THE DISTRIBUTION OF FAINT RADIO SOURCES AT 6 CM

K. I. Kellermann and E. B. Fomalont
National Radio Astronomy Observatory
Edgemont Road
Charlottesville, Virginia 22903

ABSTRACT. Deep radio source surveys made with the VLA at 6 cm wavelength show that the radio source count continues to converge down to microjansky flux densities, although there is some evidence of a flattening of the count in the range between 10 and 100 microjansky. The weak sources may be primarily an evolving population of active spiral galaxies.

1. INTRODUCTION

Advances in astronomical instrumentation over the past decade has resulted in vastly improved sensitivity in nearly all parts of the electromagnetic spectrum. At radio wavelengths, the VLA is able to detect radio sources nearly two orders of magnitude weaker than any previously catalogued source. But due to the great pressure for observing time, only recently has it been feasible to make the lengthy observations necessary to exploit the great sensitivity of the VLA.

For a number of reasons radio observations appear very attractive for cosmological investigations:

1. Even for relatively small instruments, radio sources can be easily observed out to very large redshift.

2. At radio wavelengths the sky is cold, and even weak discrete sources are easily observed.

3. In contrast to early radio measurements, modern surveys are:

    a. Complete and contain essentially all sources above the specified flux density limit.

    b. Reliable so that essentially all of the catalogue sources are real.

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   c. Accurate with measurement errors of a few percent in flux density and one arcsecond in position not uncommon.

4. At radio wavelengths, there is negligible obscuration; away from the galactic plane, confusion from galactic radio emission is negligible.

Unfortunately it is not straightforward to fully exploit the great sensitivity of radio telescopes since the absence of any characteristic spectral features makes it impossible from radio measurements alone, to determine distances. Moreover, at least for the compact sources relativistic beaming may make the apparent brightness very orientation dependent, therefore obscuring any dependence of flux density on distance.

It is difficult and time-consuming to obtain spectroscopic redshifts for optically identified sources, especially faint radio galaxies. Thus, investigations of the large-scale distribution of radio sources has depended on the interpretation of radio source counts, constrained by the optical identification and redshift measurements of complete samples to derive a Local Luminosity Function and a corresponding Evolution Function.

However, it should be appreciated that the concept of a Local Luminosity Function is mostly a mathematical convenience and does not have much physical meaning, since there are only a few sources near the high end of the luminosity function above 10^{27} WHz^{-1} at redshifts which are not cosmologically significant. Thus, even the "Local" Luminosity Function for the powerful radio galaxies and quasars must be constructed from samples of high redshift objects, and "corrected" for geometry and the population change with redshift.

When the radio luminosity function is very flat, that is when there are a relatively large number of powerful sources, then the source count is dominated by the most luminous sources, and there is a well-defined radio Hubble law relating flux density and redshift. If on the other hand, the luminosity function is very steep, then the extension of the observations to weak sources, merely samples the more numerous intrinsically less powerful sources, and there is in fact an inverse Hubble law with the weaker sources being on the average closer than the strong sources.

Clearly there is also a critical luminosity function in which each luminosity interval contributes equally at all flux densities. In this case the mean redshift does not vary with flux density (von Hoerner 1973). Over an appreciable range of luminosity, the observed Local Luminosity Function is in fact close to this critical value. Thus, contrary to early expectation of radio astronomers, the faint radio sources are not systematically more distant, and it has been difficult to infer very much about the distribution of radio sources from simple counts of number vs. flux density. A further complication is that, until recently, the range of flux density sampled by the counts was less than that of the luminosity function, and this has led to further ambiguities in the interpretation of the counts.

II. THE VLA DEEP 5 GHz SURVEYS

Sensitive single dish surveys now cover a significant fraction of the whole sky (e.g., Kuhr, et al. 1981), and reach sources as faint as 20 (Maslowski 1984) to 50 mJy (Bennett et al. 1986) over limited regions of the sky. Below this level single dish instruments become confusion limited (e.g., Condon 1974), but synthesis radio telescopes may be used to survey very small regions of sky to remarkably faint levels.

Starting in 1981 we began to use the VLA at a frequency of 5 GHz to extend the radio source count to sub-millijansky levels with the goal of better defining the radio luminosity function of galaxies and quasars, and to investigate its dependence on distance or cosmic epoch. It was also anticipated that at these low levels of flux density, we might uncover a new population of faint radio sources which do not contribute to the strong source population. This study compliments a parallel investigation made at 1.4 GHz discussed by Windhorst et al. 1984, Windhorst et al. 1985, and Windhorst 1986.

Table I

VLA 6 cm Radio Source Surveys

S_{lim}	n	Ω (sr)	Reference
0.35	25	5.9×10^{-5}	Fomalont et al. 1984, Science 225, 23
0.06	9	7.3×10^{-6}	Fomalont et al. 1984, Science 225, 23
0.18*	18*	1.4×10^{-5}*	Partridge et al. 1986, Astrophys. J. 308, 46
0.14	29	2.2×10^{-5}	Donnelly et al. 1987, Astrophys. J. in press
0.025	28	7.3×10^{-6}	Unpublished

*An additional three sources are found in a region of 7.3×10^{-6} sr complete to 100 μJy.

In Table 1 we summarize the results of our 5 GHz surveys, along with other published VLA surveys made at this wavelength. Successive columns give the limiting flux density, S_{lim}, the number of sources in the complete sample, n, the area of sky surveyed, Ω, and the reference to previously published work. Because of the longer integration time and the elimination of an instrumental effect which limited the sensitivity of our earlier surveys, our new survey reaches a substantially lower limit of flux density than previously attained. The survey covers the same region in SA 68 as that reported by Fomalont et al. 1984, and is centered on $\alpha_{1950} = 00^h15^m24^s$ and $\delta_{1950} = 15°35'00"$. We observed for 80 hours in the D-configuration to obtain 65 hours of useful data to give an effective resolution of 16.5 arcseconds and an rms noise level of about 5 μJy. We found 28 sources above a completeness level of 25 μJy map flux density. We have also examined the P(D) distribution (e.g., Condon 1974), to extend the statistical analysis down to the one microjansky level.

Figure 1 shows the 5 GHz count derived from the previously published surveys together with the preliminary data from our new Deep Survey. The count is characterized by the well-known steep slope at the high flux density end, a flat or Euclidean region, and a region of rapid convergence where the count drops to less than one percent of the Euclidean value. Below one millijansky the slope appears somewhat less steep than in the range one to ten millijansky.

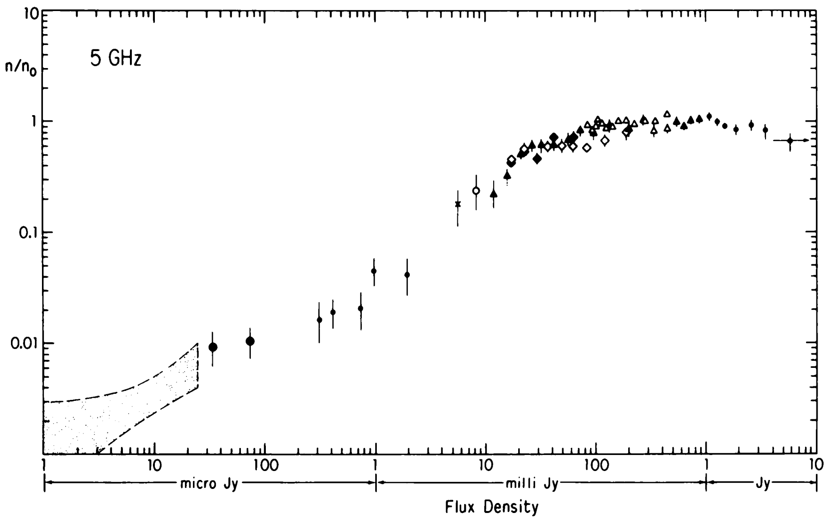

Figure 1. Composite 6 cm radio source count normalized to a static Euclidean universe with a uniform distribution of sources. Data above 10 mJy is taken from single dish surveys made with the NRAO 140-foot and 300-foot antennas and the MPIfR 100-m antenna as summarized by Kellermann and Wall (1987). Results from other VLA surveys between 0.1 and 1 mJy (Fomalont et al. 1984, Partridge et al. 1986; Donnelly et al. 1987) are shown as small closed circles while the results of the new survey are shown with large closed circles. All of the points referring to previously published data, have been "uncorrected" for resolution to be consistent with the point source models used to discuss the new survey.

The sub-millijansky count is limited primarily by the following:

1. Small number statistics. Each data point is typically derived from only about 10 sources so the statistical uncertainty is about 30 percent.

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2. Noise. The counts are normally made down to 5σ, where population bias causes a systemic overestimate of the number density. We have used the results of Murdoch et al. (1973) to calculate the correction to our count, which is about 25 percent for the weakest flux density interval.

3. Confusion at the lower limit of detection of 25 μJy, there are about 24 beam areas per source, so that the blending of sources may cause considerable error in the measured flux density, or even in distinguishing individual sources. An accurate correction of the effects of confusion is difficult and requires a detailed Monte Carol simulation. However, we estimate that the rms "confusion noise" in our map is comparable to the thermal noise of about 5 μJy, so that confusion causes a further overestimate of about 25 percent in the number density of sources in the lowest flux density interval.

4. Resolution. A major source of uncertainty in high resolution radio surveys is the reduction of the observed peak flux density when the source dimensions are non-negligible compared with the synthesized beamwidth, which in our case is only 16.5 arcseconds. This not only causes the measured flux density to be systematically low, but some sources with peak flux below the limit will not be included in samples limited by the observed peak flux density.

Fomalont et al. (1984) and Donnelly et al. (1987) have used the statistics of the size of somewhat stronger sources and the measured ratios of integrated to peak flux densities to apply source size corrections of 1.14 and 1.16, respectively. However, new high resolution observations made at 1.4 GHz suggest that the majority of millijansky sources are of the order of one milliarcsecond or less, (Oort 1987), and are unresolved by our synthesized beamwidth of 16.5 arcseconds. Because of this, and because the integrated flux densities of sources with poor SNR are subject to large random and possibly systematic errors we have not applied any source size corrections to our new data, and for comparison with our data, we have "uncorrected" the published data of Fomalont et al. (1984) and Donnelly et al. (1987) shown in Figure 1.

III. INTERPRETATION OF THE SOURCE COUNT

The shape of the source count above a flux density level of a few millijansky, together with the constraints imposed by the optical identifications and spectroscopic redshifts leads to the following generally accepted picture of the radio source distribution (e.g., Kellermann and Wall 1987; Condon 1984.

Below a few hundred millijansky, the counts converge too slowly to be interpreted in terms of a uniform distribution of sources. The apparent evolution is very dramatic, corresponding to a dramatic increase in space density and/or luminosity out to z ~ 1, followed by a sharp cutoff. Indeed the apparent changes are so pronounced, that Condon (1984) has remarked that to first order the distribution may be described by putting all sources in a thin shell near z ~ 1. There has been considerable discussion in the literature as to whether the apparent changes in the source distribution can best be described by density evolution or by luminosity evolution (e.g., Condon 1984).

The observed peak in the count is rather sharp, and there is no corresponding feature in the local luminosity function so it has been thought that only the strong sources evolve, and most recent discussions are in terms of a luminosity dependent density evolution. However, Condon (1984) has argued that because of the knee in the luminosity function, simple luminosity evolution will give a greater change in the number of high luminosity objects compared with low luminosity objects, and in this way it is possible to reproduce the observed count without requiring that the strong sources behave any differently than the weak ones. This picture for the evolution of radio sources is qualitatively similar to that of optically selected quasars (e.g., Green 1986). However, for optically selected quasars, the evolution is even more dramatic than for quasars where the number increases by a factor of eight per magnitude. Thus is equivalent to an integral log N-log S slope of -2.5 which must be compared with an observed value close to -1.5 for the strong source radio count. Similar conclusions are reached from analysis of the luminosity volume test. This means that at high z (early epochs) the probability of a quasar becoming a radio source decreases, rather than increases with z. Although this is contrary to most impressions, it is sensible if radio sources are fueled by the accretion of mass onto a black hole. Then the radio luminosity may be expected to increase with time (decrease with z) as is apparently observed.

IV. NATURE OF THE SUB-MILLIJANSKY SOURCES

Near one millijansky, or about 10^6 sources/per sr the slope of the 5 GHz count changes, suggesting the possible emergence of a new population of radio sources. A similar effect is seen in the 1.4 GHz count (e.g., Windhorst et al. 1985) There is some indication that the magnitude of this effect was previously exaggerated due to the excessively large corrections applied for resolution (Oort 1987), but even after removing these "corrections," the change in slope appears to be significant. The P(D) analysis, however, indicates that the count continues to converge down to one microjansky.

There has been some controversy over the nature of these faint radio sources. Windhorst (1984, 1986), Wall et al. (1986) and Weistrop et al. (1987) discuss the identification content of these sources which are dominated by faint blue galaxies. Only a small fraction appear to be normal spirals, elliptical radio galaxies, or quasars. Radio observations of IRAS sources (e.g., Condon et al. 1982; de Jong et al. 1985), suggest that the microjansky count is reproduced by the IRAS counts of moderately active (e.g., starburst) galaxies (Biermann et al.

1985). Such an interpretation, however, requires substantial evolution for this population of active galaxies (e.g., Danese et al.) as well as for the more familiar elliptical radio galaxies and quasars.

IV. SOURCE POPULATIONS

At 6 cm, about half of the observed radio sources are the steep-spectrum-extended sources characteristic of longer wavelength surveys, while half are flat-spectrum-compact sources. When divided into these two classes, the flat-spectrum population peaks near 1 Jy, while the steep spectrum population peaks near 0.3 Jy. Below a few hundred millijansky, the counts for both categories converges (e.g., Kellermann and Wall 1987; Donnelly et al. 1987).

Although some early studies suggested that the flat spectrum sources are more uniformly distributed than the steep spectrum sources, it now appears that all of the more powerful sources must evolve but that the lower luminosity sources may be more uniformly distributed.

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