IS THE UPTURN IN THE SOURCE COUNTS CAUSED BY PRIMEVAL RADIO GALAXIES?

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1. INTRODUCTION

During the last decade several deep surveys have been made with various aperture synthesis radio telescopes. At milliJansky levels important contributions were made with the WSRT 3 km array and the Cambridge One Mile Telescope. At sub-milliJansky levels surveys have been done with the VLA and the WSRT down to rms noise values of ~10 μJy.

There are several motivations for these efforts. Radio sources sample the most distant objects in the Universe, because their synchrotron radiation is not significantly absorbed internally, nor by an intervening medium. Statistical studies yield information about the cosmological evolution of the various radio source populations, which reflects the increase of their comoving space density and/or radio luminosity at earlier cosmic epochs. These in turn are important to understand the mechanism that made galaxies more active in the past, which could be related to the process of galaxy formation and evolution.

A very important clue to these questions resides in the discovery of the **upturn** of the milliJansky source counts (Section 2). In order to study the cosmological evolution of radio sources we first address their nature from optical studies (Section 3). The radio source redshift distribution and the redshift cut-off are discussed in section 4. Another important recent result is that the radio source population has been **almost 100%** completely identified at various flux levels down to V~26. Because some models predict a significant fraction of radio sources to exist at z>4, this means that primeval radio galaxies could be present in the ultradeep samples. This is investigated in Section 5.

2. THE SOURCE COUNTS

During the last 20 years various groups performed systematic source counts, at frequencies in the range 150 MHz<ν<10 GHz. A recent review of the radio surveys published since 1980 has been given by W85. Because the highest quality data and the best statistics are available at 1.4 GHz, I will concentrate here on the 1.4 GHz counts.

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2.1. The Observed 1.4 GHz Counts

Properly counting radio sources is not trivial. The counts in a given survey area are often systematically different when they are performed at a higher sensitivity. This occurs because at the faintest signal-to-noise levels (usually 5-7σ) various systematic effect play a role, that have to be corrected for properly. In the brighter surveys with large single beams statistical corrections for confusion must be made. In the deep radio surveys with small synthesized beams, corrections must be made for the resolution bias (faint extended sources are more easily missed than faint point sources), for the asymmetric effect of noise on the detection and flux determining algorithms, and for the apparent incompleteness in true flux due to the primary beam attenuation. For a review of these corrections see WHK or WMOKK, who show that these effects can be corrected for to within 10-20%.

Reliable, complete 1.4 GHz source counts are given in Figure 1 for the flux range 100 μJy<S<100 Jy. All individual surveys are discussed in WHK and WMOKK. The counts are given in differential form, normalized to the nonevolving Euclidean slope of -5/2. At the brighter levels (S>1 Jy) the counts show the well-known initial steep rise with a slope steeper than -5/2. Around S~500 mJy the counts reach a maximum excess w.r.t. the Euclidean prediction and between 10<S<500 mJy the counts continually converge with a slope of ~ -1.8. This behavior is the consequence of the epoch dependent radio luminosity function (RLF) of giant elliptical radio galaxies and quasars, which were more luminous and/or more frequently radio sources in the past. The convergence of the counts below 500 mJy arises because of geometrical effects in a relativistic Universe, and because at fainter fluxes most of the gE's and quasars have been seen, even out to high redshifts.

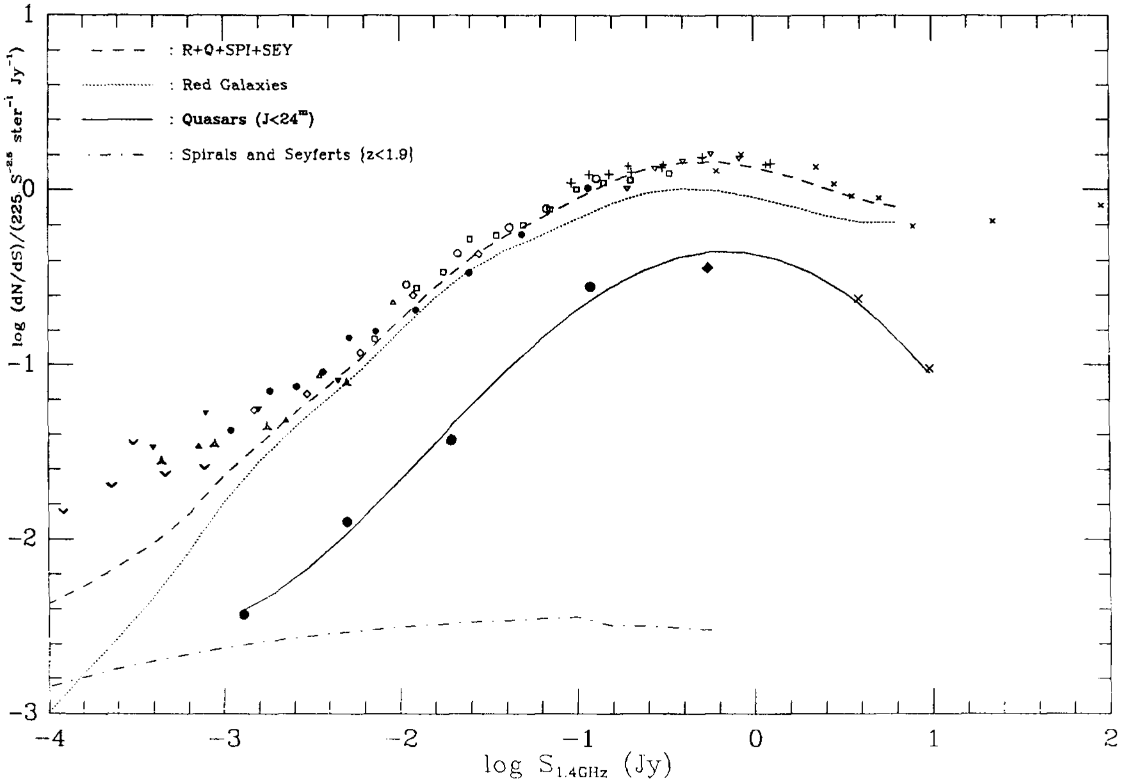
2.2. The Upturn of The 1.4 GHz Source Counts Below 10 mJy

For S<10 mJy the normalized differential source counts do not show the same continuous convergence as for S>10 mJy, but undergo a remarkable change in slope, which reflects a more strongly increasing number of fainter sources (Fig. 1). The slope of the source counts significantly resteepens to a value of -2.1 down to 100 μJy, but it does not quite attain the Euclidean slope of -2.5. This "upturn," or rather flattening of the normalized differential counts was first found in the deep 1.4 GHz VLA survey of WMOKK (also reported by L83) and was later confirmed by the survey of CM and by the deep WSRT survey of OW. It was also seen at 5 GHz in the ultradeep VLA surveys of Kellerman et al. (this volume) and PHR, albeit with fewer statistics. These surveys were done in **different** areas with **different** instruments and show the upturn in the counts with approximately the **same** slope. Hence, the upturn in the source counts is a property of the universe and is not due to instrumental effects, nor is it the property of one particular field.

The upturn in the source counts cannot be easily explained by the known radio source populations, like the evolving RLF of gE+quasars and the nonevolving RLF of normal spiral and Seyfert galaxies, as shown in Figure 1. Hence, either the RLF of the known (un)evolving populations differs in reality, or another population than the above-mentioned dominates at sub-mJy levels.

Attempts have been made by e.g. Subrahmanya (this volume) and Wall (this volume) to explain the upturn in the source counts by a peculiarity in the local RLF at very low radio luminosities. This, however, turns out to be inconsistent with existent data (see Section 3.1), and the only proper way to determine the cause of the upturn is to perform complete optical identification and spectroscopic studies.

Fig. 1. The normalized differential 1.4 GHz source counts. The total contribution of the evolving gE and quasar RLF is shown, as well as of the nonevolving spiral and Seyfert galaxy RLF out to z~2.



2.3. Field-to-Field Anisotropies?

Could the upturn in the mJy source counts be caused by statistical fluctuations or small scale inhomogeneities in the radio source distribution? The mJy counts in different areas are statistically consistent (WMOKK), but 20-30% fluctuations cannot be excluded, since the involved areas are small (<0.5 sq.deg.) and the number of sources per bin is only ~20. Some field-to-field variations at the 20-30% level could also be expected from the redshift distribution, if this is dominated by the effects of superclustering (see WKK, KKW, and Section 4.1).

3. THE NATURE OF FAINT RADIO SOURCES

Only optical studies can reveal the true nature of faint radio sources and of the upturn in the mJy source counts. This has often received too little attention in constructing models for the cosmological evolution of radio sources, leading to erroneous predictions.

3.1. Optical Morphology and Surface Brightness

The nature of bright radio sources is quite well established. At the 3CR level, 28% of the radio sources are quasars and N-galaxies, 70% giant elliptical and dB galaxies, and 2% Seyfert, spiral or irregular galaxies (LRL, SDMA). Down to the ~10 mJy level these fractions gradually decrease to ~20% quasars and ~55% gE's, while the fraction of blue radio galaxies increases to ~25% (KKW). For S<10 mJy, where the upturn in the source counts becomes prominent, the fraction of gE's and quasars further decreases at the expense of these blue radio galaxies.

What is the nature of faint radio sources? For S<10 mJy the radio source population consists of a few percent of Galactic stars and about 10% of normal spiral galaxies, but the majority of the other objects are blue, morphologically peculiar, interacting or merging galaxies, or sometimes very compact galaxies. According to KKW these blue radio galaxies are more predominant at S<10 mJy and according to WMOKK they are the best candidates to cause the upturn in the mJy source counts. They have in general lower optical surface brightness than gE's and are optically less luminous (Section 3.2). Morphologically they seem to be a heterogeneous class. If they do consist of one physical class, this manifests various stages like interacting, merging or peculiar galaxies.

This blue radio galaxy population has on average higher radio powers than normal spiral galaxies (KKW) and much higher space densities than radio selected Seyferts (W84). This is consistent with the fact that the source counts from nonevolving Seyferts and normal spirals are not sufficient by far to reproduce the upturn in the counts (Figure 1).

The brighter blue radio galaxies (V<21.5 mag) are almost exclusively unresolved radio sources at a 1" beam, while the classical double and complex radio sources almost without exception coincide with gE's and quasars (see Fig. 2 and 3). This is reflected by the dramatic drop in median angular size of the radio source population, which amounts to ~10" at S>10 mJy, where gE's and quasars dominate, decreasing to ~3" at S<5 mJy, where the blue radio galaxy class dominates (OKSW).

The accurate VLA positions of OKSW also reveal us the reliability of the faint radio source identifications: 33 out of 34 (97%) of the claimed gE identifications coincide exactly with their VLA positions, while 24 out of 30 (80%) of the claimed blue galaxy identifications are correct. The overall reliability of the sample is thus 57/64 (89%; see WKK). The contamination is strongest among the blue radio galaxies due to the high surface density of field galaxies. But the large majority of the faint blue radio galaxies are correct identifications and **not** due to field contamination, as speculated by Wall (this volume).

Most blue radio galaxies are at cosmological distances (z>0.1, see Section 3.2), in conflict with the local hypothesis of low luminosity dwarf galaxies. If the V~25 radio galaxies (discussed in Section 5.1) were indeed at z<0.1, as Subrahmanya (this volume) and Wall (this volume) imply, then their absolute magnitudes would be $M_V \sim -15.5$. Since dwarf galaxies with a compact, non-thermal active nucleus have never been found, I find it very hard to believe that the upturn in the source counts is caused by a local, very low luminosity population.

The steep slope of the upturn over a wide flux range is hard to reproduce without an evolving population of objects at cosmological distances. W84 suggests a model that allows for mild RLF evolution of the blue (interacting, merging) radio galaxies, reproducing the upturn entirely. C84 achieves the same by a model that arbitrarily evolves the RLF of normal spiral galaxies, which is inconsistent with the data of KKW. The data, however, are not yet sufficient to decide to what extent the blue radio galaxy population has undergone cosmological evolution.

In conclusion, the population of blue peculiar, interacting and merging radio galaxies dominates the mJy radio source identifications and is the best candidate for causing the upturn in the source counts.

3.2. The Hubble Diagram

The optical luminosities of radio galaxies are best studied by a magnitude-redshift diagram. Figure 2 gives the photographic F-magnitude (6100Å) vs. redshift for all radio galaxies (0.1<S<100 mJy) from the KKW sample including some recently obtained spectroscopy. The figure shows two types of radio galaxies: red, high surface brightness radio galaxies (circles) and blue, low surface brightness radio galaxies (triangles). Filled symbols are extended radio sources, which coincide without exception with the **optical luminous** galaxies, which are spectroscopically mostly like gE's. Figure 2 shows that the red galaxy class has a narrow absolute magnitude distribution (M_F=-22.80 for H_0=50, q_0=0.1) even at mJy levels, consistent with the "standard candle" behavior of gE radio galaxies in brighter surveys (S73).

In Figure 2 several model predictions for the observed magnitude-redshift relation have been plotted. These are the passively evolving C-model of B83, which has a constant star formation rate during the first Gyr after galaxy formation, the mildly evolving μ= 0.7 and the drastically evolving μ= 0.4 models, which transform 70 resp. 40% of the total galaxy mass into stars during the first Gyr after galaxy formation. All models have been computed for H_0=50, q_0=0.1, M_F =-22.80 at z=0 and galaxy ages of 15, 14, and 13 Gyr, corresponding respectively to early galaxy formation (z_f=5.3), galaxy formation at the QSO turn-on epoch (z_f=3.4) and later galaxy formation (z_f=2.4).

The models illustrate that a standard candle gE with F>22 is most likely at z>0.75 and that a gE galaxy at z=2 can have magnitudes in the range 22<F<26, depending on its precise star formation history.

3.3. The Color-Redshift Diagram

The photographic J-F (4650-6100Å) color-redshift diagram (Fig. 3) shows that the distinction between high surface brightness radio galaxies (circles) and low surface brightness galaxies (triangles) indeed corres-

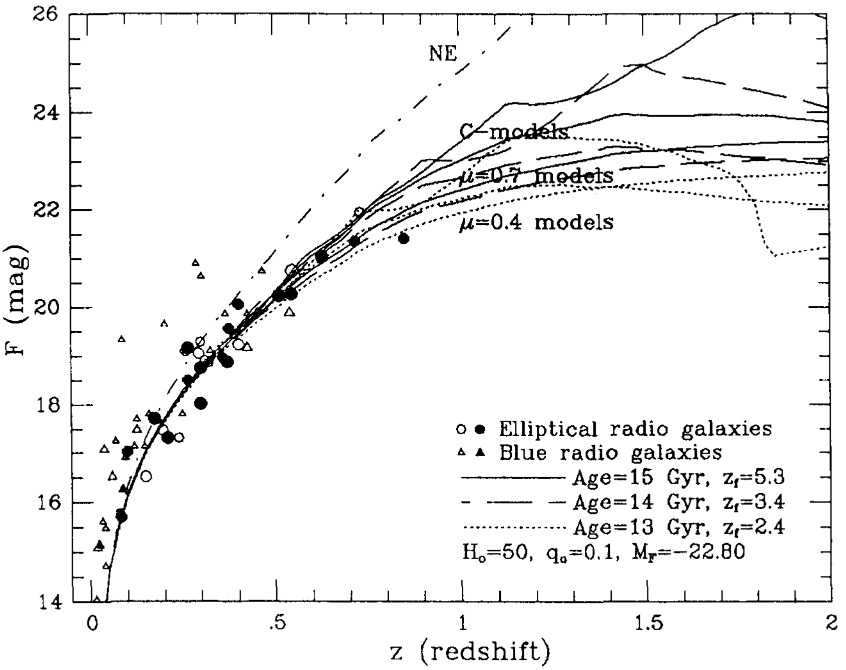


Fig. 2. The Hubble diagram for faint radio galaxies. Open symbols are compact radio sources, filled symbols are extended radio sources.

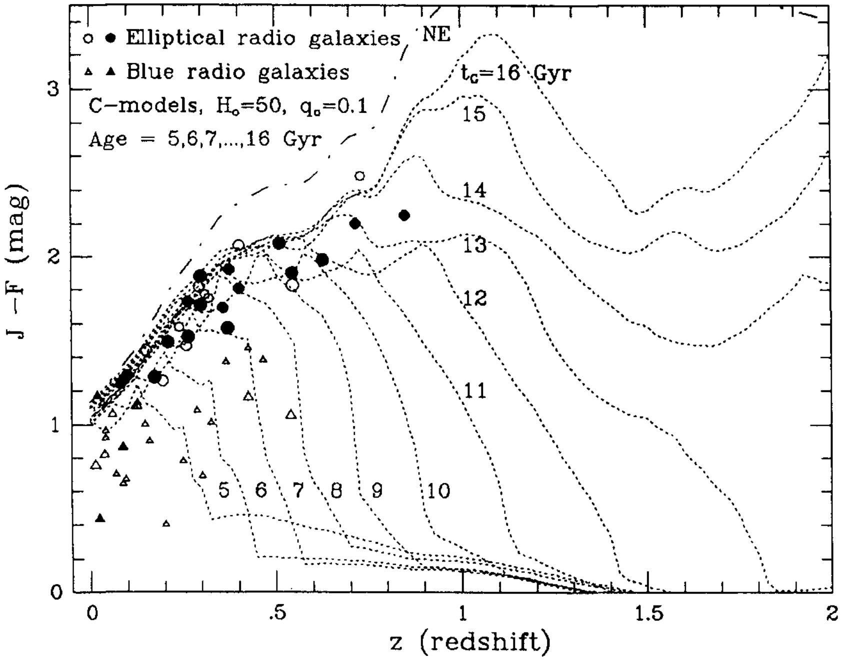


Fig. 3. The J-F color-redshift diagram for faint radio galaxies. Symbols are the same as in Fig. 2, models are described in the text.

ponds to a distinction between red and blue galaxies, the former coinciding with the extended radio sources (filled symbols).

Bruzual's (1983) passively evolving C-models are plotted for various formation epochs. A larger complete sample is discussed in detail by Windhorst, Koo, and Spinrad (1986, in preparation), together with the validity of the models. The reddest occurring colors of radio galaxies at high redshifts might place constraints on the earliest possible formation epoch of the gE galaxies.

If the models are correct, the few very red (J-F~2.4) high redshift radio galaxies seem to require ages of at least 14 Gyr. The reddest J-F color a radio galaxy ever gets is about 2.4-2.5, as shown with better statistics in Figure 5. No matter what the precise redshifts of these F>22 radio galaxies in Figure 5 are, the reddest occurring colors seem to require ages of at least 14 Gyr. This implies lower values of H_o, namely H_o~50 for q_o=0.1, or H_o~60 for q_o=0, while H_o> 60 would be only possible if $\Lambda \neq 0$. These old galaxy ages are thus in apparent conflict with high values of H_o. A similar problem exists for the apparently very old ages of Galactic globular clusters. In both cases the argument is based on the same evolutionary tracks in the HR diagram. The distant, very red radio galaxies provide **independent** evidence for this apparent inconsistency, since they must already have been **very old** at least half a Hubble time ago.

Some of the blue radio galaxies could be generically related to the red gE radio galaxies, not as very high redshift progenitors of giant ellipticals (KKW), but as their intermediate redshift progenitors. For instance, if a strong interaction or merger between two (radio) galaxies triggered a major burst of star formation 5-8 Gyr ago, the resulting radio galaxy would appear blue at z~0.5, but could end up as a red giant elliptical today, as some of the C-models in Figure 3 illustrate.

4. THE RADIO SOURCE REDSHIFT DISTRIBUTION

The only way to make proper claims about the cosmological evolution of radio sources is to measure their redshift distribution N(z). Since this will be very difficult for radio galaxies with F>23.5, some models for N(z) are discussed first in Section 4.1. A more complete discussion about the cosmological evolution of radio sources can be found in W84.

4.1. The Question of The Redshift Cut-Off

The maximum redshift in the radio source N(z) (or the redshift cut-off "zmax") is relevant to determine the epoch of first radio source triggering and perhaps also the epoch of galaxy formation itself.

In the 3CR sample of LRL and the update of SDMA, which is spectroscopically >90% complete, the highest spectroscopic redshift is 2.012. At fainter radio fluxes N(z) has been measured less completely, usually down to F~21-22, while radio galaxies extend down to F~24-26. Hence, direct spectroscopy is very hard and indirect arguments must be used to constrain zmax from fainter radio samples.

Models have been constructed by W84 that extrapolate the epoch dependent RLF of the red and blue radio galaxies smoothly in redshift, until 100% of the counts are obtained at **all** fluxe levels. The strongest constraints come from the spectroscopic redshifts in the mJy sample of KKW (Fig. 4). W84 concludes that mJy radio galaxies do not need to extend to beyond zmax=2, and to even lower redshifts for lower radio powers. Based upon the same data P85 concludes that zmax~2.5 for the whole radio source population. A similar conclusion was drawn by LLA from optical/IR Hubble diagrams at the Jansky level.

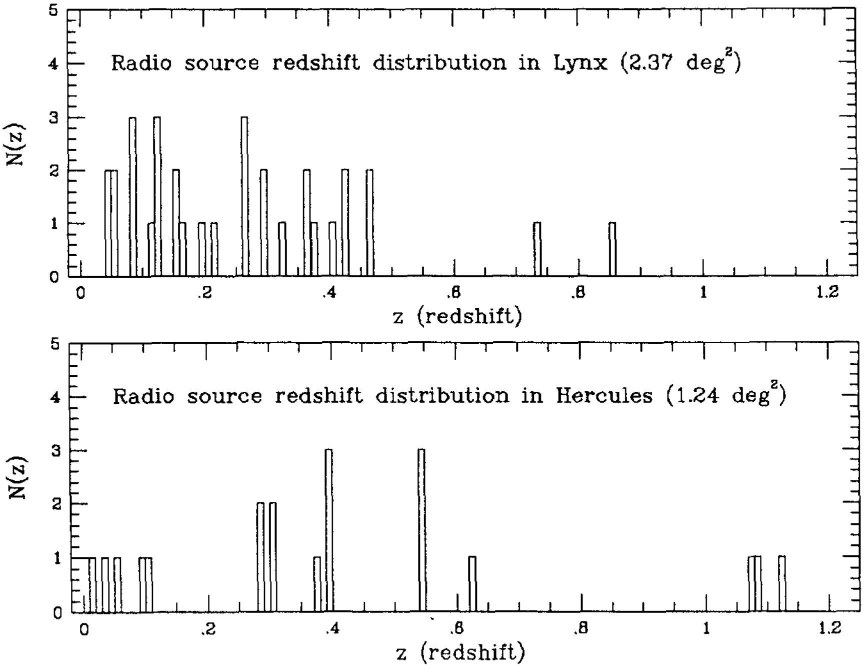
These data seem to converge to a definite value of the redshift cut-off, perhaps as low as zmax= 2.0. However, these conclusions are not model independent and some caution is in order. In fact, C84 and P85 claim that the available data allow for models that predict 10-40% of the radio sources to exist at z>4-5. If these models were correct, faint radio source samples should contain a large fraction of primeval galaxies. We will investigate this in Section 5.

4.2.Does Superclustering Affect The Radio Source Redshift Distribution?

Since at local redshifts the N(z) of field galaxies shows prominent effects of superclustering (see e.g. O83; Latham et al., this volume), we will investigate here whether there is also evidence for this effect from the N(z) of **radio** galaxies at high redshifts.

Figure 4 shows the redshift distribution of a complete sub-sample of KKW, plotted in **very small** bins of 0.01 in z. There appear to be some identical groups of redshift, with empty spaces in between. These redshift "clumps" occur on scales of <1 deg out to z<0.5 and sometimes higher. This could mean that superclustering has an important effect on

Fig. 4. The redshift distribution of milliJansky radio sources.



the radio source redshift distribution out to cosmological distances.

Apparent field-to-field fluctuations in the radio source densities could arise if: (a) the fields are small, (b) N(z) is dominated by the effects of superclustering, (c) the redshift cut-off is not a very large number and (d) the RLF within a supercluster at a given redshift is constant. The number of superclusters in the line of sight -- which would contain all the radio galaxies -- could then be only a few dozen and the random fluctuations in the source densities could be >20%. The scarce statistics in the ultradeep radio surveys have prevented us thus far from detecting significant field-to-field variations in the counts.

5. DO ULTRADEEP RADIO SURVEYS CONTAIN PRIMEVAL GALAXIES?

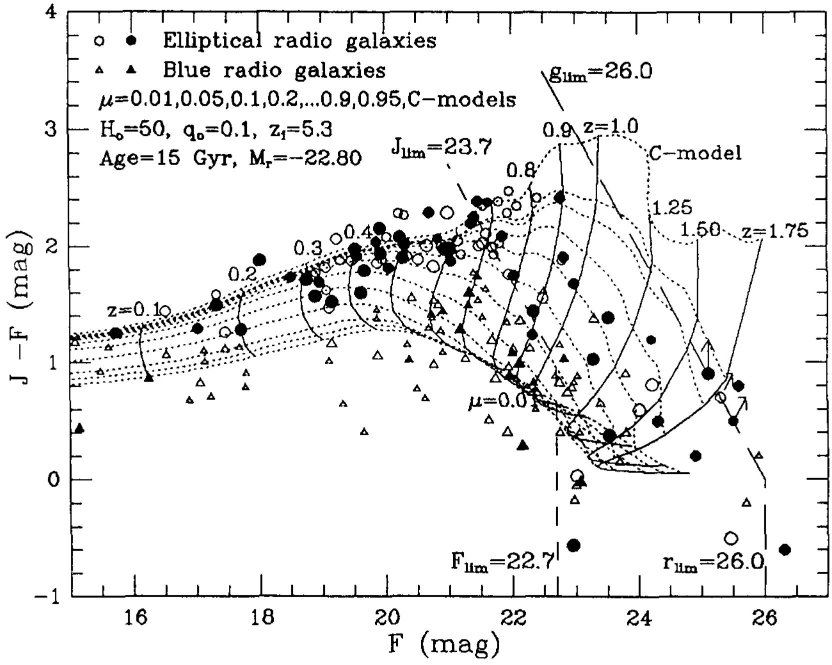
If the models of C84 and P85 are correct, (sub)-mJy radio source samples should contain significant numbers of primeval radio galaxies (z>4). In this section we explore this possibility with data.

5.1. What is The Nature of Radio Sources with F>22 mag?

According to KKW and OKSW the radio source population at F>22 contains both extended and unresolved radio sources. These could -- in analogy to the brighter sample -- consist of both high redshift gE's (z>0.8) and blue radio galaxies (z>0.5).

A complete sub-sample of 70 radio sources in KKW's Hercules field, with VLA positions accurate to 0″.1, has been studied by Windhorst and Koo (1986, in preparation), using long integrations with the Hale 200"

Fig. 5. The J-F vs. F color-magnitude diagram of faint radio galaxies.



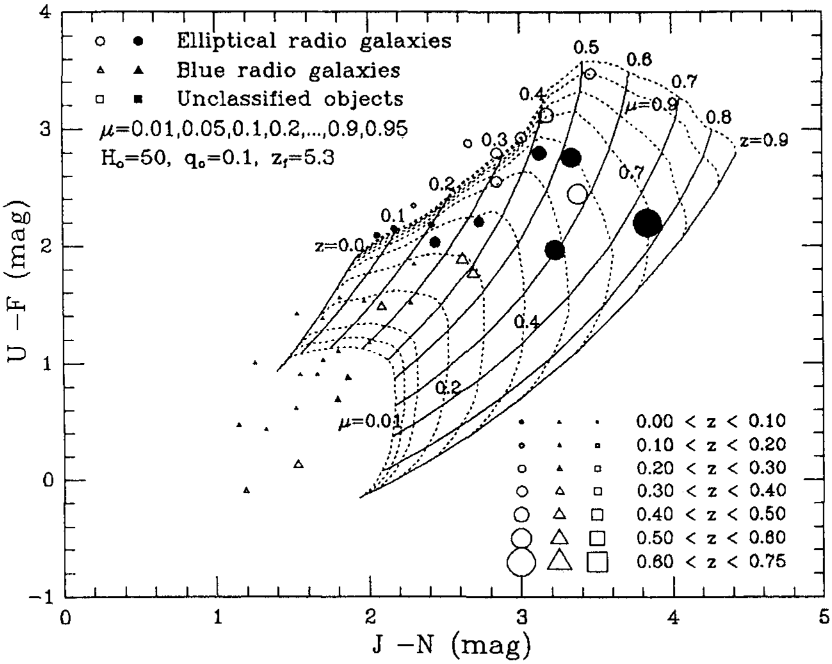
Four-shooter CCD array. Preliminary results are shown in Figure 5, the J-F vs. F color-magnitude diagram. (The CCD observations were done with the Gunn *g* and *r* filters; *g-r* is comparable to photographic *J-F*). The objects with F<22.7 and J<23.7 are from the complete photographic 4-m sample of KKW. The additional fainter objects with r<26.0 and g<26.0 are the complete Four-shooter sample in 1.25 sq.deg., together with a few upper limits. The symbols are the same as in Figure 3.

The most important point is that the Four-shooter radio source sample is essentially **completely** identified down to r<26.0. Out of 70 mJy radio sources, 68 (or 97%) have reliable optical identifications. Hence, if the models of C84 and P85 are correct, the Four-shooter sample should contain primeval radio galaxies (z>4). Note that the radio sensitivity is sufficient to detect very high redshift gE galaxies.

A range of Bruzual's μ-models have been superposed in Figure 5 (dashed lines), computed for the quoted parameters. The solid lines are redshift isochrones for M_F=-22.80. For F>22 the extended radio sources show a wide color range, -0.6<J-F<+2.4, which might be indicative for the various star formation histories of the gE radio galaxies. Most of these are consistent with μ>0.4 models, although the bluest objects might have some non-thermal contribution.

If the models are valid, the data suggest that at F~22 the redshifts would be ~0.8, consistent with Figure 2, and that the objects at F>25 could be at z<2.0, consistent with some of the models in Section 4.1. However, a color-magnitude diagram cannot be reliably used to derive redshifts. Since radio galaxies with F>23.5 are too faint to obtain absorption redshifts, even with the next generation telescopes, other constraints to their redshifts must be explored first.

Fig. 6. The U-F vs. J-N color-color diagram of faint radio galaxies.



5.2. How to Find Primeval Radio Galaxy Candidates

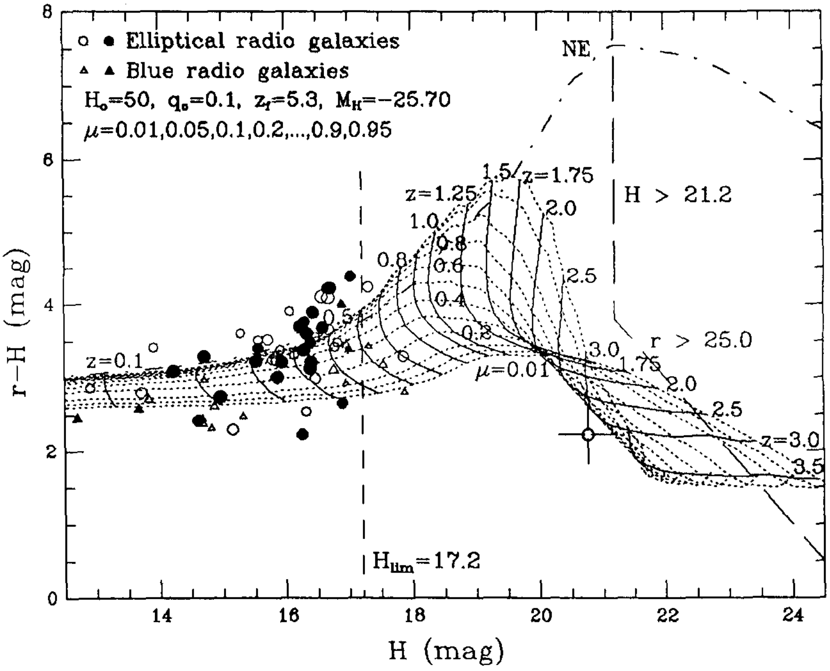
A crude but reliable redshift estimate can be obtained from color-color diagrams, if the spectral evolution models and the values of H_0, q_0, and galaxy ages are approximately correct (K85). Figure 6 shows an U-F (3600-6100Å) vs. J-N (4650-8000Å) color-color plot for the KKW sample, in combination with the same models as in Figure 5. The symbols are the same as in Figure 2, but the symbol size increases with measured **spectroscopic** redshift. The figure shows that, with a few exceptions, this color-color diagram can provide crude, but representative redshift estimates for all but the bluest radio galaxies with F<22.5 (z<1).

The same could, in principle, be done for the F>23 radio galaxies, by including passbands at longer wavelengths [e.g., g-i (5000-8000Å) vs. r-H (6500-16000Å)]. Spectroscopic calibration will be required to check if the models are adequate for z>1.

Figure 7 shows the r-H vs. H color-magnitude diagram with symbols and models as in Figure 5. Because of the longer wavelengths used, this figure allows sampling of higher redshifts. For two radio sources, very deep near IR photometry has been obtained by Windhorst, Neugebauer and Matthews (1986, in preparation), using the Hale 200" IR systems. Both are strong (S>10 mJy), compact but non-variable radio sources with very steep radio spectra. One is a radio galaxy with r=23.0 and has a rather blue r-H color (~2.1), the other object in Figure 7 is an unidentified Four-shooter radio source (r>25.0) that was also undetected at H>21.2 (2σ).

If the models in Figure 7 are taken at face value, both objects could be radio galaxies at z>2.0. Because 97% of the mJy radio sources

Fig. 7. The r-H vs. H color-magnitude diagram for radio galaxies.



are identified at r<26.0, apparently not many radio galaxies are heavily obscured in the optical. As OH suggest, primeval galaxies might be optically obscured by dust at z>3.5, and the few mJy radio sources that are unidentified at the 200" Four-shooter limit might be such objects.

6. CONCLUSIONS

The 1.4 GHz source counts show a remarkable upturn below S=10 mJy that cannot be explained by nonevolving Seyfert or normal spiral galaxies, nor by a local population of dwarf galaxies. Instead, the upturn in the source counts is most likely due to the intermediate redshift population of blue peculiar, interacting and merging galaxies.

The radio source population is essentially completely identified down to V~26. According to some models a non-negligible fraction of mJy radio sources could be at z>4, so that primeval radio galaxies might be present in mJy samples. Such objects have not been found yet, but the few unidentified radio sources (V>26, H>21) might be optically obscured primeval radio galaxies.

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