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6. The cosmological evolution of radio sources

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INTRODUCTION

Considerable progress has been made over the last few years in the study of the cosmological evolution of radio sources, both regarding the collection of deeper and higher quality observations and towards a better understanding of the physical processes that may cause the epoch dependent properties of the radio source populations on cosmological timescales. In this review it is attempted to give a fair coverage to the work of **all** groups that made relevant contributions to this field since 1981. A few very important papers from before 1980, that were not dealt with by the previous IAU commission, are covered as well. For more detailed reviews we refer to Katgert (1980), Kellerman (1980), van der Laan and Windhorst (1982), van der Laan et al. (1983), Longair (1978), Wall and Benn (1982),Wall (1983) and Windhorst (1984). Le latter review is a more detailed version of the current report to IAU commission 47 on Cosmology.

1. RADIO SOURCE SURVEYS

In this section we describe all new systematic radio surveys that have been made and published since 1980.

1a. Strong and Intermediate Strength Radio Surveys

1a1. Low frequencies : An update of the revised 3CR catalogue has been given by Laing, Riley and Longair (1983), who summarize all available morphological and radio spectral data on 3CR sources. The complete 3CR sample now consists of 173 radio sources with $S_{178} > 10$ Jy and angular size < 10'. High resolution mapping has been made for a complete sample of 59 intermediate strength Bologna sources with $1 < S_{408} < 2$ Jy in 0.11 sr by Allington-Smith (1982). A part of the 0.3 GHz Texas Survey, the +18° strip, has been published by Douglas et al. (1980).

1a2. High frequencies : The 2.7 GHz all sky equivalent of the 3CR catalogue is given by Peacock and Wall (1981) and Wall and Peacock (1984) and contains 233 sources with $S_{2.7} > 2.0$ Jy in 9.81 sr. An all sky sample at 5 GHz is given by Kühr et al. (1981a), which contains 518 radio sources with $S_{5.0} > 1.0$ Jy in 9.81 sr. The high frequency normalized differential source counts do not yet show any convergence at the Jansky level.

At somewhat lower flux levels, 5 GHz source samples have been collected in considerable patches of the sky. The Bonn 100 m sample of Kühr et al. (1981b) has 476 radio sources with $S_{5.0} > 250$ mJy in 0.401sr. The MIT-Green Bank survey con-contains about 6000 radio sources with $S_{5.0} > 50$ mJy in 1.87 sr (Bennett, 1983; Bennett et al., 1984). Other 5 GHz samples have been constructed by Owen et al. (1983) containing 480 radio sources with $S_{1.4} > 35$ mJy in 0.069 sr, and by Ledden et al. (1980), containing 237 sources with $S_{5.0} > 15$ mJy in 0.0096 sr. A southernhemisphere 5 GHz survey has been made with the Parkes 64 m telescope by Wall et al. (1982), who list 75 radio sources with $S_{5.0} > 32$ mJy in 0.0082 sr.

Only at the 50 mJy level do the normalized differential 5 GHz source counts show convincing evidence for convergence.

1b. Deep Radio Surveys

1b1. Low frequencies : A deep 408 and 1407 MHz survey of a north Galactic pole area has been made with the Cambridge one mile telescope by Benn et al. (1982), yielding 299 radio sources with $S_{0.4} > 9$ mJy in 12.2 deg^2 and 65 sources with $S_{1.4} > 1.4$ mJy in 1.2 deg^2. A 1.4 GHz VLA snapshot survey has been made by Condon et al. (1982), covering 11.0 deg^2 down to $S_{1.4} = 6$mJy. A deep 1.4 GHz survey was made with the Westerbork 3 km array by Windhorst, van Heerde and Katgert (1984) in 9 selected areas with available deep multicolor Mayall 4 m plates. This Leiden-Berkeley Deep Survey has 306 radio sources in 5.52 deg^2 with $S_{1.4} > 0.6$ mJy.

The total normalized differential 1.4 GHz source counts, obtained by the various groups, are consistent to within 10% down to $S_{1.4} \sim 1$ mJy and in the range $100 > S_{1.4} > 5$ mJy they show the well known convergence.

Surveys at 610 MHz have also been made with the 1.5 km Westerbork array by Katgert-Merkelijn (1978, 1979), yielding 232 radio sources in 25 deg^2 down to $S_{0.6} > 22$ mJy. A survey of the Einstein X-ray deep survey areas has been made by Katgert-Merkelijn et al. (1984), yielding 451 radio sources with $S_{0.2} > 10$ mJy in 29.2 deg^2 and 369 sources at 21 cm with $S_{1.4} > 1.6$ mJk in 8.71 deg. A 610 MHz WSRT survey of M31 is described by Bystedt et al. (1984) and of the Cancer cluster by Valentijn (1980). A deep 610 MHz survey has been made of the Leiden-Berkeley Deep Survey areas with the WSRT 3 km array by Windhorst and Oppe (1984), yielding 520 radio sources in 12.3 deg^2 with $S_{0.6} > 2.4$ mJy.

If one takes account of population and resolution bias, all 610 MHz synthesis counts agree to within 20% down to $S_{0.6} \sim 2$ mJy and show the well known convergence down to $S_{0.6} \sim 10$ mJy.

1b2. High frequencies : Deeper 5 GHz surveys have been made with the Bonn 100m dish by Pauliny-Toth et al. (1980) and Maslowski et al. (1981, 1984), yielding in total 320 radio sources in 67 deg^2 with $S_{5.0} > 10$ mJy. For the north Galactic pole survey 5 GHz data have been obtained with the Bonn 100 m telescope by Benn et al. (1984). A 5 GHz P(D) analysis of NRAO 90 m scans has been made by Ledden et al. (1980) and of Parkes 64 m scans by Wall et al. (1982).

A systematic 5 GHz synthesis survey of background radio sources in Westerbork maps has been made by Willis and Miley (1979), yieldind 43 radio sources in 2.8 deg^2 with $S_{5.0} > 4.5$ mJy. A deep 5 GHz VLA survey has been made in 13 small areas by Bennett et al. (1983), who found 16 radio sources in 0.52 deg^2 with $S_{5.0} > 0.5$ mJy.

The 5 GHz source counts of these surveys (for a review see Maslowski et al., 1984) confirm the convergence below $S_{5.0} = 50$ mJy, which however is not as strong as that seen in the low frequency surveys down to $S_{1.4} = 5$ mJy.

1c. Ultradeep radio surveys and background fluctuations

1c1. Low frequencies : Ultradeep VLA counts were made in the Leiden-Berkeley area Lynx.2 by Windhorst et al. (1984c), yielding 94 radio sources in 0.58 deg^2 complete to $S_{1.4} = 225$ µJy. Ultradeep Westerbork counts down to $S_{1.4} = 300$ µJy of the same field were given by Oort and Windhorst (1984). Comparison with 1.4 GHz counts at brighter levels (section 1b1) show that below 5 mJy the 1.4 GHz normalized differential source counts show a remarkable resteepening, in the sense that an increasingly larger number of fainter radio sources is found at sub-mJy levels.

Similar ultradeep VLA 1.4 GHz counts have been made of another field by Condon and Mitchell (1984), who found 116 radio sources down to $S_{1.4} = 84$ µJy. The upturn in the source counts from their data has the same slope as that of Windhorst et al. (1984c) and Oort and Windhorst (1984) in the Lynx.2 area and differs in amplitude by about 20%. Hence, the resteepening of the sub-mJy source counts is a property of the universe, its slope being well established with an uncertainty in amplitude of the order of 20%. A summary of the total 1.4 GHz source count, amalgamated from 10 different Westerbork surveys and updated to 1984, has been given by Katgert (1984).

1c2. High frequencies : Ultradeep 5 GHz sources counts have been made in one very small area with the VLA by Fomalont et al. (1984b), who detected 9 radio sources in 0.0051 deg^2 down to $S_{5.0}$ = 60 μJy. In addition, 10 surrounding areas were covered less deeply, yielding 25 radio sources in 0.051 deg^2 down to $S_{5.0}$ = 350 μJy. The 5 GHz source counts at the $S_{5.0} > 1$ mJy level are consistent with those of section 1b2, but at the $S_{5.0} \sim 100$ μJy level the slope of the normalized differential 5 GHz counts seems to be flatter than in the 1 - 50 mJy range, consistent with the upturn of source counts discovered at 1.4 GHz (see section 1c1).

From the same 5 GHz data Fomalont et al. (1984a) set an upper limit of 1×10^{-3} to the fluctuations in the background radiation at 5 GHz on scales of 18". A similar, but less strong limit of 5×10^{-3} has been set by Condon and Mitchell (1984) at 1.4 GHz on scales of 19". Several observed upper limits to fluctuations in the radio background are compared to model predictions by Danese et al. (1983).

2. SPECTRAL INDEX DISTRIBUTIONS

Spectral index distributions for various new source samples at different flux levels have been obtained over the last few years by the following groups. For the Green Bank 1.4 GHz survey two point spectral index distributions have been measured by Machalski and Maslowski (1982), for the MIT-Green Bank survey by Lawrence et al. (1983), for the NRAO 5 GHz survey by Condon and Ledden (1981), for the north Galactic pole survey by Benn et al. (1982, 1984), for the 1st and 2nd Westerbork survey by Katgert-Merkelijn (1979), for the Westerbork-Einstein deep survey by Katgert-Merkelijn et al. (1984), for the WSRT 5 GHz background survey by Willis and Miley (1979), for the Leiden-Berkeley Deep Survey by Windhorst and Oppe (1984), and for the ultradeep 5 GHz VLA survey by Fomalont et al. (1984b).

The general trend is that the spectral index distribution of radio sources selected at low frequencies ($\nu < 1.4$ GHz) is to first order independent of flux density. However, at the intermediate fluxes in **low** frequency surveys a larger fraction of **steep** (defined as having $\alpha > 0.5$) spectrum sources is seen, while at comparable flux levels in **high** frequency surveys a much larger fraction of **flat** spectrum sources is seen. The former relation has been reviewed using data from a variety of low frequency surveys by Gopal-Krishna and Steppe (1981, 1982, 1984). They notice the similar flux density dependence of the source surface densities and their median spectral index and explain this as a property of the radio sourde redshift distribution, in the sense that the most distant - and hence the most powerful - radio sources have the steepest radio spectra.

In principle it is difficult to decide whether the primary relation is between spectral index and radio power or between spectral index and redshift. Laing and Peacock (1980) argue that the primary relation is between spectral index and radio power. Katgert-Merkelijn, Lari and Padrielli (1980) argue that it may instead be between spectral index and redshift. A similar suggestion is obtained from the data of Tielens, Miley and Willis (1979), who found that the optical identification fraction of a complete sample of 4C sources on the Palomar Sky Survey decreases drastically for the sources with the steepest radio spectrum. This result has been modelled in terms of a spectral index dependent epoch dependent radio luminosity function by Blumenthal and Miley (1979). Similar spectral index dependent optical identification fraction have been found for samples at various flux levels, such as those of Lawrence et al. (1984), Kron, Koo and Windhorst (1984) and Machalski and Condon (1984). Other attempts have been made to model the spectral index dependent epoch dependent radio luminosity function by Peacock and Gull (1981) and by Peacock (1984) and Condon (1984b), who include more recent data (see section 7a).

3. ANGULAR SIZES

Systematic high resolution mapping has been carried out for the following radio source samples. The 1 Jansky sample of Allington-Smith (1982) has been mapped with the Cambridge 5 km telescope. A 4C sample has been mapped with the WSRT at 5 GHz by Kapahi (1981). An 5C subsample has been mapped by Downes et al. (1981) with the VLA and the Cambridge 5 km. Additionnal 5C samples have been similarly mapped by Fielden et al. (1983). Systematic high resolution VLA mapping of the 5 GHz MIT-Green Bank survey sources was carried out by Lawrence (1983). A detailed morphological classification of these 5 GHz sources is given by Lawrence et al. (1984). High resolution VLA mapping of the 1.4 GHz Green Bank sources is obtained by Machalski and Condon (1983a, 1983b) and by Machalski et al. 1982). Angular size distributions of 1.4 GHz sources ar the milliJansky level were also presented by Windhorst et al. (1984a) and by Oort and Windhorst (1984).

The main result from these systematic high resolution mapping programs is that the median radio source angular size decreases from 100" at $S_{1.4} \sim 10$ Jy to 20" at $S_{1.4} \sim 1$ Jy and to 10" at $S_{1.4} \sim 100$ mJy, while it stays around 10" down to $S_{1.4} > 10$ mJy. Below $S_{1.4} = 10$ mJy the median angular size seems to decrease more strongly again, reaching at most 5 - 7" around 1 mJy and is possibly even smaller.

These results have been interpreted by various groups in terms of the linear size and redshift distributions of radio sources, with or without linear size evolution. Downes et al. (1981) claimed that there is no convincing evidence for linear size evolution on the basis of 3CR, 4C, 5C and Ooty data. On the basis of the same data Kapahi and Subrahmanya (1982) argue that linear size evolution needs to be invoked à la $L(z) \propto L(z=0).(1+z)^n$, where $L(z)$ is the epoch dependent and $L(z=0)$ the local linear size and $n = 1.0 - 1.5$. On the basis of more VLA data, Fielden et al. (1983) conclude that size evolution may be requires for some, but not necessarily for all assumed redshift distributions. Allington-Smith (1984) gives a discussion of selection effects operating on the Θ_{med} - S relation. The 2.7 GHz sample of Peacock and Wall (1982) contains a rather large fraction of compact steep spectrum sources, which have to be taken into account when modelling the radio source angular size distribution and their linear size evolution. Okoye and Onuora (1982) and Onuora and Okoye (1983) analyze similar data and conclude similarly to Kapahi and Subrahmanya (1982) that some linear size evolution is required.

Despite the tremendous amount of high quality high resolution angular size data on radio sources in a wide range of flux densities the question of linear size evolution has not been resolved yet. The reason for this is that the local linear size distribution function is poorly known at **all** flux densities; it has only been measured at the brighter levels by Gavazzi and Perola (1978) and Katgert-Merkelijn et al. (1980).

4. OPTICAL IDENTIFICATIONS, PHOTOMETRY AND CLASSIFICATION

The advent of panoramic solid state detectors on large optical reflectors has considerably increased the success of identifying radio sources optically. Measuring accurate optical colors resulted in a more reliable classification.

Deep optical identifications of unidentified 3CR sources were done with a CCD detector in the 200" prime focus down to $r \sim 23.0$ by Gunn et al. (1981). Only 3% of the 3CR sources remained unidentified. A summary of all available 3CR identifications, photometry ans spectroscopic redshifts is given by Laing et al. (1983). Available optical identifications and spectroscopic redshifts of two 4C subsamples are summarized by Katgert-Merkelijn et al. (1980). Deep 200" CCD identifications of the 1 Jansky sample have been made by Allington-Smith et al. (1982), leading to 80% identifications fown to $r \sim 23.0$. Similar optical identifieations of the Parkes 2.7 GHz bright source sample ($Z_{2.7} > 1.5$ Jy) have been made by Peacock et al. (1981), who found 96% optical identifications down to $r \sim 23.0$. For the Parkes 5 GHz sample ($S_{5.0} > 32$ mJy) 40% optical identifications were found by Savage et al. (1982) on deep UK Schmidt plates down to $r \sim 22$. Optical identifications for various subsamples of the 1.4 GHz Green Bank surveys have been made on

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the Palomar Sky Survey by Machalski and Condon (1983a, 1983b), Machalski and Maslowski (1982) and Machalski et al. (1982), who find about 50% identifications down to r ~ 20. Identifications on the Palomar Sky Survey for the 5 GHz NRAO survey have been made by Condon and Ledden (1982), yielding 35% identifications for $S_{5.0}$ > 15 mJy and for the 1.4 GHz Green Bank survey by Condon et al. (1982). Optical identifications have also been done on the Palomar Sky Survey for the MIT-Green Bank 5 GHz sources by Lawrence (1983) and Lawrence et al. (1984), who found 45% identifications for $S_{5.0}$ > 50 mJy. For some 5C6 and 5C7 sources deep 200" prime focus CCD identifications have been obtained by Perryman et al. (1982), who found 40% optical identifications down to r ~ 23.0. Deep multicolor identifications have been made for the 1.4 GHz Leiden Berkeley Deep Survey sources on Mayall 4 m plates in the photographic passbands U, J, F and N by Windhorst, Kron and Koo (1984b), who found 53% optical identifications down to r ~ 22.5. A complete review of all available optical identifications of radio sources in literature, updated to 1983, is given by Veron and Veron (1983).

Swarup et al. (1982) summarized available data in literature on the fraction of optical identifications visible on the Palomar Sky Survey and showed that this fraction decreases from 65% at the 3CR level to 40% at the Bologna level and to 10-15% at the milliJansky level, a result that allowed these authors to rule out various *canonical models for the cosmological evolution of radio sources.*

Windhorst et al. (1984b) showed that identified radio sources with 1 < $S_{1.4}$ <100 mJy consist for 20% of quasars, 78% galaxies and 2% of galactic radio stars. In contrast, radio sources at brighter levels ($S_{1.4}$ > 0.5 Jy) consist for about 30% for quasars (Allington-Smith et al., 1982), while at the 3CR level 25% quasars are seen (Laing et al., 1983) and no radio stars.

Properly calibrated, homogeneous (photographic, photoelectric or CCD) photometry has been performed for only a few samples of radio source identifications : for some subsamples of the 3CR on deep CCD frames in r and i (Laing et al., 1983, and references therein), for the 1 Jansky sample on CCD frames in r (Allington Smith et al., 1982), for objects surrounding the 5C12 sources on multicolor 48" Schmidt plates (Grueff et al., 1984), for the 171 identifications in the Leiden Berkeley sample on Mayall 4 m plates in the passbands U, J, F and N (Kron, Koo and Windhorst, 1984) and for the ultradeep 1.4 GHz VLA sample on the same 4 m plates (Windhorst et al., 1984). We will follow the color classification of Kron et al. (1984), which is based upon 60 spectroscopic redshifts (section 5), to describe the nature of various radio source populations.

In survey areas of the order of several square degree, radio sources with $S_{1.4}$ > 10 mJy are either quasars or luminous giant ellipticals, both often of the classical double radio source type. The giant elliptical radio galaxies have a small dispersion in absolute magnitude. The colors of the giant elliptical radio galaxies are without exception red at the brighter optical levels and become quickly redder at fainter magnitudes due to the K-correction. Below $S_{1.4}$ < 10 *mJy (Kron et al.,1984) find that a blue radio galaxy population becomes* increasingly more important. These blue radio galaxies are mostly unresolved radio sources at arcsecond resolution and have often peculiar optical morphology, either indicative for interacting or merging galaxies or very compact galaxies. Their optical luminosities turn out to be 2 - 3 magnitudes fainter than those of the giant elliptical radio galaxies and have also a larger dispersion. Windhorst et al. (1984c) show that it is this blue radio population that dominates the radio source population at the sub-mJy level and that causes the upturn in the 1.4 GHz source counts below a few mJy.

Systematic near-infrared photometry of radio sources has been done by Lebofsky (1981) and Lilly and Longair (1982, 1984). The J-H and H-K colors of 3CR radio galaxies are consistent with those of passively or mildly evolving luminous giant elliptical galaxies out to redshifts of unity. The optical-infrared V-K and R-K colors show in some cases a blue excess at high redshifts, which may be due to some star formation at a later epoch, or due to the presence of emission lines or non-thermal contributions in these extremely powerful radio galaxies. Near-infrared photometry has also been obtained by Lilly et al. (1984) for the 1 Jansky sample, yielding several new radio source identifications not found previously on deep CCD frames.

Near-infrared photometry has been carried out for a sample of Jodrell Bank radio sources by Puschell et al. (1982) and for several dozen Leiden Berkeley Deep Survey radio sources by Thuan et al. (1984) and Katgert, Windhorst and Isaacman (1984). The near-infrared and optical-infrared colors of the milliJansky radio galaxies are similar to those of the 3CR sample confirming that the stellar population is the main component of the near-infrared spectrum of radio galaxies.

5. REDSHIFTS

In the last few years CCD spectrographs on large optical telescopes have made crucial contributions to the redshifts distribution od radio sources.

For the 3CR sample the spectroscopic redshift measurements have proceeded furthest, because most 3CR radio galaxies are relatively bright and the faintest ones have in general emission lines. Important contributions have been made by Spinrad et al. (1981), who found the first radio galaxy absorption redshift in excess of unity and by Spinrad (1982). Recently emission line redshifts have been measured for some 3CR radio galaxies as high as 1.82 (Spinrad and Djorgovski, 1984b). Another 6 redshifts were measured for faint 3CR radio galaxies by Perryman et al. (1984). The available 3CR spectroscopic redshifts are summarized by Ling et al. (1983) and including the latest measurements the complete sample of 173 3CR sources has now 151 spectroscopic redshifts measured (or 87%).

Noticeable is that the few radio galaxies known today with spectroscopic redshifts in excess of unity have very often narrow emission lines and sometimes spatially extended structure in their emission lines, with velocity dispersions up to 500 km sec^{-1} (Spinrad and Djorgovski, 1984a, 1984b). A similar result was found for one of the 12 radio galaxies from the 1 Jansky sample by Allington-Smith et al.(1984).

A systematic redshift survey has been undertaken during the last years in a long term project by Koo, Kron and Windhorst with the Kitt Peak 4m Cryogenic Camera. Using multiaperture techniques low resolution spectra are simultaneously obtained for field galaxies, radio galaxies and QSO's down to $r \sim 22.0$ in the selected areas where also the Leiden Berkeley Deep Survey was done. In total for a representative sample of more than 60 milliJansky radio sources spectroscopic redshifts are now available (Kron, Koo and Windhorst, 1984). Radio galaxies with $S_{1.4} > 10$ mJy are spectroscopically like giant elliptical galaxies, with a small dispersion in absolute magnitude ($\langle M_F \rangle = -23.2 \pm 0.5$ for $H_0 = 50$), comparable to that measured at the 3CR level. The rather red colors of the giant elliptical radio galaxies are consistent with those of a non-evolving or at most a mildly evolving model spectral energy distribution out to redshifts of at least 0.6, such as those computed by Bruzual (1981, 1983). There is no evidence for drastic evolution of the spectral energy distribution of elliptical radio galaxies out to these redshifts, such as initially suggested by Katgert et al. (1979) and Windhorst et al. (1982) to explain the faint blue radio galaxies. Kron et al. (1984) also show that amongst this blue radio galaxy population, which dominates the source counts for $S_{1.4} < 10$ mJy, **no** very high redshifts ($z > 1$) are found, so that these objects are **not** the high redshift progenitors of elliptieal galaxies in an early blue phase.

6. THE LOCAL RADIO LUMINOSITY FUNCTION OF RADIO GALAXIES

Since studies of the cosmological evolution of radio sources compare the radio luminosity function (RLF) at high redshift with the local RLF, **any** study of the cosmological evolution **must** properly consider the local RLF of all possiblerelevant radio source populations. Because the nature of radio sources is a priori inknown at **all** flux levels, only completely identified **radio** selected samples will provide an unbiassed view of the local RLF.

The local RLF of quasars and of elliptical, S0, spiral and irregular galaxies is reviewed by Fanti and Perola (1977). A more detailed determination of the local the bivariate (radio-optical) luminosity function of elliptical and S0 galaxies is made by Auriemma et al. (1977). Similar results have been found by Meier et al. (1979), who also noted that the RLF of elliptical galaxies apparently does not undergo significant evolution out to $z \sim 0.3$. This was also found by Katgert et al. (1979) from deep optical identifications of Westerbork sources. A further determination of the local RLF of elliptical and S0 galaxies has been given by Dressel (1981).

The local fractional RLF from "normal" spiral galaxies has been determined by Hummel (1980, 1981a) and by Gavazzi and Trinchieri (1981) from large samples of optically selected nearby galaxies. For interactring (spiral) galaxies a similar determination of the RLF has been made by Hummel (1981b). He and also Dressel (1981) and Heckman (1983) noted that interacting galaxies or galaxies in groups have statistically higher radio powers. The local 1.4 GHz RLF has been determined for Seyfert galaxies (both type I and II) by Meurs (1982), who shows that these objects have radio powers typically a factor 10 higher, but space densities at least a factor of 10 lower than those of normal spiral galaxies.

The local RLF for elliptical galaxies has also been determined from the ultradeep radio selected Leiden Berkeley Deep Survey sources by Windhorst (1984). A determination of the local RLF of the blue radio galaxy population that causes the upturn in the source counts below $S_{1.4} \leqslant 5$ mJy was also made. These objects have radio luminosities at least a factor of 5 higher than those of normal spiral galaxies, more like those of Seyferts, but space densities at least 20 x higher than those of Seyferts, in fact comparable th those of elliptical radio galaxies with $P < P^*$. This is consistent with the findings of Hummel (1981b) and Heckman (1983). The blue sub-milliJansky radio galaxy population has for $P < P^*$ the largest space density of all radio galaxy classes, which was not realized before from the RLF determinations from optically selected samples. It is therefore crucial to consider the blue radio galaxy population in the studies of cosmological evolution.

An important contribution to the physical undestanding of the local RLF of giant elliptical radio galaxies has been made by Valentijn and Bijleveld (1983), who determined the trivariate (radio-optical-X-ray) luminosity function using a homogeneous sample of cD galaxies in clusters and groups (Bijleveld and Valentijn, 1984). The cD galaxy mass is determined by the local galaxy density, while the optical luminosity of the cD galaxy is also proportional to its mass. The mass of the cD galaxy in turn determines the accretion rate of intergalactic gas, which emits the hot X-rays, while a stronger accretion flow in the galaxy nucleus will indirectly also fuel a more powerful radio source.

7. STUDIES OF THE EPOCH DEPENDENT RADIO LUMINOSITY FUNCTION

In this section we discuss the various methods that have been employed over the last few years to describe and understand the cosmological evolution of radio sources. The central theme of these studies is the epoch dependent radio luminosity function, $\rho(\log P, z)$, which is the space density of various classes of radio sources as a function of radio power.

7a. Parametric and non-parametric methods

The epoch dependent radio luminosity function has been described by several parametrizations, such as the Schmidt type power laws ($\rho \propto (1+z)^n$) or exponential laws ($\rho \propto e^{n\tau(z)}$), where the exponents are constant with radio power for $P > P^c$ and zero for $P < P^c$ (Katgert, 1977) or some smooth function of radio power for $P > P^c$ (Wall, Pearson anf Longair, 1980, 1981), which allows the most powerful radio sources to evolve more strongly (differential evolution). The local quasar RLF had to be bootstrapped in these models for $P < 10^{27.5}$ W Hz^{-1}, because their local space density is so low, that cosmological volumes - where evolutionary effects are already important - are required for adequate statistical sampling. Another parametrization that explains multifrequency source counts and luminosity distributions has been given by Subrahmanya and Kapahi (1983).

In the power law models a redshift cut-off (at $z_{max} \sim 3.5$ or 5) had to be

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applied, in the other models integration was usually performed to $z = \infty$. These models thus imply the presence of a substantial number of primeval galaxies amongst the radio source population. In most parametric evolution is usually only assumed for $P > P^c$, where the latter is taken to be $> 10^{26.5}$ W Hz^{-1}.

Non-parametric models were first introduced by Robertson (1978, 1980), who adopted a purely free-form array of adjustable delta functions for the redshift dimension of $\rho(\log P,z)$, while the dependence on radio was only assumed for $P > P^c \sim 10^{26.5}$ W Hz^{-1}. Significant evolution was only required for $z > 0.3$. An two dimensional extension of this method has been given by Peacock and Gull (1981), who used limited series of expansion to fit $\rho(\log P,z)$ to multifrequency source counts, luminosity distributions, V/V_{max} data and optical identification statistics. The flat and steep spectrum populations are dealt with simultaneously and Peacock and Gull conclude that also the flat spectrum source population undergoes some evolution, although not as strong as the deep spectrum sources. Peacock (1984) includes new 2.7 GHz data and optical identification data at low flux levels. Especially the latter considerably improve the constraints to $\rho(\log P, z)$, requiring the presence of a redshift cut-off at $z_{max} > 2.5$, as described in more detail by the direct method in section 7b.

Another parametrization of $\rho(\log P,z)$ has been given by Condon (1984a, 1984b), who also uses multifrequency source counts, spectral index distributions, the local RLF and the 3CR redshift distribution. The method is similar to that of Blumenthal and Miley (1979). In Condon's model normal spiral galaxies must evolve in the same way as ellipticals in order to explain the upturn in the source counts. It was demonstrated by Windhorst et al. (1984) that instead the blue, interacting and merging population - with much higher radio powers than those of spirals already at local redshifts - are responsible for the upturn in the source counts at milliJansky levels. It should be kept in mind that some of the parametric models require to extrapolate the 3CR redshift distribution over more than 4 decades in flux density, which must be treated with great care.

7b. The direct method

The basic idea behind the direct method is to use all available optical identification information, and to use a statistical reliable distance indicator, such as apparent magnitude for giant elliptical radio galaxies, in those flux regimes where redshifts are mostly unknown. The method has been first employed by de Ruiter (1978) and Katgert et al. (1979), using the magnitude redshif relation as measured at the 3CR level for several faint Westerbork samples. As found by Kron et al. (1984), radio sources with $S_{1.4} < 10$ mJy are progressively more of the blue radio galaxy class, with optical luminosities typically 2-3 magnitudes below those of giant elliptical radio galaxies. As a consequence, the previous direct determinations of $\rho(\log P,z)$ from data below $S_{1.4} = 10$ mJy needed to be revised.

A more detailed direct determination of the epoch dependent radio luminosity function has been made by Windhorst (1984), who made a distinction between the RLF of red giant elliptical radio galaxies and the blue (interacting, merging) radio galaxies, according to the classification of radio galaxies of Kron et al. (1984). In addition, 9 other radio surveys with available redshifts or good optical identification data are used to sample the epoch dependent RLF in a wide range of radio power and redshifts. Spectroscopic redshifts were known and incorporated for 300 out of 685 radio galaxies.

The findings from previous Westerbork surveys are confirmed that there is no evidence for evolution in the RLF of giant elliptical radio galaxies out to $z < 0.3$ for a wide range of radio powers ($25.0 < P < 27.5$). For $z > 0.3$ evolution in the RLF of giant elliptical galaxies occurs for all radio powers $P > P^* = 10^{25}$ W Hz^{-1} somewhat differential with radio power in the sense that the evolution is stronger for the more powerful galaxies ($\log P > 26.0$). The RLF evolution for giant elliptical radio galaxies is mild, not more than a factor of 10 at $z \sim 0.8$. Most of the apparently stronger evolution at the highest radio powers ($\log P > 27.0$) at high redshifts, as derived from the bright source surveys alone, is due

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to the most powerful radio quasars.

For the blue radio galaxy population only a reliable determination of their **local** RLF is possible due to the lack of spectroscopy at faint magnitudes. Because the space density of the blue radio galaxy population is already very high at local redshifts, little evolution of their RLF is needed to explain the upturn in the sub-mJy source counts, although Windhorst (1984) argues that some mild RLF evolution may required to explain the slope of th upturn in the counts **and** the large surface densities of faint blue radio galaxies.

Little can be said about the RLF evolution of quasars by the direct method, since they are not standard candles. Since at no flux levels fainter than $S_{1.4}$ < 1 Jy complete spectroscopy exists for **radio selected** quasars as yet, their epoch dependent RLF remains largely unknown. In the direct method applied by Allington-Smith (1984) to the 1 Jansky sample, a Hubble relation is adopted for the quasars as derived from spectroscopy at the 3CR level ($S_{1.4}$ > 3 Jy). In the direct method of Windhorst (1984) the contribution to the source counts is determined for quasars with B < 24.0, at which level mosts of the optical quasar luminosity function is seen out to z < 3.5. This quasar contribution is then subtracted from the total source counts.

Windhorst (1984) presents models that fill in the remaining (radio galaxy) source counts by extrapolating the epoch dependent RLF of the giant elliptical and blue radio galaxies to redshifts beyond those of the faintest observed optical identifications. The conclusion is that extension of the milliJansky radio galaxy population to redshifts well in excess of unity is **not required** by the existing data. More powerful radio galaxies can be extended to gradually higher redshifts, ranging from ~ 1.5 for log $P_{1.4}$ ~ 26.5 and ~ 2.0 for log $P_{1.4}$ > 27.0. In contrast, in several of the parametric and non-parametric models discussed in section 7a, the faint radio source redshift distribution needed to be extended to redshifts in excess of 5.0 mainly because RLF evolution was not considered for log P < 26.5.

The direct method has been applied by Jaffe (1982) to 13 VLA detections of the optically selected distant clusters of Gunn and Oke. He concludes, that although there is evidence for RLF evolution at the brighter radio powers, for P < P^* there may well be negative evolution, this in contrast with the findings from the deep radio samples in the field.

7c. Physical methods

One elegant way to approach the physics behind the cosmological evolution of radio sources is an **ab initio** theoretical treatment of the epoch dependence of the physical processes that are potentially important in the behaviour of radio sources and the triggering of their nuclear engines.

In the model of Bailey and McDonald (1981) the epoch dependent stellar mass loss rate in galaxies powers the central engine, such that the critical galaxy mass, above which activity is possible, decreases at earlier epochs. Stocke and Perrenod (1981) argue that quasars can only originate in galactic nuclei if the surrounding intergalactic density is smaller that some critical value that decreases with epoch.

In the model of McMillan, Lightman and Cohn (1981) stellar collisions and tidal disruptions in a dense star cluster trigger the central engine in an epoch dependent way that depends on the mass and the dynamical evolution of the system. In the model of Cavaliere et al. (1982) the central engine accretes collisional debris from a dense star cluster until its exhaustion. In the models of Roos (1981a, 1981b) the effect of merging is considered on the tidal disruption rate of stars near the central engine. The intruding (smaller) galaxy perturbs the gravitational field of the other galaxy such that stars are scattered into loss cone orbits around the central engine of the latter. The local behaviour of this mechanism is considered by Roos (1984a), who also predicts a bivariate luminosity function consistent with the data. The epoch dependent effect of mergers on the luminosity function is modeled by Roos (1984b), who reproduces the total 1.4 GHz source counts and the optical QSO' counts.

7d. Relation to the spectral evolution of radio galaxies

The study of the evolution of the optical spectrum of radio galaxies may provide constraints to the epoch(s) of galaxy formation, hence confining the earliest possible epoch of nuclear activity. Inversely, constraints to the earliest possible epoch of radio source triggering may, when obtained from independent data, tell us something about the epoch of (radio) galaxy formation.

The spectral evolution history of radio galaxies was first studied by Kristian, Sandage and Westphal (1978), who provided a homogeneous set of BVR photometry for a sample of brightest cluster galaxies and 3CR radio galaxies and demonstrated that the powerful radio galaxies do not show evidence for spectral evolution for $z \leqslant 0.3$. Similar studies have been performed by Djorgovski, Spinrad and Marr (1984) and Djorgovski and Spinrad (1984), who combine recent samples of first ranked cluster and 3CR radio galaxies, some of the latter extending to redshifts well in excess of unity. In their Hubble diagram the 3CR radio galaxies at $z > 1$ appear to be 2-4 magnitude brighter than the non-evolving prediction, while their V-R color-redshift relation shows colors > 1 magnitude bluer than those predicted by a non-evolving giant elliptical spectrum or Bruzual's (1983) passively evolving C-model. Since these 3CR sources are at $z > 1$, they are the most powerful radio galaxies in the universe. Consequently, there may also be major non-thermal contributions to their optical light, moreover because all their redshifts could only be measured thanks to the presence of emission lines.

Using also near-infrared photometry similar studies have been performed of 3CR radio galaxies by Lilly and Longair (1984) and of radio galaxies from the 1 Jansky sample by Lilly, Allington-Smith and Longair (1984). These authors show that the position of the horizontal branch is unchanged at a redshift of unity and suggest that the stellar population of these luminous radio galaxies has undergone about one magnitude luminosity evolution since $z \sim 1$ and that at least some fraction of them has optical-infrared colors blue enough to be consistent with star formation ongoing at significant later times than the epoch of formation. They argue that not all of the blue optical-infrared colors can be caused by non-thermal contributions or redshifted emission lines, since in some cases the blue excess seems to be spatially extended.

The spectral evolution of the faint radio galaxies in the Leiden Berkeley Deep Survey has been studied by Kron, Koo and Windhorst (1984) with photographic UJFN photometry and 60 spectroscopic redshifts. As discussed in section 4 and 5, radio sources with $S_{1.4} > 10$ mJy are mostly giant elliptical galaxies with colors that are out to $z \sim 0.6$ sufficiently red to be consistent with Bruzual's passively evolving C-model or at most his mildly evolving $\mu = 0.7$ model, that processes 70% of the galaxy mass into stars during the first Gyr after formation. Hence for at least a considerable fraction of the less powerful elliptical radio galaxies in the milliJansky sample the star formation occured very early on, presumably of the order of 15-16 Gyr ago or at $z > 4.0$ (for $H_0 = 50$ and $q_0 = 0$).

Summarizing, there seems to exist a population of very old elliptical radio galaxies in all samples that must have had most of their star formation very early on, presumably at $z > 4$. In addition it is possible, but not not yet unequivocally proven, that some considerable fraction of them had later ongoing star formation, perhaps extending to epochs as late as $z \sim 1$. Such objects have not yet been found in the milliJansky samples as yet. If blue milliJansky radio galaxies with $z > 1$ were to be found in significant numbers, they would provide crucial constraints to the epoch of galaxy formation and first triggering of the central engines.

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