RADIO PROPERTIES OF OPTICALLY SELECTED HIGH-REDSHIFT QUASARS. I. VLA OBSERVATIONS OF 22 QUASARS AT 6 cm

DONALD P. SCHNEIDER
Institute for Advanced Study, Princeton, New Jersey 08540

J. H. VAN GORKOM
Columbia University, 538 West 120th Street, New York, New York 10027

MAARTEN SCHMIDT
Palomar Observatory, California Institute of Technology, Pasadena, California 91125

JAMES E. GUNN
Princeton University Observatory, Princeton, New Jersey 08544
Received 18 November 1991; revised 28 January 1992

ABSTRACT

A total of 22 optically selected high-redshift ($z > 3.1$) quasars have been observed at 5 GHz (6 cm) with the VLA. The measured radio properties of low-redshift optically selected quasars indicate that we should have detected radio emission from $\approx$5–10 objects in our sample, but only one quasar ($z = 4.093$) has a radio flux above our 5σ limit of $\approx$0.2 mJy.

1. INTRODUCTION

With the interpretation of quasars as intrinsically luminous sources of optical and radio emission (Schmidt 1963), it seemed likely that it would be just a matter of time before the most distant quasar would surpass the maximum redshift known for galaxies [the remarkable measurement of $z = 0.4614$ for 3C 295 by Minkowski (1960)]. This expectation was realized a year later by the discovery of 3C 147 ($z = 0.545$; Schmidt & Matthews 1964). Over the subsequent two and a half decades, quasars have not relinquished the position of being our most distant discrete probes of the Universe, and until recently [the discovery of $z \approx 3$ radio galaxies; see Chambers *et al.* (1988) and Lilly (1988)] were not even challenged for this role. Detection of ever more distant quasars has yielded a rich scientific return to date; the very existence of these objects places strong constraints on the quasar energy source and on models of galaxy formation (see Turner 1991), and high resolution spectra of distant quasars permits one to study the properties of the intergalactic medium at early epochs (e.g., Jenkins & Ostriker 1991).

Table 1 gives a condensed history of the rise of the maximum known quasar redshift as a function of time. (We use the date of publication of the discovery paper to determine precedence; sorting out unpublished claims requires rather more effort than we deem worthwhile for the purpose of this exercise.) There are four eras in this chronicle of the maximum known quasar redshift: (1) An initial rapid rise from 1963–65 (over a factor of 10 in two years!); (2) a slow but steady increase over the next eight years; (3) a long period of stagnation when $z_{\rm max}$ increased but once in a thirteen year span; and (4) a resumation of the slow, steady increase between 1986–91. The most striking feature in Table 1, however, is the change in the nature of the most distant known quasar; before 1985, each of the objects in Table 1 was initially found via its radio emission, while all of the post-1985 entries were discovered by optical observations and have not yet been detected at radio wavelengths.

Some of the features of this radio/optical dicotomy are easy to understand. Strong radio emission was one of the early defining characteristics of quasars; not until two years after the initial discovery was there much serious discussion of a large population of radio quiet quasars (Sandage 1965). There has been a tremendous advance in the sensitivities of optical surveys since the mid-1960's (particularly at "red"

TABLE 1. Highest known quasar redshift.

Quasar	$z_{\rm max}$	Month–Year	Reference
3C 273	0.158	03–1963	1
3C 48	0.367	03–1963	2
3C 147	0.545	02–1964	3
3C 9	2.012	04–1965	4
PKS 0106+01	2.107	02–1966	5
PKS 1116+12	2.118	04–1966	6,7
PKS 0237−23	2.223	02–1967	8
4C 25.05	2.358	06–1968	9
5C 02.56	2.390	12–1968	10
4C 05.34	2.877	05–1970	11
OH 471	3.40	04–1973	12
OQ 172	3.53	06–1973	13
PKS 2000−330	3.78	09–1982	14
Q 1208+1011	3.80	07–1986	15
Q 0046−293	4.01	01–1987	16
PC 0910+5625	4.036	10–1987	17
Q 0051−279	4.43	12–1987	18
PC 1158+4635	4.733	12–1989	19
PC 1247+3406	4.897	09–1991	20

References: (1) Schmidt 1963; (2) Greenstein and Matthews 1963; (3) Schmidt and Matthews 1964; (4) Schmidt 1965; (5) Burbidge 1966; (6) Schmidt 1966; (7) Lynds and Stockton 1966; (8) Arp *et al.* 1967; (9) Schmidt and Olsen 1968; (10) Burbidge 1968; (11) Lynds and Wills 1970; (12) Carswell and Strittmater 1973; (13) Wampler *et al.* 1973; (14) Peterson *et al.* 1982; (15) Hazard *et al.* 1986; (16) Warren *et al.* 1987a; (17) Schmidt *et al.* 1987b; (18) Warren *et al.* 1987b; (19) Schneider *et al.* 1989b; (20) Schneider *et al.* 1991b.

 0004-6256/92/051451-06$00.90

wavelengths), so it is not surprising that many of the later entries in Table 1 were found in optical surveys. The recent prevalence of optical discoveries, however, was by no means predicted when the first $z>3$ quasars were discovered. Kraus & Gearhart (1975) found that the fraction of centimeter excess (CE) quasars (the radio spectrum peaks at centimeter wavelengths) increased with redshift. The most distant quasars known at that time were CE sources, and these quasars would remain CE objects up to a redshift of 5 or more; the implication of this result was that future advances in z_{max} would continue to come via radio observations. A possible explanation of why this prediction failed to be fulfilled is that there is some significant change in the radio properties of quasars at large redshift.

One approach to determine the evolution of radio emission of quasars is to compare the radio luminosity function of optically selected quasars at various redshifts. Kellerman *et al.* (1989) have recently published an extensive VLA survey of a complete sample of low-redshift, optically selected quasars (from Schmidt & Green 1983). Miller *et al.* (1990) used the VLA to investigate the radio properties of over 100 optically selected quasars with $1.8<z<2.5$, and McMahon (1991) discusses the preliminary results of a VLA survey of quasars with $z>3.5$. The latter two studies present evidence that the fraction of optically selected quasars that are "radio loud" declines with redshift. In this paper we describe VLA observations of 22 optically selected quasars with $z>3.1$. Absolute properties will be calculated with $H_0=50$ km s^{-1} Mpc^{-1} and $q_0=0.5$. The radio (α_R) and optical (α_O) spectral energy indices are defined such that the flux density is proportional to (frequency)$^{\alpha}$.

2. OBSERVATIONS

2.1 Sample Selection

The 22 quasars that comprise our VLA high-redshift survey are listed in Table 2. These sources do not represent a complete sample of distant optically selected quasars, but they should be an unbiased set as far as the radio properties are concerned. This sample was drawn up in two stages. The first step was to include all of the quasars known to us in early 1990 with $z>4$ and $M_B>-28$; this produced a list of 13 quasars. Table 2 gives the discovery technique of each quasar. Of the 13 highest redshift objects, 12 were found by surveys designed to detect $r\approx20$ quasars with redshifts greater than three over relatively large (≈60 sq. deg) areas using either multicolor direct images from photographic plates or CCD grism spectra. The astonishing serendipitous discovery of the other $z>4$ object, Q2203+29, is discussed by McCarthy *et al.* (1988). This set of 13 quasars includes one broad absorption line object (Q0051−279).

The final nine objects were selected from the 4-Shooter CCD grism survey [see Schmidt *et al.* (1987a) and refer-

TABLE 2. High redshift VLA sample.

Quasar	R.A. (1950.0)	Dec.	z	$AB_{1450(1+z)}$	M_B	$S_{6cm}(\max)^a$	$S_{6cm}(\min)^a$	1σ Noise^a	Ref
Q 0046−293	00 46 03.5	−29 19 42	4.014	19.26	−26.96	107	−127	39	1
Q 0051−279	00 51 49.8	−27 58 24	4.402	19.21	−27.16	114	−75	44	2
Q 0101−304	01 01 14.1	−30 25 04	4.072	19.98	−26.27	89	−110	48	2
PC 0104+0215	01 04 15.0	+02 15 00	4.171	19.67	−26.61	107	−96	41	3
PC 0307+0222	03 07 15.4	+02 22 00	4.379	19.92	−26.44	94	−119	40	3
PC 0344+0222	03 44 22.6	+02 22 29	3.377	20.09	−25.86	105	−115	40	4
PC 0345+0130	03 45 27.0	+01 30 08	3.638	19.49	−26.58	85	−101	35	4
PC 0751+5623	07 51 40.7	+56 23 06	4.281	19.65	−26.67	92	−77	39	3
PC 0910+5625	09 10 57.3	+56 25 49	4.035	20.86	−25.37	67	−92	39	5
PC 0953+4749	09 53 13.3	+47 49 00	4.457	19.09	−27.30	151	−87	40	4
PC 1158+4635	11 58 02.9	+46 35 29	4.733	19.62	−26.86	58	−101	40	6
PC 1233+4752	12 33 08.3	+47 52 37	4.447	20.11	−26.27	77	−117	39	4
PC 1301+4747	13 01 50.8	+47 47 35	4.004	21.32	−24.90	83	−119	40	4
PC 1548+4637	15 48 32.9	+46 37 56	3.544	19.07	−26.96	106	−81	39	4
PC 1619+4631	16 19 51.3	+46 31 25	3.471	20.54	−25.45	85	−148	40	4
PC 1640+4628	16 40 37.2	+46 28 01	3.700	19.29	−26.80	101	−92	41	4
PC 1643+4631A	16 43 33.5	+46 31 38	3.790	20.05	−26.08	70	−118	41	4
PC 1643+4631B	16 43 52.4	+46 31 02	3.831	20.35	−25.80	95	−109	45	4
PC 2047+0123	20 47 50.7	+01 23 56	3.799	19.23	−26.91	105	−91	40	4
PC 2132+0126	21 32 37.9	+01 26 06	3.194	19.69	−26.17	76	−108	27	4
Q 2203+29	22 03 47.0	+29 15 24	4.399	20.41	−25.96	131	−155	65	7
PC 2331+0216	23 31 58.5	+02 16 47	4.093	19.84	−26.41	3300	−101	45	3

References: (1) Warren *et al.* 1987a; (2) Warren *et al.* 1987b; (3) Schneider, Schmidt, and Gunn 1989a; (4) Schneider, Schmidt, and Gunn 1991a; (5) Schmidt, Schneider, and Gunn 1987b; (6) Schneider, Schmidt, and Gunn 1989b; (7) McCarthy *et al.* 1988.

[a] Radio fluxes in μJy; the first two columns are the maximum and minimum noise peaks in a 3″ wide box centered on the quasar position.

ences therein] based on the following criteria: (1) Quality of Optical Spectra. High signal-to-noise moderate resolution spectra have been published for each of the $z>4$ quasars (for some examples see Schneider *et al.* 1989a). Similar data have been published for nineteen $3.1<z<4.0$ quasars as part of a project to extend the study of Lyman α absorption in quasars at these redshifts (Schneider *et al.* 1991a). This set of 19 quasars forms the base from which the rest of the VLA sample is drawn. (2) Right ascension. The R.A. distribution of the $z>4$ quasars is not very uniform, so lower redshift quasars located in the R.A. gaps were selected in order to make efficient use of a continuous block of VLA time. (3) Redshift. Whenever there were more quasars satisfying the two constraints at a given R.A. than the VLA program could accomodate, the objects with the lowest redshifts were dropped.

The final high-redshift VLA sample consists of 22 quasars. In Table 2 we list the position, redshift, $AB_{1450(1+z)}$ and M_B magnitudes (from Schneider *et al.* 1991a), and, in the last column, a finding chart reference. The redshifts in the sample vary from 3.194 to 4.733; only four of the sources have $z<3.5$. The observed optical magnitude in Table 1, $AB_{1450(1+z)}$, is the observed AB magnitude, corrected for Galactic reddening, at a wavelength $\lambda_{\rm obs}=1450(1+z)$ Å. [See Oke & Gunn (1983) for a discussion of the AB system; $AB=-2.5\log f_\nu-48.60$.] The absolute B magnitude is calculated using $AB_{1450(1+z)}$ and an optical spectral energy index of -0.5. The $AB_{1450(1+z)}$ and M_B magnitude ranges are 19.07 to 21.32 and -24.9 to -27.3, respectively. (In our adopted cosmological model 3C 273 has $M_B=-27.0$.)

2.2 *VLA Observations*

The VLA observations were made on 11/12 May 1990 with the east and north arms in the 30 km (A) configuration and the west arm in the 10 km (B) configuration; this yields longest and shortest spacings of 36.4 and 0.21 km, respectively. A description of the VLA is given by Napier *et al.* (1983). The observations were made at 4885.1 MHz employing a total bandwidth of 100 MHz. Each quasar was observed for 50 min; short observations of phase calibrators were interspersed every 20 min. The data were calibrated with flux standards 3C 286, 3C 48, and 3C 147 (Baars *et al.* 1977). Natural weighted images 77″ on a side were constructed for each of the quasars; larger images were made when there were strong sources near the edge of the field. The images were CLEANed using the AIPS routine MX and restored with a Gaussian beam, typically with a FWHP of 0.65″. The rms noise in all but one of the CLEANed images lies between 35 and 40 μJy; these measurements are close to the theoretical value. The measured rms noise in the 2203 + 29 data is about 50% higher than that seen in the other 21 observations; this difference arises because of the limited dynamic range in this field caused by the proximity of 3C 441 (see McCarthy *et al.* 1988).

The uncertainties in the positions of the quasars ($\approx 1.5''$) are considerably larger than the size of the synthesized beam (0.65″). Thus we cannot present a measured value of the radio flux at the position of the quasar. Table 2 lists the rms noise in each field and the maximum and minimum values found in the 3″ wide error box. For all but one of the quasars the maximum and minimum values in the box agree with what is expected from a Gaussian noise distribution. The maximum detected flux for one quasar, PC 2331 + 0216, is nearly 100 times larger than the rms noise; this is our only detection. The radio and optical positions for PC 2331 + 0216 ($z=4.093$) agree within the uncertainties of the measurements. (Radio position (1950.0): R.A. $23^{\rm h}31^{\rm m}58.6^{\rm s}$, Dec $+02°\ 16'\ 46.0''$; positional uncertainty $\approx 0.1''$.) The radio emission is unresolved in the data. The density of background sources in the images indicates that this radio detection (3.3 mJy) is almost certainly to be identified with the optical quasar.

One must note that only sources with structure on scales smaller than 15″ (≈ 100 kpc at $z=4$) can be detected with this configuration of the VLA.

3. DISCUSSION

Figure 1 displays the relationship between the absolute radio and optical luminosity of the low- (crosses; Kellerman *et al.* 1989), intermediate- (diamonds; Miller *et al.* 1990) and high- (circles; this paper) redshift samples. (Only the sources with $M_B<-23$ are shown.) The radio luminosities are calculated with $\alpha_{\rm R}=-0.5$. Measurements with arrows are 5σ upper limits to the radio luminosity. The upper limits for the Kellerman *et al.* nondetections are calculated assuming an rms error of 0.065 mJy. Since the angular resolution in our data is much higher, on average, than that in the low-redshift observations, we have used only the "core" fluxes from the Kellerman *et al.* measurements. [Despite the large difference in redshift between the samples ($\approx$0.5–4), the physical scales (kpc arcsec^{-1}) are nearly identical.]

The bimodal structure of the low-redshift sample (discussed in Kellerman *et al.* and Miller *et al.*) is readily evident in this figure: the majority of the objects are "radio quiet"; a sizable minority, from around a quarter up to nearly one half of the sources (a fraction that strongly depends on optical luminosity), are "radio loud", and a few objects lie between the two populations. The one radio detection in the high-redshift sample indicates that PC 2331 + 0216 is a typical radio loud quasar; it is a luminous radio source, but by no means an extreme one. The upper limits for the intermediate- and high-redshift samples lie in a line at $\log L_\nu$(6 cm)≈ 25 that is about a factor of 3 fainter than the radio loud branch. Figure 2 shows the relationship between redshift and 6 cm luminosity for the quasars in Fig. 1 with $M_B<-24.0$; the three datasets are represented by the same symbols as in Fig. 1.

Unless we have been unfortunate in the selection of our observational parameters (i.e., we barely missed detecting several objects), it is unlikely that the low-, intermediate-, and high-redshift samples have the same optical/radio properties given in our model of a constant $\alpha_{\rm R}$. Approximately 25% of the low-redshift objects brighter than $M_B=-24.0$ have radio luminosities brighter than our observational limit; we would have expected to detect five or six quasars, not one, with our VLA measurements. If one constrains the optical luminosity to $-27.5<M_B<-25.25$, the region that contains 21 out of 22 high-redshift objects, then $\approx 50\%$ of our sources should have been detected if they had the same properties as the low-redshift sample.

Looking at the material in a different way, assume that one-third of quasars at all redshifts are radio loud; we would then have detected, on average, seven high-redshift quasars in the VLA observations. Using the binomial distribution, the probability of finding only 0 or 1 radio loud quasars is less than 1%. Taking an extreme case, suppose that the radio

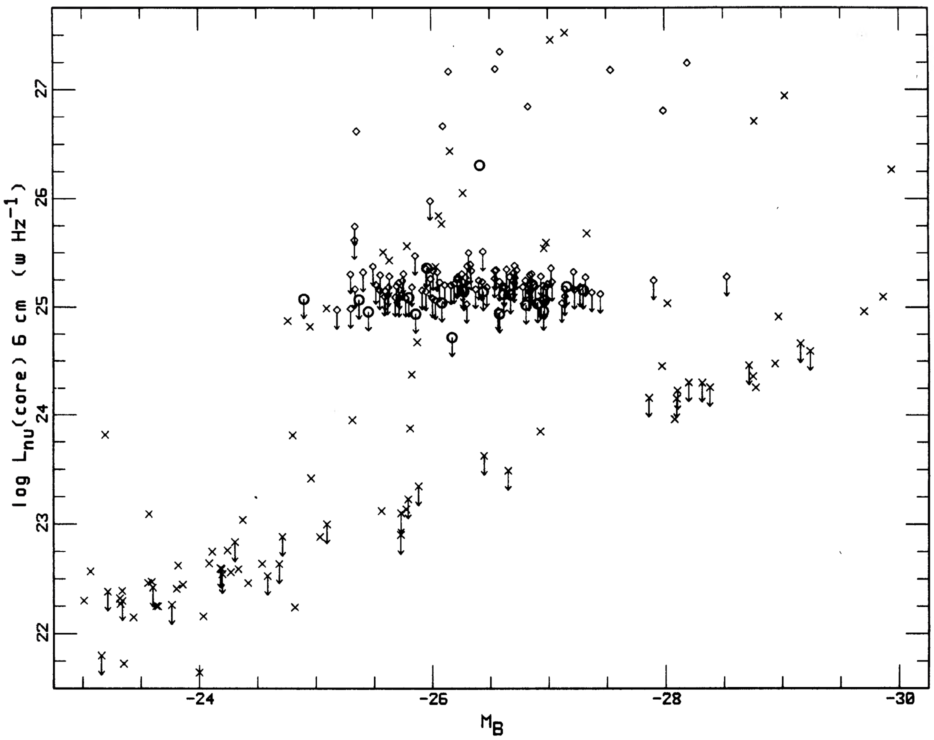

FIG. 1. The relation between absolute luminosities in the optical (B band) and the radio (6 cm) for the sources in Kellerman *et al.* (crosses), Miller *et al.* (diamonds), and the high-redshift quasars in our sample (circles). Measurements with arrows are 5σ upper limits.

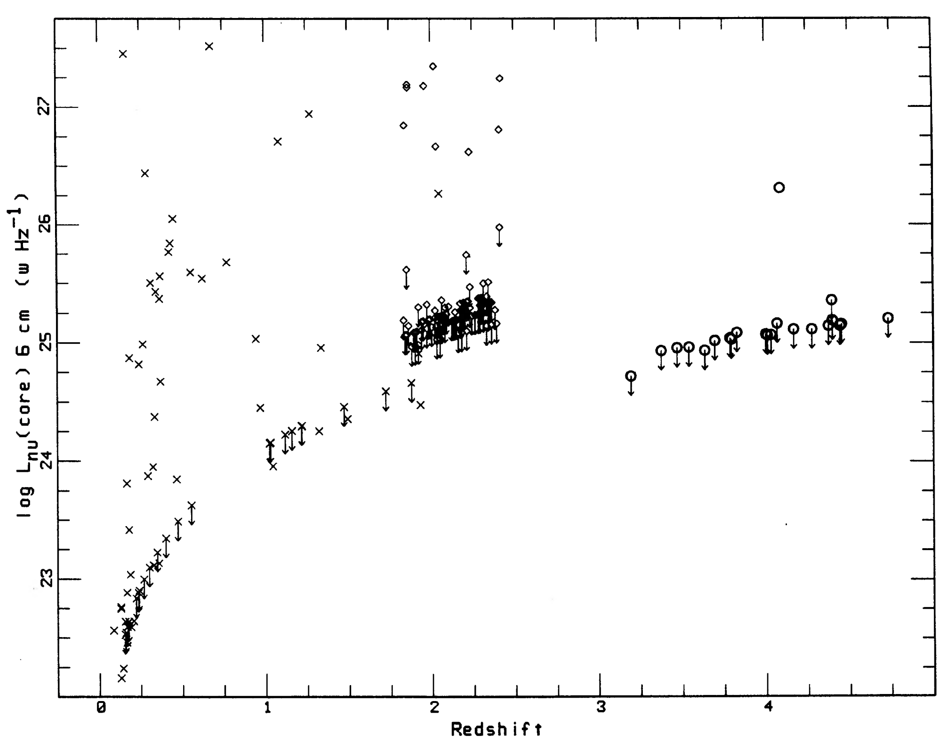

FIG. 2. The relation between redshift and radio luminosity for the objects in Fig. 1 with $M_B < -24.0$. The three datasets are represented by the same symbols as in Fig. 1; arrows indicate 5σ upper limits.

loud fraction at all redshifts is 20%; the chance that we would detect 0 or 1 in the high-redshift sample is $\approx 5\%$.

We are aware of one other published radio observation of a $z > 4$ object. The $z = 4.098$ quasar Q0000 − 2619 was observed at 6 cm with the *D* configuration of the VLA; no radio emission was found down to a 5σ limit of 0.8 mJy (Turnshek *et al.* 1991). In the preliminary summary of his high-redshift ($z > 3.5$) VLA survey, McMahon (1991) reported detection of four out of 29 high-luminosity ($M_B < -26$) quasars in his sample. McMahon's observations were performed at 6 cm in the *D* configuration of the VLA; the 5σ limits on the radio emission were ≈ 0.8 mJy.

To attempt to quantify the evolution of radio properties of optically selected quasars as a function of redshift, we have made the following assumptions/definitions: (1) All quasars with a radio luminosity larger than some value are radio loud, otherwise they are radio quiet; (2) all nondetections have radio luminosities equal to the 2σ measurement limit; and (3) the quasars have been divided into three redshift bins ($z < 1.5$, $1.5 < z < 3.0$, and $z > 3.0$; this corresponds closely, but not exactly, to the three datasets described above). Figure 3 shows the fraction of quasars that are radio loud as a function of redshift using $\log L_\nu(6\,\mathrm{cm}) = 25.25$ as the division between radio loud and radio quiet quasars. This value was selected because it is slightly larger than all but one of the 5σ limits of the $z > 3$ measurements and it lies above most of the 5σ limits for the Miller *et al.* quasars (see Fig. 2). The fraction of radio loud quasars for three lower limits of the optical luminosity is displayed in Fig. 3. The error bars for the low- and intermediate-redshift measurements are the square root of the variance {if f is the fraction of radio loud quasars based on N measurements, then the variance in f is $[f(1-f)]/N$}. The errors for the high-redshift points, which are all based on but one radio detection, are the 68% confidence limits calculated by extending the procedure for low-signal poisson distributions described in Regener (1951) to the binomial distribution.

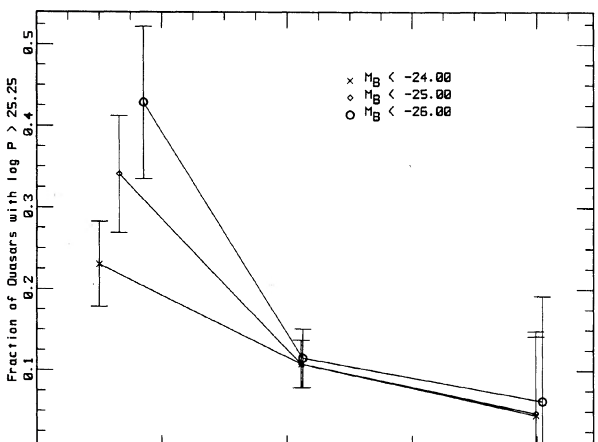

FIG. 3. The measurements in Fig. 1 have been broken down into three redshift bins to show the fraction of "radio loud" [$\log L_\nu(6\,\mathrm{cm}) > 25.25$] quasars as a function of redshift. See text for detailed description.

Changing the $\log L_{6\,\mathrm{cm}}$ radio loud cutoff level between 25.0 and 25.75 does not radically modify the shape of the relations shown in Fig. 3. The high-redshift points are unchanged, the intermediate redshift fractions vary from 0.15 ($M_B < -26$, $\log L_{6\,\mathrm{cm}} = 25.0$) to 0.09 ($M_B < -24$, $\log L_{6\,\mathrm{cm}} = 25.75$), and the low-redshift points range from 0.46–0.12. Only the case of $M_B < -24$, $\log L_{6\,\mathrm{cm}} = 25.75$ is reasonably consistent with no evolution of the radio properties.

Our data support the results of Miller *et al.* as well as that of McMahon: the fraction of optically selected quasar that are radio loud does seem to decline at redshifts above one. Our measurement of the radio loud fraction at $z > 3$ is smaller (by a factor of ≈ 3) than that reported by McMahon; this difference, however, is not significant when one considers the statistical uncertainties of the results. Our observations do not provide significant evidence that the fraction of radio loud quasars declines between redshifts of 2–4.

There are a number of plausible explanations for the decline with redshift. Perhaps high-redshift quasars are, on average, much less luminous in the radio than their low-redshift counterparts. It is also possible that the populations are the same, but that the spectrum of the quasar steepens at rest wavelengths below 6 cm. Since the datasets presented in Fig. 1 are all observed at 6 cm, the redshift difference between the samples translates into a large change in the rest region of the spectrum that is sampled. The low-redshift data are observed at rest wavelengths of 3–5 cm, whereas the high-redshift observations are performed at $\lambda_{\mathrm{rest}} \approx 1.2$ cm. If the flux at 1.2 cm is a factor of 3 less than expected based on an extrapolation of the $\alpha_{\mathrm{R}} = -0.5$ power law ($\alpha_{\mathrm{R}} \approx -1.4$ between 1.2 and 4 cm), the properties of the two samples could be reconciled. Values of q_0 larger than 0.5 decrease the difference between the high- and low-redshift datasets; the high-redshift points in Fig. 1 move down and to the left relative to the Kellerman *et al.* measurements as q_0 is increased. Even the choice of $q_0 = 1$, however, does not completely remove the discrepancy. In any case, it is clear that the current database is much too meager to do much more than peak one's interest; larger radio surveys at several frequences must be undertaken to resolve these issues.

We are grateful to an anonymous referee for several useful suggestions on the manuscript. We thank the NRAO for generous allocation of observing time. NRAO is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation. This work was supported in part by National Science Foundation Grant Nos. AST89-17744 (J.H.vG.), AST87-15508 (M.S.), and AST86-18257A02 (J.E.G.) and NASA Contract No. NAG5-1618 (D.P.S.).

REFERENCES

Arp, H. C., Bolton, J. G., & Kinman, T. D. 1967, ApJ, 147, 840
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., & Witzel, A. 1977, A&A, 61, 99
Burbidge, E. M. 1966, ApJ, 143, 612
Burbidge, E. M. 1968, ApJ, 154, L109
Carswell, R. F., & Strittmatter, P. A. 1973, Nature, 242, 394
Chambers, K. C., Miley, G. K., & van Breugel, W. J. M. 1988, ApJ, 327, L47

Greenstein, J. L., & Matthews, T. A. 1963, Nature, 197, 1040
Hazard, C., McMahon, R. G., & Sargent, W. L. W. 1986, Nature, 322, 38
Jenkins, E. B., & Ostriker, J. P. 1991, ApJ, 376, 33
Kellerman, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. F. 1989, AJ, 98, 1195
Kraus, J. D., & Gearhart, M. R. 1975, AJ, 80, 1
Lilly, S. J. 1988, ApJ, 333, 161
Lynds, C. R., & Stockton, A. N. 1966, ApJ, 144, 446
Lynds, R., & Wills, D. 1970, Nature, 226, 532
McCarthy, P. J., Dickinson, M., Filippenko, A. V., Spinrad, H., & van Breugel, W. J. M. 1988, ApJ, 328, L29
McMahon, R. G. 1991, in The Space Distribution of Quasars, edited by D. Crampton (Brigham Young University, Provo, UT), p. 129
Miller, L., Peacock, J. M., & Mead, A. R. G. 1990, MNRAS, 244, 207
Minkowski, R. 1960, ApJ, 132, 908
Napier, P. J., Thompson, A. R., & Ekers, R. D. 1983. Proc. IEEE, 71, 1295
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Peterson, B. A., Savage, A., Jauncey, D. L., & Wright, A. E. 1982, ApJ, 260, L27
Regener, V. H. 1951, Phys. Rev., 84, L161
Sandage, A. 1965, ApJ, 141, 1560
Schmidt, M. 1963, Nature, 197, 1040
Schmidt, M. 1965, ApJ, 141, 1295
Schmidt, M. 1966, ApJ, 144, 443
Schmidt, M., & Green, R. F. 1983, ApJ, 269, 753
Schmidt, M., & Matthews, T. A. 1964, ApJ, 139, 781
Schmidt, M., & Olsen, E. T. 1968, AJS, 73, S117
Schmidt, M., Schneider, D. P., & Gunn, J. E. 1987a, ApJ, 316, L1
Schmidt, M., Schneider, D. P., & Gunn, J. E. 1987b, ApJ, 321, L7
Schneider, D. P., Schmidt, M., & Gunn, J. E. 1989a, AJ, 98, 1507
Schneider, D. P., Schmidt, M., & Gunn, J. E. 1989b, AJ, 98, 1951
Schneider, D. P., Schmidt, M., & Gunn, J. E. 1991a, AJ, 101, 2004
Schneider, D. P., Schmidt, M., & Gunn, J. E. 1991b, AJ, 102, 837
Turner, E. L. 1991, AJ, 101, 5
Turnshek, D. A., Macchetto, F., Bencke, M. V., Hazard, C., Sparks, W. B., & McMahon, R. G. 1991, ApJ, 382, 26
Wampler, E. J., Robinson, L. B., & Baldwin, J. A. 1973, Nature, 243, 336
Warren, S. J., Hewett, P. C., Irwin, M. J., McMahon, R. G., Bridgeland, M. T., Bunclark, P. S., & Kibblewhite, E. J. 1987a, Nature, 325, 131
Warren, S. J., Hewett, P. C., Osmer, P. S., & Irwin, M. J. 1987b, Nature, 330, 453