean value (e.g., Scheuer 1975). Therefore, it may be argued that the source counts can equally well be interpreted as a deficiency of a relatively small number of strong sources rather than a huge excess of weak sources (e.g., Kellermann 1972), and that it is inappropriate to base cosmological models on the distribution of these few strong sources. The number of "missing" sources in these "local hole" models is surprisingly small. Jauncey (1975) estimates that only 35 strong sources need to be added over the whole sky to reproduce a Euclidean slope for the 178 MHz 3CR count. As seen in Figure 4, at 6 cm the observed count is close to Euclidean over a wide range of flux density, except for about 20 "missing sources" over the whole sky.

In view of the apparent isotropy of the source counts, it is often argued that "local hole" models are untenable since it would imply that we are preferentially located near the center of such a hole in violation of Copernican principles. However, the isotropy measurements apply only to the weaker sources where the source count slope appears consistent with a uniform distribution of sources. For the strong sources, where the slope appears is steeper than the Euclidean value, there are too few sources to put firm limits on the isotropy or lack of isotropy, (e.g., Pauliny-Toth et al. 1978). Moreover, the apparent recent detections of superclusters, strings, and voids on scales of 10 to 100 Mpc suggests that the universe may be less smooth than previously suspected, and that the departure of a few dozen strong sources from the -3/2 law does not require large-scale cosmic evolution or departure from accepted Copernican concepts.

However, comparison of the counts with those expected from a realistic luminosity function based on identified samples and redshifts indicates that the counts at low flux density should fall off even faster than observed, and (independent of the strong source count) this is commonly accepted as the result of the evolution of the source population toward higher space density or greater luminosity at large redshift. Thus in its current form, the argument for evolution depends on the cosmological interpretation of redshifts. While we do not wish to raise the issue of non cosmological redshifts, we do want to emphasize that the source counts by themselves do not necessarily require departure of the radio source population from homogeneity on a cosmological scale.

The interpretation of radio source counts has thus "evolved" considerably over the years, although the basic conclusions have remained essentially unchanged, as it has proven possible to accommodate the observational refinements with a correspondingly refined interpretation. It is interesting to speculate how the field might have developed had the first source counts been compiled at 6 cm (e.g., Fig 1) instead of at long wavelengths, and had the early counts reached source densities of a few hundred thousand per ster thus not emphasizing the high flux density - steep count end.

6. The Future

At a source density of about 10^5 sources per ster essentially all of the evolving radio-powerful sources have been counted. Surveys to higher source density primarily contain less luminous sources which appear to be bright Seyfert or starburst galaxies with a luminosity of about 10^{22} Watts/Hz and only moderate redshift. While it would be of interest to investigate the cosmological evolution of these sources, there are two fundamental limits which are independent of any future advances in instrumentation, and which may limit the depth to which radio surveys can be extended.

The deepest radio surveys now reach a source density of almost 10^6 sources per ster, so that the mean separation between sources is only a few minutes of arc. Even a small further improvement in sensitivity will reach a source density where the separation between sources becomes comparable with the typical component spacing of individual sources;

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the source count becomes a source component count, and interpretation becomes unclear.

A further limit may be introduced by small scale fluctuations in the microwave background radiation. The deepest VLA survey reaches an rms noise level of only 5 micro Jy, corresponding to an equivalent sky temperature less than one milli degree at 18 arc second resolution, and they are sensitive to fluctuations of a few tenths a degree (Kellermann et al. 1986). This is approaching the level where many models predict observable fluctuations due to the formation of galaxies, and more sensitive surveys may be influenced by this effect.

LITERATURE REFERENCES

Aizu, K 1987, this volume.
Auriemma, C., Perola, G.C., Ekers, R., Fanti, R., Lari, C., Jaffe, W.J., Ulrich, M.H. 1977, Astron. and Astrophys. 57, 41.
Biermann, P., Eckart, A, and Witzel, A. 1985, Astron. Astrophys. 142, L23.
Condon J.J, Condon, M.A., Gisler, G., Puschell, J.J. 1982, Astrophys. J. 252, 102.
Condon, J.J. 1984, Astrophys J. 287, 461.
Crawford, D.F., Jauncey, D.L., and Murdoch, H.S. 1970, Astrophys. J. 162, 405.
de Jong, T., Klein, U., Wielibinkski, R., and Wunderluch, E. 1985, Astron. and Astrophys. 147, L6.
Green, R. 1986, I.A.U. Symposium No. 119, eds G. Swarup and V.K. Kapahi, Reidel, p 429.
Jauncey, D. 1967, Nature 216, 877.
Kellermann, K.I. 1972, Astron. J. 77, 531.
Kellermann, K.I. 1980, Physica Scripta 21, 664.
Kellermann. K.I, Fomalont, E., Weistrop, D., and Wall, J.V. 1986, Highlights of Astronomy, Reidel 6, 367.
Laing, R.A., Riley, J.M., Longair, M.S. 1983, M.N.R.A.S. 204, 151.
Longair, M.S. 1966 M.N.R.A.S. 133, 421.
Masson, C.R. and Wall, J.V. 1977, M.N.R.A.S. 180, 193.
Meurs, E.J.A. and Wilson, A.S. 1984, Astronomy and Astrophys. 136, 206.
Murdoch, H.S., Crawford, D.F.,and Jauncey, D. 1973, Astrophys. J. 183, 1.
Pauliny-Toth, I.I.K. et al. 1978, A.J. 83, 451.
Peacock, J.J. and Wall, J.V. 1981, M.N.R.A.S. 194, 331.
Peacock, J.J. 1985, M.N.R.A.S. 217, 601.
Peacock, J.A. and Gull, S.F. 1981, M.N.R.A.S. 196, 611.

https://doi.org/10.1017/S0074180900159546 Published online by Cambridge University Press

Peacock, J. J., Perrymann, M.A.C., Longair, M.S., Gunn, J.E., and Westphal, J.A. 1981, M.N.R.A.S. 194, 601.
Robertson, J.G. 1980, M.N.R.A.S. 190, 143.
Sandage, A. 1972, Astrophys. J. 178, 25.
Scheuer, P. 1975, Galaxies and the Universe, Stars and Stellar Systems, vol 9, ed. Sandage, A., Sandage, M., and Kristian, J., p 725, University of Chicago Press.
Schmidt, M. 1976. Astrophys. J. 209, L55.
Spinrad, H., Djorgovski, S., Marr, J., Aguilafr, L. 1985, Publ. Astron. Soc. Pac. 97, 932.
van der Laan, H. and Windhorst, R.A. 1982, Astrophysical Cosmology, p 349.
von Hoerner, S. 1973, Astrophys. J. 186, 741.
Wall, J.V. and Peacock, J.J. 1985, M.N.R.A.S. 216, 173.
Wall, J.V., Benn, C.R., Grueff, G., and Vigotti, M., 1986, Highlights of Astronomy 6, in press.
Wall, J.V., Pearson, T.J., and Longair, M.S. 1980, M.N.R.A.S. 193, 683.
Weistrop, D., Wall, J.V., Fomalont, E.B. and Kellermann, K.I., 1987, Astron. J. (in press).
Windhorst, R.A. Miley, G.K., Owen, F.N., Kron, R.G., and Koo, D.C. 1985, Astrohys. J. 289, 494.
Windhorst, R.A., van Heerde, G.M., and Katgert, P. 1984, Astron & Astrophys. Suppl. 58, 1.
Windhorst R. 1984, Ph. D. Thesis, University of Leiden.
Windhorst, R.A. 1986, Highlights of Astronomy, Reidel.
Zawislak-Raczka, J. and Kumor-Obyrk, B. 1986, M.N.R.A.S. 222, 487.

DISCUSSION

SWARUP: Could you comment on why 6 and 21 cm source counts look so similar, in contrast to that at 75 cm.

WALL: Not very constructively, you raise a point which has not received enough attention from radio surveyors. The most striking similarity between the 6 and 21 cm source counts is in the region of "convergence", where the coincidence of the counts implies a median spectral index near zero. However we know that sources selected at these flux density levels do not all show flat high-frequency spectra, together with the steep low-frequency spectra required to translate the 75-cm count to the 21-cm count. Some combination of more subtle effects must be responsible, presumably including the count normalization used here, luminosity functions <u>and</u> spectral indices. It all bears further investigation.

MILEY: Do you know of any attempts that have been made to study luminosity evolution as a function of spectral index for the steep

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spectrum sources? This is interesting since we know that the ultra-steep spectrum sources are much more luminous than the normal-spectrum sources.

WALL: I don't know of such attempts, and only now do we have data sets which permit us to reconsider it. The situation is not as simple as you suggest, because some cluster sources of relatively low radio luminosity also have very steep spectra. A criterion in addition to radio spectrum would be needed to select the sample.

WINDHORST: To what extent has the radio K-correction been taken into proper account by those who performed model descriptions of multi-frequency radio source counts? We know that the radio K-correction is negligible for low z, but the situation at $z \gtrsim 1$ might be more complicated due to spectral curvature. Donnelly, Partridge and I recently found in a deep 6-21-50 cm survey that radio sources with $V \gtrsim 23.0$ mag (probably $z \gtrsim 0.75$) have generally very significant concave or convex spectra, which illustrates this complication.

WALL: This complication is well known in the sense that no "flat-spectrum" radio source has a flat-spectrum; all are curved, either simply concave, simply convex, or in combinations. Single bulk K-corrections are typically used, which obviously do not consider individual spectra. However this assumption does not bias space densities and is at present certainly not the major source of uncertainty in these estimates.

SZALAY: You mentioned marginal evidence of large scale anisotropies in the bright sources. Could you give more details?

WALL: These 'anisotropies' were reported some 10 years ago, on the completion of cm-wavelength surveys of large areas of extragalactic sky (Pauliny-Toth, Wall and colleagues; see e.g. Proc. IAU Symp. 74). They are on scales of steradians, and are at a significance level of about 2σ. Because the very radio-brightest objects are involved, there is no way to improve the statistics.

PARTRIDGE: Jasper, you showed an overlay comparing two histograms, one of instrument noise alone, and one of instrument plus sky noise. The positive flux sides of the two histograms agree well except for a small tail, perhaps due to residual sources. But the negative sides don't agree well at all - there appears to be a lot of excess sky noise. If this additional variance is due to microwave background fluctuations, it should appear symmetrically on both sides of the histogram, but yours doesn't. Can you explain why? Is there a problem with the zero spacing flux?

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WALL: It's possible, a shift of 1μ Jy/beam evens the balance, and then provides excess signal both positive and negative. Wrong flux in the zero spacing doesn't make this signal disappear. But obviously we want to understand the limits on the zero spacing flux (as well as other effects) before stronger statements of results can be made.

BURKE: What cleaning procedure was used to derive your evidence for background fluctuations?

WALL: We used standard NRAO 'cleans', from extremely light to heavy; and we found that the excess signal does not depend primarily on the degree, at least for moderate 'cleaning'. It is essential to carry out numerical simulations to find the full and combined effects of 'cleaning' + noise + confusion by extremely faint sources. Even then, residual instrumental errors may mean that yet another upper limit is the best we can do.

BURKE: Since the CLEAN procedure is not well understood when applied to very noisy data, I don't think your evidence for background fluctuations is believable yet.

NARLIKAR: I have two comments. (1) You mentioned the shape of the log N-log S curve at the bright end as arising from inhomogeneities in the distribution of galaxies on the scale of 50-100 Mpc. In 1961, during the Hoyle-Ryle controversy about the steep source counts, Hoyle and I had suggested inhomogeneities of precisely this order to explain the observed effect. However, at that time we were accused of proposing a model that was too inhomogeneous to be realistic. The balance of opinion has shifted in the last twenty five years. (2) In a recent work P. DasGupta, G. Burbidge and I have constructed a non-evolving radio luminosity function from the observed N-z plot for 3CR radio galaxies. The S-z plot generated by this RLF does not differ from the observed S-z plot in a statistically significant manner. We have repeated the exercise for the Wall-Peacock catalogue of sources at high frequency, with the same result. We would be interested in applying this technique to samples at fainter flux densities once their redshift determinations are complete. This exercise would tell us whether evolution is really necessary.

WALL: With regard to the second point, catalogues of the brightest sources span a factor of 10 or so in apparent luminosity, while the absolute-luminosity functions are known to cover at least 7 orders of magnitude. This was a major criticism in the early days of source-count interpretation. We now have counts for tens of thousands of radio sources at several frequencies, spanning 7 orders of magnitude in intensity, and complete with identifications and redshifts for many of the samples involved. Any successful description of the space density of radio sources and its epoch dependence must be able to account for these data.