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A Search for Radio Emission from a Sample of Optically Selected Quasars

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Summary. 62 optically selected quasars (QSO) have been searched for radio emission at 1415 MHz with the Westerbork Synthesis Radio Telescope. Eight of them have been radio detected. The remaining ones are radio quiet at levels of about 10 mJy.

These data are combined with those of Katgert et al. (1973) on the QSO's of Braccesi et al. (1970), obtaining a sample of 85 objects. The distribution function $\psi(R)$ of the ratio of radio to optical emission is derived. It is shown that there is a disagreement with the one obtained from radio selected samples. A brief discussion is given on such a discrepancy.

Key words: quasars — luminosity function

I. Introduction

This paper presents new observations with the Westerbork Synthesis Radio Telescope (WSRT) of 62 optically selected quasars (QSO's). Its purpose is to study the distribution function of the ratio R of radio to optical emission [hereafter called $\psi(R)$]. This function plays a key role in both the astrophysical and cosmological discussions of QSO's. It was introduced by Schmidt (1970), who, as a working hypothesis, assumed its independence from both redshift and optical luminosity. This means that the radio luminosity function scales with optical luminosity for all z. This assumption was prompted by the fact that the redshift distribution of 18th magnitude quasars in an optically selected and in a radio selected sample are statistically similar.

The $\psi(R)$ function is reasonably well known for $\log R > 3.0$ from data on 3CR and 4C quasars. Values in the range $2.2 < \log R < 3.0$ from the B2 catalogue have also been added (Fanti et al., 1973, 1975).

Katgert et al. (1973) made a survey of QSO's from the catalogue of Braccesi et al. (1970). They detected very few QSO's and sampled the $\psi(R)$ function in the range $2.0 < \log R < 3.5$; there is a discrepancy between the Katgert et al. result (1973) and that from the B2 quasars. It was therefore suggested (Fanti et al., 1973, 1975) that $\psi(R)$ may not be independent from the redshift.

A better knowledge of $\psi(R)$, specifically its possible dependence on redshift and on optical luminosity is important not only in order to study the physical processes which determine the radio to optical coupling, but it is also needed to interpret radio source counts and the identification contents at different flux levels.

II. Observations

We have observed, with the WSRT at 1415 MHz, three samples of optically selected quasars (QSO's). The first, that of Sandage and Luyten, was studied spectroscopically by Schmidt (1974). This list contains 51 quasars. Seven of them have a continuous spectrum and two have only one line, so that their redshift is unknown although their quasar nature is established. Photoelectric photometry is available for all objects except nine (Sandage, private communication). The second sample consists of seven bright QSO's selected by various authors on the basis of optical studies from the Tonantzintla catalogue of blue stars in the north galactic pole region (Iriartes and Chavira, 1957). One of these objects was previously known as a radio source (TON 202 ≡ B2 1425 + 26), but the discovery of its quasar nature was based on optical studies and not on its identification with a radio source. This second sample is not complete in any sense, but it is unbiased as far as radio properties are concerned. Photoelectric photometry is lacking for five objects. Finally, four spectroscopically confirmed QSO's from the Braccesi et al. (1970) sample were observed. Two of them were listed as possible detections by Katgert et al. (1973), while for the other two, optical spectra have been obtained by Wills and Wills (1976) only recently, and high sensitivity radio observations were lacking.

For objects without photoelectric photometry, magnitudes have been estimated on the P.S.S. prints. Optical positions have been measured on the P.S.S. prints with an accuracy of $\sim 0\farcs8$ in both coordinates.

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Table 1. Optical and Radio Data of QSO's

NAME	R. A. DEC. 1950	Z	m_b	S 1.4GHz	Log L_o	Log F 0.5 GHz	Log R	*
PHL 847	004634.42 152404.5	1.24 (1)	17.9	<10.	23.6	<25.5	<1.9	
PHL 850	004655.49 111206.3	0.27 (1)	17.1	<10.	22.7	<24.3	<1.6	
PHL 881	005041.18 103703.6	0.32 (1)	17.4	<10.	22.7	<24.4	<1.7	
PHL 891	005157.09 143914.1	0.87 (1)	18.1	<10.	23.2	<25.2	<2.0	
PHL 892	005206.23 143031.4	0.91 (1)	18.1	<10.	23.3	<25.3	<2.0	
PHL 909	005431.94 142958.6	0.17 (1)	16.1	<10.	22.6	<23.8	<1.2	
PHL 915	005523.36 153703.7	1.26 (1)	18.1	<10.	23.6	<25.6	<2.0	
PHL 921	005603.42 124007.2	1.09 (1)	18.3	<10.	23.3	<25.4	<2.1	
PHL 957	010033.39 130010.6	2.69 (1)	16.9	<10.	24.7	<26.2	<1.5	
PHL 964	010056.57 095429.1	0.46 (1)	18.1	<10.	22.7	<24.7	<2.0	
PHL1033	013107.82 034213.5	0.26 (1)	(18.2)	<10.	(22.2)	<24.2	<2.0	
PHL1049	013231.70 074346.8	0.15 (1)	17.8	<20.	21.8	<23.7	<1.9	*
PHL1070	013443.27 032314.0	0.08 (1)	17.9	<10.	21.2	<23.1	<1.9	
PHL1072	013512.27 054011.7	0.62 (1)	(17.8)	<10.	(23.0)	<24.9	<1.9	
PHL1092	013719.02 060410.5	0.40 (1)	(16.7)	<20.	(23.1)	<24.9	<1.8	
PHL1114	013922.08 042717.8	c.sp.(1)	(16.7)	<10.			<1.5	
PHL1106	013922.73 055656.7	0.35 (1)	(18.2)	<10.	(22.4)	<24.5	<2.1	
PHL1119	014016.78 080707.0	0.12 (1)	(17.1)	<10.	(22.1)	<23.6	<1.5	
PHL1127	014133.13 051514.8	1.98 (1)	18.4	<10.	23.8	<25.9	<2.1	
PHL1141	014356.20 074348.1	c.sp.(1)	(18.1)	<10.			<2.0	
PHL1194	014852.13 090237.0	0.30 (1)	17.4	<15.	22.6	<24.5	<1.9	
PHL1222	015117.43 044815.1	1.91 (1)	18.0	<20.	24.0	<26.3	<2.3	*
PHL1226	015151.65 043337.7	0.41 (1)	18.0	<20.	22.6	<24.9	<2.3	*
PHL3375	012825.21 072814.5	0.39 (1)	18.3	<10.	22.5	<24.6	<2.1	
PHL3424	013108.98 053232.2	1.85 (1)	18.4	<10.	23.8	<25.9	<2.1	
LB 8684	084459.03 184130.2	c.sp.(1)	16.9	<10.			<1.5	
LB 8741	084738.65 190503.1	0.57 (1)	(17.3)	<10.	(23.2)	<24.9	<1.7	
LB 8755	084804.48 153331.4	2.01 (1)	17.9	495.	24.0	27.6	3.6	*
LB 8775	084853.70 162339.8	1.93 (1)	17.8	<10.	24.0	<25.9	<1.9	
LB 8796	084947.35 152957.8	1.32 (1)	18.3	<20.	23.5	<25.9	<2.4	
LB 8863	085159.64 194205.4	2.21 (1)	17.9	<20.	24.1	<26.3	<2.2	
LB 8891	085248.23 180657.1	0.22 (1)	18.1	<10.	22.0	<24.0	<2.0	
LB 8948	085415.78 192029.0	0.33 (1)	17.3	<20.	22.7	<24.7	<2.0	
LB 8956	085436.54 190700.5	1.89 (1)	17.6	54.	24.1	26.6	2.5	
LB 8991	085540.17 184848.4	1.01 (1)	17.9	<20.	23.4	<25.6	<2.2	
LB 9010	085600.72 183745.1	1.71 (1)	18.3	<20.	23.7	<26.1	<2.4	
LB 9013	085604.09 170309.1	1.45 (1)	18.1	459.	23.7	27.3	3.7	*
LB 9029	085637.45 185532.2	1.29 (1)	17.7	<20.	23.7	<25.8	<2.1	
LB 9086	085809.46 151450.1	1 ℓ. (1)	18.7	<15.			<2.4	
LB 9179	090035.21 152545.1	0.18 (1)	18.3	<20.	21.8	<24.2	<2.4	
LB 9308	090344.16 165816.0	0.41 (1)	17.8	1523.	22.7	26.7	4.0	*
LB 9388	090628.68 164736.0	1.07 (1)	17.7	<15.	23.6	<25.6	<2.0	
LB 9436	150512.28 215334.2	2.13 (1)	18.7	<10.	23.7	<25.9	<2.2	
LB 9440	150555.61 220204.7	c.sp.(1)	17.2	<10.			<1.6	
LB 9576	151522.57 330711.5	c.sp.(1)	18.0	<10.			<2.0	
LB 9612	151708.19 235652.6	1.90 (1)	(17.5)	<10.	24.2	<25.9	<1.7	
LB 9657	151956.59 254542.4	c.sp.(1)	17.5	<10.			<1.8	
LB 9707	152308.83 212436.3	1.92 (1)	18.0	<10.	23.9	<25.9	<1.9	
LB 9737	152533.05 220747.4	1 ℓ. (1)	17.8	<10.			<2.0	
LB 9743	152545.69 224325.3	0.25 (1)	16.3	295.	22.9	25.7	2.7	*
LB 9763	152725.48 204922.8	c.sp.(1)	17.6	<10.			<1.8	
TON 490	101105.65 250411.0	1.63 (2)	(17.2)	571.	(24.1)	27.0	2.9	*
TON 153	131734.24 274352.0	1.02 (2)	(16.1)	<10.	(24.1)	<25.3	<1.2	
TON 155	131853.65 290330.3	1.70 (3)	(16.9)	<15.	(24.2)	<25.9	<1.7	
TON 156	131854.78 290300.6	0.55 (3)	(16.1)	<15.	(23.6)	<25.0	<1.4	*
TON 157	132100.03 292544.8	0.96 (2)	(16.4)	<20.	(23.9)	<25.5	<1.6	
TON 202	142521.86 264537.8	0.37 (4)	16.0	270.	23.2	25.8	2.6	*
TON 256	161208.73 261146.1	0.13 (5)	16.0	18.	22.4	23.7	1.3	
AB 55	125350.82 363849.2	c.sp.(7)	17.0	<15.			<1.8	
AB 69	125607.84 354453.7	1.86 (6)	18.6	18.	23.5	25.9	2.5	
AB 118	130246.42 342250.8	c.sp.(7)	17.2	<15.			<1.8	
AB 154	130816.63 381242.1	2.09 (7)	17.9	<15.	23.8	<25.9	<2.3	

Column 1: Name

Columns 2 and 3: Optical right ascension and declination. We have measured them on the P.S.S. prints. A comparison of these positions with those measured independently by B. Wills (private communication) indicates an accuracy of about 1″

Column 4: Redshift and its reference "c. sp." indicates continuous spectrum: "1*l*" indicates only one line

References are: *1* Schmidt (1974); *2* Jones and Lynds (1969); *3* Stockton (1972); *4* Greenstein and Oke (1970); *5* Ford and Rubin (1965); *6* Braccesi et al. (1970); *7* Wills and Wills (1976)

Column 5: Blue magnitude, corrected to the North galactic pole, by the formula

$m_b = 0.25(\mathrm{cosec}\, b_{\mathrm{II}} - 1)$.

These magnitudes are from Sandage (private communication), except those in parenthesis, which have been estimated on the Palomar Sky Survey

Column 6: Radio flux (or upper limit to it) at 1415 MHz (in mJy $= 10^{-29}$ watt $\mathrm{Hz}^{-1}\,\mathrm{m}^{-2}$)

Column 7: Log. of absolute optical luminosity at 2500 Å (W/Hz), computed according to Schmidt (1968). We use $H = 100\,\mathrm{km\,s^{-1}\,Mp^{-1}}$ and $q_0 = 1$

Column 8: Log. of absolute radio luminosity (or upper limit) at 500 MHz (W/Hz). When the spectral index is not known, a value of 0.7 is assumed

Column 9: Log. of ratio between radio and optical luminosity (see Schmidt, 1970)

Column 10: Asterisk indicates a note relative to the object

PHL 1049: Confused by a strong nearby source.
PHL 1222: Confused by a strong nearby source.
PHL 1226: Confused by a strong nearby source.
LB 8755: See also Mills and Little (1970). $S_{408} = 1250$ mJy; $S_{2700} = 248$ mJy; $S_{8000} = 47$ mJy (Wardle and Miley, 1971).
LB 9013: 4C 17.46; $S_{408} = 1900$ mJy.
LB 9308: 3C 215; $S_{408} = 5300$ mJy.
LB 9743: B2 1522+22; $S_{408} = 780$ mJy.
Ton 490: B2 1011+25; $S_{408} = 410$ mJy.
Ton 156: Confused by a nearby source.
Ton 202: B2 1425+26; $S_{408} = 750$ mJy.

The radio data are provided by short observations (6 min long) at two different position angles (corresponding to hour angles in the intervals of 0^h to 2^h and -4^h to -5^h or $+4^h$ to $+5^h$. At each position angle four observations with different sets of baselines have been made (except in a few cases where some observations were missed), thus obtaining in each p.a. a set of 80 interferometers with baselines spaced by 18 m, with a minimum spacing of 54 m. Grating lobes are 40′ $(\sin^2\delta \sin^2 \mathrm{HA} + \cos^2 \mathrm{HA})^{-1/2}$ apart from each other. Since the HPBW of the primary beam is ~35′, confusion from sources distant from the field center where the QSO is located is greatly reduced by the primary beam.

The output of the 80 interferometers was used to compute, by Fourier transform, a one-dimensional brightness distribution across the position of the QSO in the two position angles. The resolution along each p.a. is 20″ $(\sin^2\delta \sin^2 \mathrm{HA} + \cos^2 \mathrm{HA})^{-1/2}$.

The r.m.s. noise level in the four combined observations referring to the same p.a. is ~2 mJy. The sensitivity limit is determined, however, not only by the noise but also by confusion. An analysis of the fluctuations of the strip brightness distribution obtained gives an r.m.s. value (due to both noise and confusion) of about 4 mfu for a complete set of baselines, a result which scales roughly as the reciprocal of the number of baselines for incomplete sets of observations. In a few cases, due to the presence of a very strong nearby source, this value is significantly larger.

We consider a QSO detected when a source is found, within ±3″ from the optical position, which is stronger than three times the r.m.s. in the nearby region of each strip. The flux is taken equal to the average of the two fluxes. Upper limits to undetected objects are taken equal to three times the combined r.m.s. of the two strip distributions. In a few cases in one of the two positions angles, near the optical position, there is a very strong source which in the other strip is far away. This confusing source forces us to estimate the upper limit of the QSO's radio emission from one strip only. Upper limits estimated in this way are obviously larger. The various upper limits range from 10 to 20 mfu.

III. Results

The list of observed objects and the results obtained are given in Table 1.

Five QSO's from the Sandage and Luyten sample and three from the Tonantzintla sample (also including TON 202 ≡ B2 1425 + 26) are found to be associated with radio sources. Six out of the total eight were already listed in existing catalogues of radio sources, although the radio positions available were not always accurate enough to allow for definite identification. Despite the large increase in the sensitivity of the present observations, only two QSO's (LB 8365 and TON 256) were radio detected as faint (< 100 mJy) previously unknown radio sources. Moreover, we confirm the detection of AB 69 (from the sample of Braccesi et al.), which was previously suggested as a possibility by Katgert et al. (1973).

None of the detected QSO's showed significant extension, except for LB 9308 ≡ 3 C 215 and TON 202. The former has an angular size of 14″ (gaussian model deconvolved for the beam) and is in good agreement with the higher resolution observations of Pooley and Henbest (1974). TON 202 was studied by Miley and Hartsuijker (1977) and was found to be a giant radio source. This finding is consistent with the angular size distribution currently found for radio selected quasars (QSS's).

For the six previously known sources, a two frequency spectral index is computed between 408 and 1415 MHz (408 MHz fluxes are taken from the B2 catalogue or measured with the E–W arm of the Bologna cross). The two new detections are too weak to be measured at 408 MHz. Five of them have a spectrum normal for transparent synchrotron sources and only one (TON 490 ≡ B2 1011 + 25) has a flat spectrum. AB 69 was also detected at 610 MHz (Katgert-Merkelijn, private communication) and may also have a normal spectrum consistent with the observations by Wardle and Miley (1972).

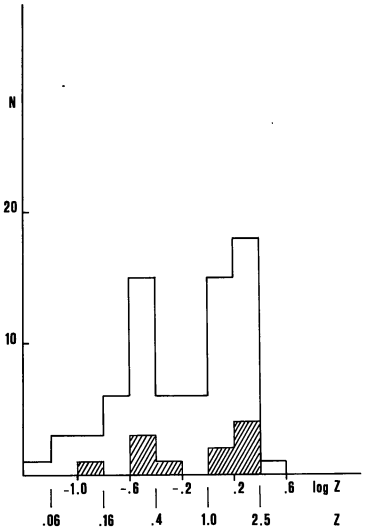

Fig. 1. Redshift distributions for the 73 QSO's. Dashed rectangles represent radio detected QSO's

It seems that the proportion of flat to steep spectrum sources is similar to that found in low frequency surveys like 3CR, 4C or B2.

IV. Discussion

By combining our new observations with those by Katgert et al. (1973), we can use a total of 85 optically selected and spectroscopically confirmed quasars, 73 of which have measured redshifts. There are eleven radio detected objects among them.

This sample is not complete to a specified magnitude, being composed of three samples with each covering a different magnitude range. The sample by Braccesi et al. is complete in the infrared at $m_i = 17.65$, which very roughly corresponds to $m_v \simeq 18.4$. The sample of Sandage and Luyten contains objects as weak as 18.5, but from their differential $\log N - m$, the sample appears largely incomplete beyond 18.0. The last sample from the Tonantzintla catalogue contains only objects brighter than $\simeq 17.0$. Care must be taken when using this composite sample. It is not suitable for statistical considerations (like redshift distribution, absolute luminosity distribution, number-magnitude relationship, ...), which require completeness to a specified magnitude. As far as the following discussion is concerned, however, completeness is not necessary. However, it is required that the sample remains unbiased with respect to radio emission, which is the case already mentioned in Section II.

Figure 1 shows the comparison of the redshift distributions of the full sample and of the eleven radio detections. The distribution of the radio detected objects

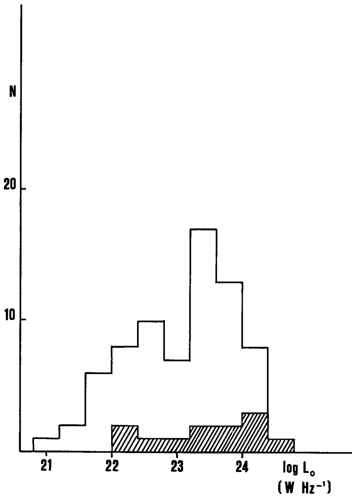

Fig. 2. Distribution of absolute optical luminosities at 2500 Å for the 73 QSO's with measured redshifts. Dashed rectangles represent radio detected QSO's

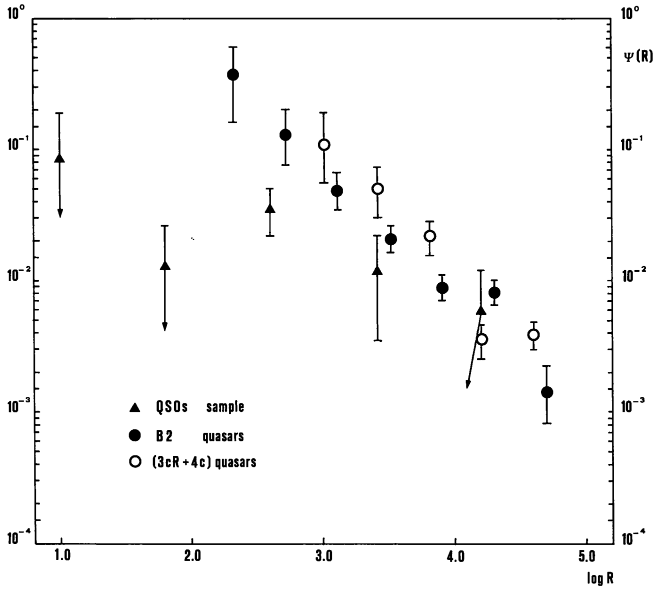

Fig. 3. $\psi(R)$ function, as determined from QSO's and B2 and (3C+4C) samples. Values refer to intervals of $\Delta \log R = 0.4$. For the QSO's sample values are the average of two contiguous intervals of $\log R = 0.4$. Only those objects with $\log L_0 > 22.0$ W/Hz are considered

may be considered a random subset of the total sample. This is similar to the result found by Schmidt (1970) when comparing the redshift distributions of QSS's and QSO's at the 18th magnitude[1]. It was interpreted by Schmidt (1970) in terms of a bivariate luminosity function which factorizes into the optical luminosity function and the distribution function $\psi(R)$, the distribution of ratio between the radio and optical luminosities. However, it has been suggested by several authors (Petrosian, 1972, 1973; Schmidt, 1972; Fanti et al., 1973) that this factorization applies only to quasars with high optical luminosity ($\log L_0 > 22$). The optically weaker quasars would very rarely be radio emitters, and, therefore, they should be described by a completely different bivariate luminosity function.

Actually, in the present sample there are no radio detections at all below $\log L_0 = 22$ (see Fig. 2). This finding is in agreement with the previously mentioned suggestions, even if it is statistically insignificant by itself. In the following, when computing $\psi(R)$, we will consider only those quasars with $\log L_0 > 22$.

The $\psi(R)$ function can be computed from the sample in the following way. For any given range of $\log R$ we divide the number of detected QSO's in that range by the number of objects which could have been radio detected if they had a value of R in that range. The $\psi(R)$ function obtained here is displayed in Figure 3, together with those functions obtained from the B2 sample and the 4C and 3C samples. The latter are taken from Fanti et al. (1975).

There is a discrepancy, in the range $\log R < 3.0$, between $\psi(R)$ from the QSO samples and those from the radio samples.

In this paper we do not intend to propose models or explanations, in terms of more sophisticated luminosity functions or cosmic evolution laws which account for observed discrepancy. We want, however, to stress some uncertainties which are present in the simple frame-work hypothesis that we have assumed. The first uncertainty is the number-magnitude relationship $N(m)$ of QSO's, which enters as the normalization factor when computing $\Psi(R)$ from radio samples (see Schmidt, 1970; Fanti et al., 1973).

Observationally this $N(m)$ law is very uncertain for $m_b < 17.0$ and one must compute it by making specific assumptions on the evolution law in the redshift range where the evolution is very poorly known ($z < 0.6$). The determinations of $\psi(R)$ from the QSO sample and the radio quasar samples would be in agreement only if the $N(m)$ law were to have a slope of, at most, 0.6 for $m_b < 17.0$. In other words, the surface density of bright QSO's should be higher than that extrapolated from $m_b \sim 18.0$ on the basis of a strong density evolution law such as $\varrho(z) = \varrho_0(1+z)^n (n = 6 \pm 1)$. Consistency of the two independent $\psi(R)$ determinations would therefore imply that, although the $(1+z)^{6\pm1}$ law is a reasonable representation for $z > 1.0$, its extrapolation to values of z much less than 1 is too drastic, and the proper density at the present epoch is rather larger than that law implies.

Second, we recall that the various $\psi(R)$ determinations are meaningful only if the distribution function of the ratio R per unit volume is epoch independent, as in the case of pure density evolution. Petrosian (1973) suggested the existence of two quasar populations, with

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[1] We note that the Schmidt result refers to samples of QSO's and QSS's which have different independent original selections. The first is selected on colour criteria; the second is selected mainly on positional coincidences with radio sources. In the present study there is a single selection which produces the optical sample, after which the selected objects are searched for radio emission. Therefore, no bias arising from different selections or uncompleteness can affect the result

the first dominating at low luminosities ($\log L_0 \approx 22$) and not evolving and with the second having a strong evolution and dominating at high optical luminosity. Schmidt (1976) has shown from the V/V_m test that radio quasars with flat radio spectrum exhibit a density evolution considerably less than those with normal or steep spectrum.

The existence of populations, among quasars, which undergo different cosmic evolution contradicts the hypothesis of pure density evolution. In that case, the $\psi(R)$ function obtained by our procedure would be some weighted average luminosity ratio function of the different populations in the range of the observed redshifts. In such a context, the two differing determinations shown in Figure 3 could be due to a different redshift range for the two samples.

On the basis of the QSO sample studied here, there is no evidence that $\psi(R)$ is changing with redshift, but the statistics are very poor. If, for instance, we consider QSO's with $z<0.6$, the fraction being radio sources with $\log R > 2.5$ is $(18 \pm 10)\%$, against the average value of $(13 \pm 5)\%$ for $z>0.6$. These two values are not significantly different, but the low statistical weight allows for a possible difference up to a factor 2.

In a continuing combined optical and radio effort, we intend to improve the statistical basis of the radio emission properties of optically selected quasars.

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