LUMINOSITY FUNCTIONS FOR EXTRA GALACTIC RADIO SOURCES

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1. DEFINITIONS

The monochromatic luminosity function of radio sources (RLF) is the number of sources per unit volume as a function of the luminosity P at a frequency ν and of the cosmic epoch (z). Symbol: $n(P(\nu),z)$. It is often given per interval of log P, or M_r, the absolute radio magnitude. This function is determined only for sources associated with optical objects (galaxies and QSO's). It can be given for all kinds of associations, or for sources associated with a specific type of object. In this case the normalized, or fractional, RLF is sometimes used, $F_i(P,z) = n_i(P,z)/\rho_i(z)$, where ρ_i is the space density of type i objects. The word "bivariate" is used for the RLF defined per interval of the optical luminosity (or magnitude M). A RLF can be determined using either a radio-optically complete sample of identified sources, or the radio observation of an optically selected sample. The merits of methods used to estimate a RLF from a complete sample are discussed by Felten (1976). Translation of a RLF from one frequency to another must be done with care if, at the two frequencies, different radio components (like the extended and the compact) would be preferentially sampled. We shall review the estimates of local (z = 0) RLF's using $H_O = 100$ Kms^{-1} Mpc^{-1} and the unit WHz^{-1} for P.

2. OVERALL RLF

Wall, Pearson and Longair (this volume) use a sample of 87 3CR sources with S(408 MHz) $\geq$ 10 Jy, of which 74 are identified with galaxies and QSO's having a measured redshift. Thus, they obtain a luminosity distribution that extends down to log P(408) = 21 with the help of Cameron (1971) and Caswell and Wills (1967) (see Sections 3 and 4). The n(P,z) is then estimated by fitting both this distribution and a distribution of source counts down to S(408) = 12 mJy. The best fit of n(P,0) in a Friedmann universe with $q_O = 1/2$ is shown in Fig. 1. This procedure must be followed for sources with log P > 26, whose local densities are too low for a direct determination. Below this power a local n(P) for galaxies can be constructed using sources within z = 0.1, where evolutionary effects can be neglected and the choice of the universe geometry

is not critical. We shall consider separately the contribution of the
elliptical and SO galaxies, (E + SO), and of the spiral and irregular
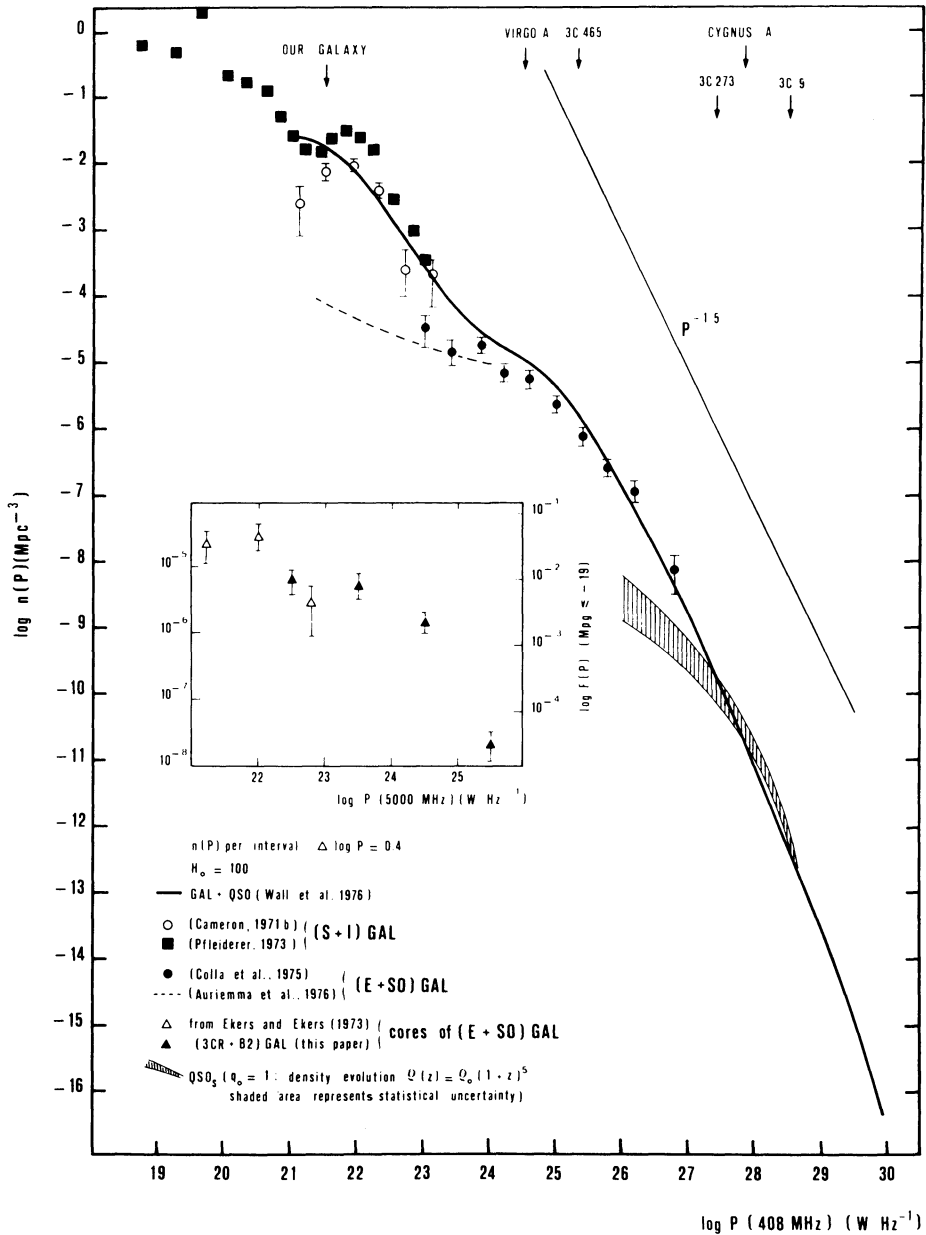galaxies, (S + 1).

Fig. 1. The overall Radio Luminosity Function.

3. (E + SO) GALAXIES

Colla et al. (1975) use a sample of 53 B2 sources (S(408) > 0.20;0.25 Jy) and 53 3CR sources (S(408) > 5 Jy) identified with E and SO galaxies brighter than m_p = 15.7 and m_v = 17, respectively (the redshift available for all galaxies). Their RLF is given in Fig. 1 along with an extension down to log P = 21.5 by Auriemma et al. (1976; see Section 5) (error bars here and later are equal to $N^{-1/2}$ percent). No attempt is made to separate the E from the SO. Note the rather sharp change of slope at about log P = = 25. Earlier estimates of n(P) for log P > 23, where the spiral contribution is negligible (Caswell and Wills, 1967; Merkelijn, 1971), are not as reliable because the distances were mostly estimated indirectly using a fixed absolute magnitude for radio galaxies (see Section 5). However, the flattening below log P = 25 seen by Caswell and Wills but not by Merkelijn is confirmed.

4. (S + I) GALAXIES

Cameron (1971a,b) observed an optically complete sample of bright galaxies (m < 11.0; 12.5) at 408 MHz and detected a total of 85 galaxies with known distance. 72 of these are (S + I) and have log P < 23.5; the corresponding RLF is shown in Fig. 1. The contribution of this type of galaxy peaks at log P = 22 and drops to a density comparable to that of the (E + SO) type at about log P = 23.5. The results of a similar work by Pfleiderer (1973) at 1.4 GHz on a larger sample of galaxies (twice as many detections with known distance) are also given in Fig. 1 (the RLF has been shifted to 408 MHz using a mean spectral index = 0.75). The discrepancy with Cameron's result is probably due to a rather uncertain correction for incompleteness. However, the peak at log P = 22 is confirmed. The extension to lower luminosities shows a minimum at about log P = 21, followed by a new rise. Pfleiderer's data indicate that this structure may be due to a different form of the RLF of the S and I galaxies, the irregulars becoming dominant at log P < 21. This part of the curve, however, is very uncertain due to the limited number of detections available.

5. CORRELATIONS BETWEEN OPTICAL AND RADIO LUMINOSITY IN GALAXIES

To investigate this property, the (E + SO) bivariate RLF has been studied by Ekers and Ekers (1973) at 5 GHz (see Section 7) and by Colla et al. (1975) at 408 MHz. Auriemma et al. (1976) extend the latter work by combining the B2 and 3CR samples with a sample of 17 radio galaxies in rich clusters (Jaffe and Perola, 1976) and a sample of 23 non-cluster radio galaxies (Ekers et al. 1976) to obtain a bivariate F(P) at 1.4 GHz for M_p ≤ -18 per interval of one magnitude. Fig. 2a shows the result of fitting power laws to the data. Note the break in the slope for each interval of M_p at about the same power log $P^*_{1.4}$ = 24.5; at larger P the slope is equal to 1.3 ± .1 independent of M_p up to log P = 26; at smaller P the slope decreases with M_p. The latter property reflects the approach to the saturation (100%) of the integral value of F(P). Above P^* the
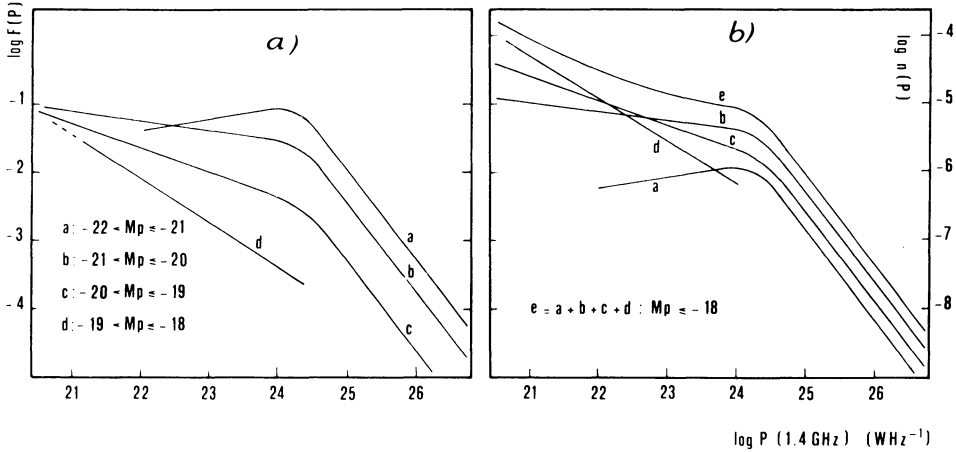
Fig. 2. a) bivariate fractional RLF and b) bivariate RLF.

$F(P)$ depends on the optical luminosity L as $L^{-1.5}$. From the bivariate $n(P)$ (Fig. 2b) a most probable value of M_p = -20.3 for radio galaxies is derived for $P > P^*$, independent of P, while this value increases as P decreases for $P < P^*$. The first result corresponds to that obtained by Sandage (1972) for a sample of 3CR sources, $\langle M_v \rangle$ = -21.48, and shows that the use of a constant $\langle M \rangle$ to construct a distance modulus for radio galaxies is justified locally only for $24.5 < \log P_{1.4} < 26$. Beyond $\log P = 26$ a purely local determination of $\langle M \rangle$ is not possible for statistical reasons, while evolutionary effects might change its value at $z > 0.1$.

For the (S + I) galaxies, using the data from Cameron (1971a), one finds that the bivariate peaks at about $\log P_{408} = 22$ for $-21 < M_p \leq -20$ and $-20 < M_p \leq -19$, and $\log P_{408} = 21.4$ for $-19 < M_p \leq -18$, showing that the average radio luminosity is larger for the brighter galaxies.

6. GALAXIES INSIDE AND OUTSIDE CLUSTERS

The results of the observations of the (E + SO) in 5 rich clusters by Jaffe and Perola (1976) at 1.4 GHz are compared by Auriemma et al. (1976) with those obtained also at 1.4 GHz by Ekers (1976) on a sample of (E + SO) galaxies outside rich clusters (but still mostly in aggregates of various sizes). In Fig. 3 the two $F(P)$ for $M_p \leq -19$ are shown. To take care of the effects of the dependence on M of the bivariate F, in constructing the $F(P)$ from the second sample its optical luminosity distribution has been normalized to that of the cluster sample. From the comparison there seems to be no systematic difference in the two function below $\log P_{1.4} = 24$. Above this power, Riley (1976), from a critical
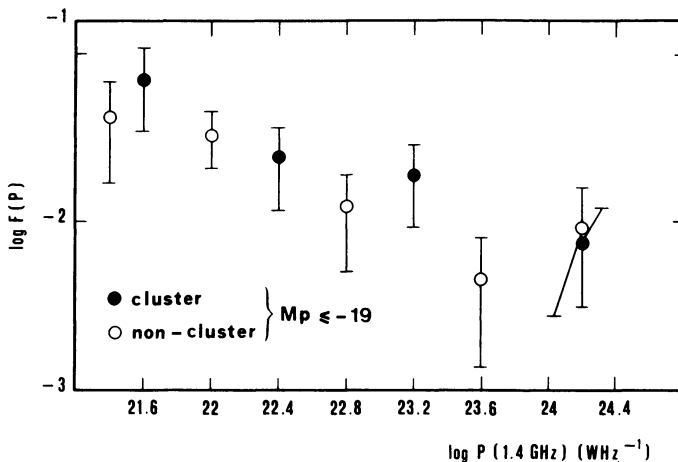
Fig. 3.   RLF for cluster and non-cluster radio galaxies.

analysis of the identification of sources in various surveys with Abell clusters, concludes that a) the RLF of those sources is similar in form to the general one from the 3CR, and that between 1/10 and 1/4 (this gives a measure of the uncertainties) of all radio sources up to $\log P_{1.4}$ = = 26.5 lie in Abell clusters; b) galaxies brighter than M_p = -20 have the same probability of being a radio source inside as well as outside Abell clusters; and c) no correlation is evident between the richness of a cluster and its probability of containing a source. On the other hand Owen (1975), on the basis of observations of over 500 Abell clusters with the 300 foot NRAO telescope at 1.4 GHz, finds a form of the RLF that peaks at $\log P_{1.4}$ ≃ 24.5. He tentatively explains this feature as being due to the summation in its beam (10') of the radio emission of more than one galaxy per cluster (see also Jaffe in this volume). McHardy (1974), using 3CR and 4C sources in clusters, finds that powerful radio sources tend to be more common in Bautz-Morgan class I clusters, a property which does not seem to be explicable only with the difference in the bright end of the optical luminosity function between class I and the other BM classes. Owen (1975) finds an analogous trend (higher detection proba- bility of clusters dominated by a giant central galaxy) using the Rood- Sastry classification.

     For the (S + I) Jaffe and Perola (1976) (see also Jaffe et al. 1976) find evidence that the spirals in Coma (a spiral poor cluster) are more powerful relative both to the nearby spirals and to those in a spiral rich cluster like Hercules. More clusters need to be studied to see if this is a general property differentiating spiral poor from spiral rich clusters.

7. STATISTICS ON COMPACT SOURCES IN ELLIPTICAL GALAXIES

High resolution, high frequency observations show the existence of small
diameter (< 1-2 arcsec) radio sources (cores) in the central region of
elliptical galaxies. These cores are generally found either by high
frequency observations of nearby elliptical galaxies (e.g. Heeschen, 1970;
Ekers and Ekers, 1973) or by high frequency, high resolution observations
of previously known radio galaxies (e.g. Pooley and Henbest, 1974; Riley
and Pooley, 1975; Colla et al. 1975).

   The physical sizes of these cores, as derived from VLBI observations,
range from ~ 1 parsec (e.g. Cyg A, Kellermann et al. 1975) to about 1 Kpc
(e.g. 3C 236, Fomalont and Miley, 1975). However, the actual size distri-
bution is not known due to the incompleteness of the sample studied with
the VLBI technique. Typically core sources of "Cyg A" type have a flat
spectra, while core sources of "3C 236 type" have normal radio spectra.
These cores are often considered as a manifestation of the explosive
phenomena occurring in the nuclei of elliptical galaxies, which ultimately
supply energy to the extended component of the radio source. A statis-
tical study of the properties of cores could shed light on the problem
of how extended radio sources are formed and then powered during their
evolution.

   With the data presently available in the literature we obtain:
a) the distribution of the ratio $\underline{r} = P_{ext.}/P_{core}$ as a function of the
total radio luminosity P_{tot}; b) the RLF $n(P)$ of the cores in elliptical
galaxies; and c) the frequency of cores as a function of the optical
luminosity of the parent galaxy.

   The present analysis is based on: i) a sample of 53 elliptical radio
galaxies from the B2 catalogue as studied by Colla et al. (complete sample)
ii) a sample of 34 radio galaxies brighter than $m_v = 17.0$, from the 3CR
catalogue (almost a complete sample) and an incomplete subset of 25 op-
tically weaker 3CR radio galaxies. All these radio galaxies have been
observed at 5 GHz at Westerbork and Cambridge (see references above).
Several core sources have been detected (31, 20 and 9, respectively)
among them corresponding to percentages ranging from 35 to 60%. Since
many cores are near the detection limits, we expect that there may be more
which have not been detected, especially among more distant galaxies.
From the available maps it is possible to estimate upper limits on the
intensity of undetected core sources. On the other hand, for radio
galaxies which appear "core-like" (9 in the B2 sample and 1 in the 3CR
sample), we have estimated an upper limit to the intensity of an extended
component.

   a) Through proper use of the upper limits on $\underline{r}$, we estimate the "true"
percentage of cores in radio galaxies, as a function of $P_{tot}(408 \text{ MHz})$
and of the ratio $\underline{r}$ (at 5 GHz). The result is given in Table 1. Each
box contains the ratio between cores which could have been detected if
they had equal or smaller $\underline{r}$ values. Table 1 shows: i) for each interval
of P_{tot} the fraction of radio galaxies with a core is > 70%; ii) the

core luminosity does not seem to increase with the total luminosity. However, a correlation of the type $P_{core} \propto P_{tot}^{1/2}$ is equally possible as a null correlation. This result, if subsequently confirmed, is rather important in connection with the problem of an energy supply to the extended radio components. It would seem that the core luminosity is not a good indicator of the energy supply required to maintain the current luminosity of the extended component.

b) We obtain a RLF at 5 GHz of cores of elliptical galaxies from Table 1 and from the RLF of radio galaxies. It is displayed in Fig. 1, along with that derived from the survey at 5 GHz of nearby elliptical galaxies by Ekers and Ekers. Because the selection was made at a much lower frequency, where the extended components dominate, our determination may be biased against core-like flat spectrum sources. However, agreement with the results of Ekers and Ekers shows that this selection effect is not significantly large and that most of the cores are therefore associated with extended components. In the range $21 < \log P_{5000} < 24$, about 50% of the cores are associated with extended components of a similar or stronger radio luminosity (as noted also by Ekers and Ekers). The RLF of the cores seems to have a break around $\log P_{5000} \simeq 24.5$, as does the general RLF. The slope beyond the break is not well determined, but it may be even steeper than that of the general RLF since there are no known core radio galaxies much stronger than $\log P_{5000} \simeq 25$. A determination of the cores RLF at these radio luminosities should be derived in the future from optical identifications of radio sources in the 5 GHz NRAO radio survey.

c) Colla et al. (1975), using 5 GHz Westerbork observations of the B2 sample, gave evidence that the frequency of cores in elliptical galaxies depends on the optical luminosity of the parent galaxy in a way similar to the overall radio emission. Adding the galaxies of the 3CR samples, for which accurate magnitudes are available, confirms this result. Specifically, the fraction of ellipticals in the ranges $(-22 < M_p < -21)$, $(-21 < M_p < -20)$, $(-20 < M_p < -19)$, with cores having $\log P_{5000} > 22.8$, is $(19 \pm 10)\%$, $(6 \pm 2)\%$ and $(1 \pm .5)\%$, respectively.

Table 1

Percentages of Cores of Different r as Function of P_{tot}

$\log r$	$2.5 \pm .5$	$1.5 \pm .5$	$.5 \pm .5$	< 0.0
$\log P_{tot}$				
$> 26.$	$29 \pm 14\%$	$34 \pm 12\%$	$4 \pm 4\%$	
$25.5 \pm .5$	$5 \pm 5\%$	$30 \pm 11\%$	$20 \pm 9\%$	$23 \pm 9\%$
$24.5 \pm .5$	$13 \pm 9\%$	$20 \pm 11\%$	$25 \pm 11\%$	$24 \pm 11\%$
$23.5 \pm .5$		$8 \pm 8\%$	$34 \pm 14\%$	$24 \pm 11\%$

8. QUASARS

It is not possible to determine a local RLF for quasars, since their local
density (z < 0.1) is too low for a direct determination. All of our
information comes from objects at larger distances (z >> 0.2), where
evolutionary effects are dominant. Therefore, a determination of the
RLF of quasars at the present epoch is strictly connected to the deter-
mination of their evolution law. Evidence concerning the evolution of
quasars has been reviewed by Schmidt (1972a) who showed that it can be
accounted for by a pure density evolution described either by an expo-
nential law $\rho(z) = \rho_0 \, 10^{5\tau}$ (τ being the look-back time in units of the
age of the universe) or by a power law $\rho(z) = \rho_0 \, (1+z)^n$, with n = 6±1.

We assume, in that which follows, the second expression with n = 5.
From the complete samples of radio quasars (QSS's) available in the
literature, 3CR (see Smith et al. 1976) and 4C (Lynds and Wills, 1972),
a RLF extrapolated to z = 0, by means of the assumed evolution, is derived
This is shown in Fig. 1. A comparison with the overall RLF of radio
sources shows that, for $\log P_{408} > 27.5$, quasars contribute to most of
the space density of radio sources, while at $\log P_{408} < 27.0$, the contri-
bution of the radio galaxies is dominant (see also Schmidt, 1972b). Chang
of n by ±1 would change the local space density of quasars by about a
factor 3 at the bright end but would not change the lower end significantl
The total space density of quasars down to $\log P_{408} \simeq 26.0$ is $(10 \pm 2.5) \cdot$
$\cdot \, 10^{-9}$ Mpc^{-3}. This value may be compared with the density of all quasars
obtained from optically selected samples regardless of their radio emissio
(QSO's) (Braccesi et al. 1970; Schmidt, 1970). The optical luminosity
function of quasars, determined from these optical samples adopting the
same evolution law as for the radio quasars, is a power law with slope
1.5 ± .15. Above an absolute optical luminosity, at 2500 Å, $F_{2500} = 10^{22}\cdot$
the integrated space density, at zero redshift, is $(1.3 \pm .4) \cdot 10^{-7}$ Mpc^{-3}
and above $\log F_{2500} = 21$ it might be up to $\simeq 10^{-5}$ Mpc^{-3}. It has been shown
(Fanti et al. 1973) that strong radio emission is a property of only those
quasars with $\log F_{2500} > 22.4$, while optically weaker quasars are very
seldom strong radio emitters. Thus, it appears that only about 8% of all
quasars with $\log F_{2500} > 22.4$ are radio sources with radio luminosity
larger than 10^{26}.

Several attempts have been made to extend the determination of the
RLF at lower radio luminosities. Most of these attempts are done through
the use of the so-called $\Psi(R)$ function. This represents the fraction of
all quasars, per unit volume, having ratio R between the monochromatic
radio and optical luminosities at 500 MHz and at 2500 Å, respectively
(see Schmidt, 1970). The introduction of this function came from Schmidt'
finding (1970) that the redshift distributions at the 18th magnitude for
QSS's and QSO's are very similar, which seemed to imply that the radio
and optical luminosities are correlated. $\Psi(R)$ may be determined on the
basis of complete samples of QSS's, by knowing the number-magnitude, N(<m)
relationship for QSO's (see Schmidt, 1970; Fanti et al. 1973) and by the
formula

$$\Psi(R) \cdot \Delta R = \frac{N(<m,r)}{N(<m)} \qquad\qquad (8.1)$$

where $N(<m,r)$ is the number of QSS's in the considered sample which are brighter than m and possess a radio to optical flux ratio equal to R ± ± $\Delta R/2$. Alternatively, it can be found by searching radio emission from optically selected quasars. $\Psi(R)$ is reasonably well determined for log R > 3.5 from the 3CR and 4C samples. Attempts to determine $\Psi(R)$ below that value have been made in the past by Fanti et al. (1973, 1975) and Katgert et al. (1973) on the basis of: i) a sample of quasars from the B2 catalogue; ii) a search of radio emission down to ≈5 - 10 mJy, from the sample of QSO's studied by Braccesi et al. (1970).

From the first sample it appeared that ≈30 - 100% of quasars (with log F_{2500} > 22.4) have radio luminosities with log R > 2.0. From the second sample it was determined that at most 20% of all quasars have log R > 2.0. Since the two determinations of $\Psi(R)$ were thought to be significantly different, and were also obtained from two samples at different depths in space, the discrepancy was assumed as evidence of an evolutionary effect in quasars with 2.0 < log R < 3.0 (Fanti et al. 1973, 1975). Recently other attempts have been made to determine $\Psi(R)$, at log R < 3.0, using: i) a sample of QSS's from the Westerbork survey (de Ruiter, Willis and Arp, 1976); ii) a search for radio emission from a new sample of 51 QSO's studied spectroscopically by Schmidt (1974) plus 8 bright QSO's from the Tonantzintla catalogue (Iriarte and Chavira, 1957). This search led to 8 radio detections above 10 mJy (Fanti et al. 1976). This figure is in excellent agreement with the previous result by Katgert et al. concerning the QSO's studied by Braccesi et al. The various determinations of $\Psi(R)$ are shown in Fig. 4 (again only for those quasars with log F_{2500} > 22.4). The new radio data on QSO's have been combined with the previous measures by Katgert et al. There is still a systematic difference (at ∿2σ level) between the $\Psi(R)$ determinations from the optically selected and the radio selected samples in the range 2.0 < log R < < 3.0. However, the previously suggested explanation of an evolutionary effect has now been ruled out, since most of the new radio observed QSO's span the same range of apparent optical luminosity and, therefore, of redshift as the radio samples. The difference may be just a large statistical fluctuation or it may be due to an incorrect N(<m) relationship at the very bright end (16.0 < m < 17.5), which is used to compute the $\Psi(R)$, and, therefore, to an evolutionary behaviour at small redshifts (z < 0.5) different from the assumed power law.

If we assume the determination from the QSO samples in the range 2.0 < log R < 3.0 as the best estimate of $\Psi(R)$, we see that at log R > > 1.5 only about 17% of all quasars are radio emitters. Presumably, the bulk of them have log R values much lower than 1.0. $\Psi(R)$ might also have a maximum near log R = 2.5 and then decrease at low R's. This shows that the phenomenon of strong radio emission is not more frequent among the quasars than it is among the elliptical galaxies. We are led to think either that the radio emission is a transient phenomenon in the life of quasars or that only in a small number of cases the physical conditions favour a strong emission at radio wavelengths.
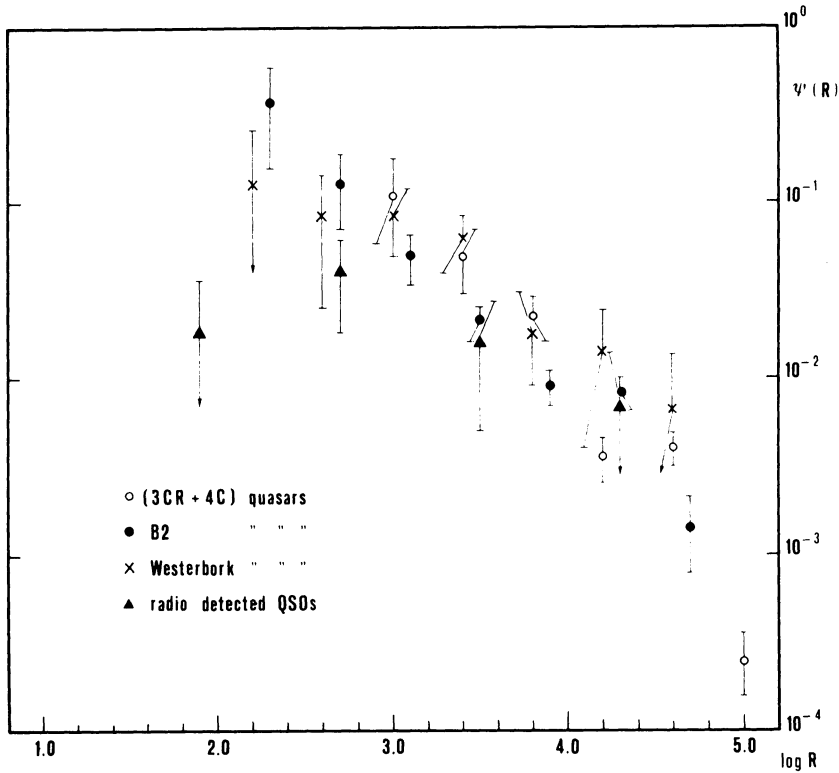
Fig. 4. The Ψ(R) function.

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DISCUSSION

H.E. Smith: If I understand correctly, your luminosity function requires that $< M_p >$ for powerful radio galaxies increase by 0.4^m per decade of radio power. However, if you look at 3CR galaxies with $m \lesssim 19'$ where there is some measure of completeness, then there is a difference of less than 0.3 mag over about 4 decades of radio power.

Perola: I have shown that $< M_p >$ depends on the power of the sources onl if P is less than 10^{24} WHz^{-1} and that at larger powers $< M_p >$ is independe of P. This result is in full agreement with what you say about 3CR galaxies, whose powers, at z larger than 0.03, are larger than $10^{24.5}$. In fact the result you mention also indicates that $< M_p >$ in the large power range stays about constant beyond the limit z=0.1 imposed in the determination of the bivariate n(P) in our Fig. 2b.

Conway: Data by Edwards at Jodrell Bank gives the power emitted by central components vs. the power emitted by the whole source for 26 bright 3C sources, and suggests that these are proportional to each other for radio galaxies. The ratio is higher for quasars.

R. Fanti: If one plots core luminosity against luminosity of the whole

source, one actually finds a proportionality between the two luminos-
ities. But this is largely due to a selection effect. More powerful
radio galaxies are generally far away and therefore, owing to the limited
sensitivity of radio telescopes, one detects only stronger cores.

Rowan-Robinson: I have tried to tie together what we know about activity
in galaxies - radiogalaxies, N-galaxies, Seyferts and quasars - into a
single picture. I assume that the probability of a galaxy being active
depends on optical luminosity, declining from 100% for the most luminous
to 2% for the least luminous. I then construct probability functions
for the luminosity of radio cores, optical cores, extended radio sources
(for active ellipticals) and disc emission (for all spirals). I assume
a range of dust optical depths in front of the optical cores to explain
the infrared emission from active galaxies.

QSOs are then simply active galaxies whose optical cores outshine the
parent galaxy, while in Seyferts the optical core has to contribute at
least 1% of the total light. The distribution functions for the various
observable parameters fit most of what we know about active galaxies
(the bulk of the data reviewed by Fanti & Perola, for example). A sur-
prising prediction is that most optically selected QSOs are in spirals,
explaining their low radio to optical ratio. Although the scheme has
yet to be evolved to earlier epochs, a prediction could be that compact,
flat spectrum radio sources do not show much evolution.