THE EVOLUTION OF THE RADIO GALAXY POPULATION AS DETERMINED FROM DEEP RADIO-OPTICAL SURVEYS

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1. INTRODUCTION

A first step in the study of the evolution of the radio galaxy population is the determination of the radio luminosity function (RLF), i.e. $\rho(\log P, z)$, which results from (and must finally be interpreted in terms of) 'light curves' of individual objects (i.e. P(t)) and the 'birth rate' function $\dot{n}$ (log P, t).

Information on the RLF is obtained from deep optical identifications and spectroscopy of complete radio samples. At high radio flux densities identifications are virtually complete, as are spectroscopic redshift determinations. At lower flux densities (say below the "bump" in the normalized source counts) only about 50% of the radio sources can be identified on 4m plates, and as yet only a small, but quickly growing, fraction has spectroscopic redshifts.

In the absence of complete spectroscopic z information, photometric redshifts have been used. It is then assumed that the radio galaxies are ellipticals, for which a 'standard candle' hypothesis (SCH) is justified. As shown by Auriemma et al. (1977) the absolute magnitude of elliptical radio galaxies does not depend on radio luminosity when $\log P \gtrsim \log P^*$ ($\sim$ 25.0 at 1.4 GHz, for H_o = 50 km sec^{-1} Mpc^{-1}). When z_{photom} determined with the SCH yields $\log P > \log P^*$ one has at least consistently interpreted the data in terms of an elliptical radio galaxy. However, only when the ratio of radio to optical luminosity (or flux, with K-corrections taken into account) is larger than those found locally for Seyfert and spiral galaxies, is this interpretation (and therefore the redshift) very likely to be correct. On the other hand, when either the implied log P $< \log P^*$, or the ratio of radio to optical flux is in the range also populated by Seyferts and spirals, the interpretation is uncertain and z_{photom} is probably an overestimate.

G. O. Abell and G. Chincarini (eds.), Early Evolution of the Universe and Its Present Structure, 73–79.

Table 1. The radio surveys with deep optical data.

observer(s) +reference	freq. MHz	$S_{1.4}^{lim}$	pass band	m_{lim}	N_{gal}	$N(z_{spec})$
Peacock & Wall (MNRAS 194, 331)	2700	3.5 Jy	V	23^m	61	49
Laing et. al. (MNRAS 184, 149)	178	1.3 Jy	V	23	33	21
Katgert-Merkelijn et. al.	178	0.9 Jy	V	20.5	28	12
(A&A suppl. 40, 91)	408	0.9 Jy	V	20.5	41	19
Allington-Smith (preprint)	408	0.4 Jy	r	23	29	0
Grueff & Vigotti (A&A suppl. 20, 57)	408	0.4 Jy	V	22	21	0
Katgert et. al. (A&A 38, 87)	1412	8 mJy	B/R	22.5/21	39	0
de Ruiter et. al. 48" (A&A suppl. 28, 211)	1412	3 mJy	B/R	22.5/21	118	0
de Ruiter et. al. 4m (A&A suppl. 28, 211)	1412	3 mJy	B	23.5	13	0
Windhorst, Kron, Koo (preprint)	1412	0.2 mJy	U/J	24/24	175	46
			F/N	23/22		
Total					558	147

2. RADIO-OPTICAL SURVEYS OF LARGE DYNAMIC RANGE.

As described by Van der Laan and Windhorst (1982) combined deep radio and optical surveys, primarily at Westerbork and KPNO respectively, have led to large identified samples. In Table 1 the surveys used in our studies are listed. $S_{1.4}^{lim}$ is the limiting flux of a complete 1.4 GHz sample taken from the sample defined at the original finding frequency. N_{gal} is the number of identified radio galaxies in the 1.4 GHz sample. The last column gives the present number of spectroscopically determined redshifts in each sample.

For $S_{1.4} \gtrsim 10$ mJy the elliptical radio galaxy SCH is quite likely to be correct for the majority of the radio galaxy identifications. On that basis we have determined $\rho(\log P, z)$ out to $z_{photom} \sim 0.85$ for log $P \gtrsim 24.6$ (see Van der Laan and Windhorst). This determination is based on more than half (the identified portion) of the radio galaxy population with $S_{1.4} \gtrsim 10$ mJy. We have therefore asked whether one can account for the remaining, non-identified fraction of the source count by very simple extrapolation of the $\rho(\log P, z)$ determination.

As is well-known, the comoving density of radio galaxies increases strongly from $z \sim 0.3$ to ~ 0.85. In one model, we could reproduce the unidentified portion of the source count (and hence the total source count) for $S > 10$ mJy to within a few percent, by conservatively assuming $\rho(\log P, z)$ beyond $z \sim 0.85$ to be identical to $\rho(\log P, z \sim 0.85)$ except for a slight increase of the average log P towards higher redshifts. In this very simple model, $\rho(\log P, z)$ for radio galaxies must be set to zero beyond $z \sim 1.5$ in order not to exceed the observed count. This interesting, but clearly not unique model suggests that beyond z ∿ 1.5 practically all radio galaxies appear as radio quasars (which we did not include in our RLF determinations, and which were separately accounted for in the source count, see Fig. 1).

3. VERY DEEP 1.4 GHz SURVEYS.

Choosing a field in the Lynx area ($8^h42^m, 44^o47'$, radius 0^o43) which lacks strong (S > 10 mJy) radio sources, a Westerbork survey (σ_W = 120 μJy) was deepened in a VLA exposure of 2 x 6h to σ_{VLA} = 45 μJy (Windhorst, Miley, Owen, Kron and Koo, 1983). From this a complete sample was distilled consisting of a total of 94 sources, 60 above the WSRT 5 σ limit and an additional 34 between the VLA 5 σ limit and the Westerbork limit. These counts are shown in Figure 1 by open circles and crosses. Also shown are VLA counts by Condon and Mitchell (1982) which are quite consistent with our result.

The interesting feature of the counts below 10 mJy would seem to be

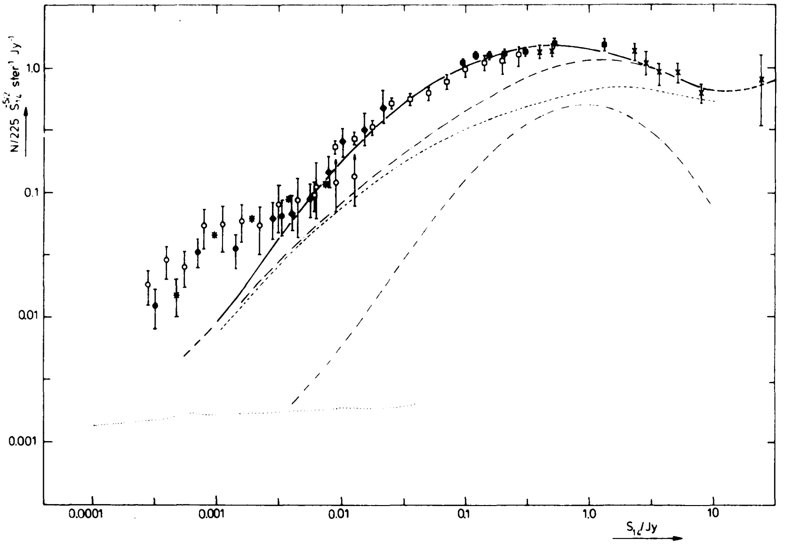

Figure 1. The 1.4 GHz differential source count normalized to a differential Euclidean count (225 $S^{-5/2}Sr^{-1}$ Jy^{-1}). References to older data (S ≳ 10 mJy) can be found in Willis et al. (1977). Filled circles: Condon and Mitchell (1982), open circles: Windhorst et al. (1983 5σ sample, asterisks: Windhorst et al. 6.5σ sample, - .. -: observed count of radio-loud quasars, ----: count of powerful radio ellipticals out to z ∿0.85, calculated from observed RLF, and assuming non-evolving RLF below log P ∿ 25.0, —.—: sum of two above, ——: total count of quasars and powerful ellipticals, with elliptical RLF extrapolated out to z ∿ 1.5 (as described in text), and again assuming no evolution below log P ∿ 25.0.

the lack of continued convergence, or rather the steepening, similarly visible in all datasets. In our opinion there is also consistency on this point with recent very deep 6 cm source count data (Fomalont, this volume).

It is obviously of great interest to determine the nature of the faint source population responsible for the steepening of the count. One important step to this end is the optical identification of the sample, using the deep KPNO 4m plates available for this (and other) deep Westerbork field(s).

For the Lynx sample the identification status is given in Table 2. A first conclusion is that local spiral galaxies contribute to the source count in this flux range at the expected level. In Figure 1 that level, computed from the radio luminosity function data recently reviewed by Meurs (1982), is shown as a dotted line. It falls short of the actual counts by a factor 20, consistent with the bright spirals identification of this deep sample.

4. AN EVOLVING, WEAK SOURCE POPULATION.

Current data are insufficient to determine the nature of the weak sources' parent population. The fuzzy blue objects require both high angular resolution photometry, ultimately with Space Telescope, and modest resolution spectroscopy for the recognition of their character. The 4m multi-colour photometry is proceeding and will be reported in Windhorst, Miley, Owen, Kron and Koo (1983).

Spectroscopic work on blue galaxy identifications in the two to thirty mJy range has started, at McDonald for optically bright and with the KPNO 4m cryogenic camera for the fainter galaxies in the sample. First results (see also Koo, this volume) indicate a mixture, some galaxies close to the 'standard candle' Hubble curve, and others two to three magnitudes fainter. These results confirm that below 10 mJy the 'standard candle' hypothesis is no longer applicable. While at higher flux densities the well-known powerful radio galaxy population associated with luminous ellipticals dominates, below $\sim$ 10 mJy intrinsically fainter galaxies (possibly both ellipticals and spirals) are important.

Table 2. Lynx identifications.

600 μJy < $S_{1.4}$ < 10 mJy	225 μJy < $S_{1.4}$ < 600 μJy
60 sources	34 sources
2 bright spirals	3 bright spirals
1 bright elliptical	
1 fainter galaxy	1 fainter galaxy
20 faint (mainly fuzzy) objects	15 faint (mainly fuzzy) objects
4 stellar objects (2 galactic)	

In Figure 2 the hatched area roughly indicates the location of these sources, if they have redshifts in the range 0.2 - 0.6 as implied by the Lynx sample identifications for absolute magnitudes 2 to 3^m fainter than the elliptical standard candles. Whether this population is associated with weak ellipticals, or with spirals/Seyferts cannot be decided on present evidence. Recent near-IR observations (Windhorst, this volume) of these faint radio galaxies show both 'thermal' and non-thermal IR spectra.

Given the continuity of quasars, Seyferts and active galaxy nuclei (cf. Maccacaro and also Braccesi in this volume) one may speculate that this population consists of active spirals, relatively quiescent at z = 0 but evolving in the manner of the giant ellipticals, with a greatly enhanced comoving density in the range $10^{22.5} < P_{1.4} < 10^{24.5}$ at $z \sim 0.4$.

In addition to more optical spectrophotometry, high resolution radio maps may help to distinguish this class of sources from the strong source population. The latter are generally symmetric and large, the former are expected to be rather more amorphous and smaller.

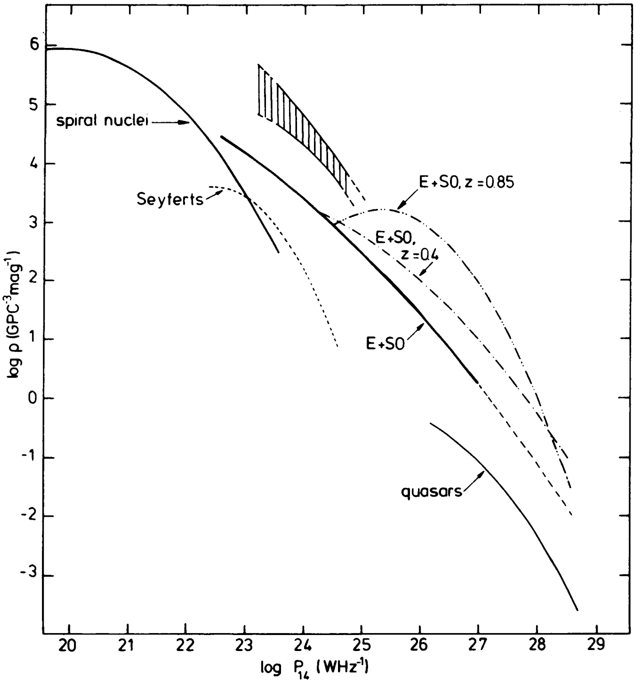

Figure 2. Schematic representation of the observed local RLF for: spiral galaxy nuclei (Hummel, 1980, thesis). Seyfert galaxies (Meurs, 1982, thesis), elliptical galaxies (Windhorst, 1983, thesis) and radio quasars (Fanti and Perola, 1977). Also shown are the elliptical RLF's at $z \sim 0.4$ and ~ 0.85. The hatched area indicates the possible location of mJy objects responsible for the steepening of the count, for an assumed redshift of 0.4 ± 0.2.

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DISCUSSION

Segal: In the analyses of radio luminosity functions that you quote, did you allow for the (probably severe) flux cutoff bias, and if not, isn't that a weak link in your argument?

van der Laan: We are fully aware of the pitfalls in converting the luminosity distribution of flux-limited complete samples to the luminosity function of comoving populations.

Ekers: Your use of the constancy of optical luminosity of radio galaxies introduces a dependency on the small sample of radio galaxies with known redshift (the mainly 3 CR sample of radio galaxies in your Hubble diagram). The bivariate luminosity function, for both elliptical galaxies (Auriemna et al. 1977) and spiral galaxies, shows that the probability of radio emission is a function of the optical luminosity. This will affect the predictions of your models and may also explain the difference in $<M_p>$ which you presented for your weak radio galaxy sample.

van der Laan: There was no time to discuss the refinement of the bivariate luminosity function here. We have in fact used it in our analyses as published thus far. Whether the range of the bivariate luminosity function can be extended to the optical and radio luminosities at issue in this faint sample remains to be established. We can speculate about, but not yet make, the choice between spirals/Seyferts or ellipticals as parent population for these weak sources. In both instances a strong epoch dependence is inescapable.

Menon: In making statements about luminosity evolution, it is usually assumed that it is a continuous function of time only. Is it physically more reasonable to assume that luminosity is a discontinuous function of time, the periods of discontinuity themselves depending on luminosity?

van der Laan: I have no quarrel with your statement as it applies to individual sources. After convolution over a whole source population, however, I expect the luminosity function to vary smoothly with epoch.

Melnick: Gas-rich dwarf galaxies (H II galaxies) appear to be very abundant in the universe. Their luminosity function is not known but there is some evidence that it may be significantly different from that of normal galaxies. H II galaxies are thermal radio sources just as normal H II regions, but significantly brighter (the luminosities reach 10^{42} ergs/sec). Have you estimated the contribution of these galaxies to your deep (VLA) radio source counts?

van der Laan: Although I am not aware of a systematic study of dwarf galaxies' radio luminosity function, enough is known to exclude dwarf galaxies as the main contributors. I say this on the basis of the identifications and the spectroscopic redshifts obtained thus far.