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Discovery of radio-loud quasars with $z=4.72$ and $z=4.01$

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ABSTRACT

We report the discovery of two radio-loud quasars with redshifts greater than 4: GB1428 + 4217, with $z=4.72$, and GB1713 + 2148 with $z=4.01$. This doubles the number of published radio-selected quasars with $z>4$, bringing the total to 4. GB1428 + 4217 is the third most distant quasar known and the highest redshift radio and X-ray source currently known. It has a radio flux density at 5 GHz of 259 ± 31 mJy and an optical magnitude of $R \sim 20.9$. The rest frame absolute UV magnitude, $M_\nu(1450\,\text{Å})$, is -26.7, similar to that of the archetypal radio-selected quasar 3C273 [$z=0.158$; $M_\nu(1450\,\text{Å})=-26.4$]. GB1428 + 4217 is tentatively detected in *ROSAT* PSPC observations, which has been confirmed by more recent *ROSAT* observations described in a companion paper by Fabian et al. Both quasars were discovered during the CCD imaging phase of an investigation into the evolution of the space density of radio-loud quasars at high redshift. Combined with our earlier survey results, these objects give a lower limit on the space density of quasars with radio power $P_{5\,\mathrm{GHz}} > 5.8 \times 10^{26}$ W Hz^{-1} sr^{-1} between $z=4$ and $z=5$ of $1.4 \pm 0.9 \times 10^{-10}$ Mpc^{-3}. This can be compared to $2.9 \pm 0.2 \times 10^{-10}$ Mpc^{-3} at $z=2$ from Dunlop & Peacock for flat-spectrum sources of the same luminosity.

Key words: quasars: general – quasars: individual: GB1428 + 4217 – quasars: individual: GB1713 + 2148.

1 INTRODUCTION

In two recent papers we have described results from the first phase of a survey for high-redshift, radio-loud quasars (Hook et al. 1995, 1996). Our approach involves the optical identification of flat spectrum radio sources and the spectroscopic follow-up of the red stellar identifications. This approach exploits the observation that quasars at high redshift have redder optical colours than their low-redshift counterparts because of absorption by intervening H I (see fig. 1 in Hook et al. 1995).

Our aim is to study the evolution of the quasar population at high redshift, using a well-defined, statistically complete sample. Whilst radio-loud quasars are only a small subset of the quasar population, the selection of radio-loud quasars is less prone to selection effects than is that of optical samples, since the spectral energy distribution of radio sources is smooth and radio emission is unaffected by either intrinsic or extrinsic absorption due to dust. See Fall & Pei (1993) for a discussion of how dust within intervening galaxies may affect the observed evolution in optically selected samples of quasars. Our work complements the numerous investigations into the redshift evolution of the space density of radio-quiet quasars (e.g. Hall et al. 1996; Hawkins & Veron 1996; Irwin, McMahon & Hazard 1991; Kennefick, Djorgovski & De Carvalho 1996; Schmidt, Schneider & Gunn 1995; Warren, Hewett & Osmer 1994).

Our earlier work was restricted to sources that were detected on Automated Plate Measurement (APM) scans of POSS-I plates and hence was incomplete for optically fainter quasars. Since it is our aim to determine the evolution of the space density of high-redshift quasars independent of optical selection effects, we have now begun CCD imaging of sources that were not detected on the POSS-I plates.

Throughout this paper we have assumed cosmological constants of $H_0=50$ km s^{-1} Mpc^{-1} and $q_0=0.5$.

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2 THE RADIO SAMPLE AND THE OPTICAL IDENTIFICATION PROCEDURE

The parent radio sample used in this study consists of ~ 1600 flat-spectrum ($\alpha_{1.4\,GHz}^{5\,GHz} \geq -0.5$, $S \propto \nu^{\alpha}$) radio sources with $S_{5\,GHz} > 0.2$ Jy studied with the VLA by Patnaik et al. (1992). Initial optical identification of the radio sources was carried out using the APM facility at Cambridge. Further details of this program and the procedures can be found in Hook et al. (1995, 1996).

For the second phase of the survey, we have concentrated on the radio sources with no APM/POSS-I identification within a search radius of 3.0 arcsec. The area studied lies in the region with $9^h50' < \alpha$(B1950) $< 17^h45'$, $20° < \delta$(B1950) $< 75°$, ($|b| > 10°$ for 0^h to 12^h and $|b| > 30°$ for 12^h to 24^h), an area of 1.27 sr containing 526 sources. There were 82 blank fields with $S_{5\,GHz} > 0.2$ Jy in this region, after our earlier work. Of these, 16 had redshifts from other sources prior to the start of this project (NED;[1] Vermeulen et al. 1996; Vermeulen, private communication).

An unbiased subsample of 38 of the remaining 66 sources were imaged during one week (1995 May 29 to June 4) at the prime focus of 2.5-m Isaac Newton Telescope (INT), La Palma. We used the 1024 × 1024 pixel thinned TEK CCD with a projected pixel size of 0.59 arcsec. Mould *B* and *R* filters (the 'Kitt-Peak' set at La Palma) were used with 300-s exposures in *R* and 600-s exposures in *B*, and typically reaching limiting magnitudes of $R = 23$ mag, $B = 24$ mag.

Photometric calibration was carried out using observations of the photometric standard star fields from Landolt (1992). The data were reduced using standard procedures with the IRAF[2] software environment including photometry using the DAOPHOT package (Stetson 1990).

After this INT imaging, 10 sources are still blank in the *R* band, i.e. they had no optical counterpart within a radius of 3 arcsec (*K*-band imaging of these sources is being obtained). A colour–magnitude diagram for the 28 objects detected in *R* is shown in Fig. 1.

Thus, after the INT imaging, the fraction of sources observed is 38/66 = 0.58. To estimate in a fair manner the effective area observed, we include the same fraction (9 out of 16) of the sources with previously known redshifts. The effective area is then 0.58 × 1.27 sr = 0.73 sr. Scaling from the original 526 radio sources in 1.27 sr, there are 302 radio sources in this sub-area of which all but 10 (3 per cent) are now identified.

3 SPECTROSCOPIC OBSERVATIONS AND RESULTS

We have selected for spectroscopic follow-up a complete sample of the 12 stellar identifications with $B - R \geq 1.0$. Redshifts became available for 3 of the 12 selected objects prior to the spectroscopic phase of this study (Vermeulen, private communication), including the $z = 3.82$ quasar GB1239 + 3736 (Vermeulen et al. 1996). Seven of the other nine were observed at either the Shane 3-m telescope at Lick Observatory or the 4.2-m William Herschel Telescope (WHT), La Palma. The Lick spectra were obtained using the KAST double spectrograph at its lowest resolution covering the range 5000–10 500 Å. The WHT spectra were obtained using the red arm of the ISIS double spectrograph. A 158 line mm^{-1} grating and a thinned TEK CCD with 1024 × 1024 24-μm pixels was used, giving a useful wavelength range of 5970–8940 Å at 2.9 Å pixel^{-1}.

Of the seven objects observed, one still has an inconclusive spectrum. Another (GB1712 + 4919) has a recently-published redshift of 1.552 (Falco, Kochaneck & Muñoz 1997), consistent with the single emission line seen in our spectrum being identified with Mg II. The spectrum of one other object also shows a single broad emission line (probably also Mg II) which we can rule out as being Lyman alpha (Lyα) at $z > 4$ by the lack of other strong emission lines or Lyα forest absorption. Here we give details for two objects, GB1428 + 4217 and GB1713 + 2148, which were identified as high-redshift quasars. The INT *B*- and *R*-band images of the two new $z > 4$ quasars are shown in Fig. 2.

GB1428 + 4217 ($z = 4.715 \pm 0.010$)

GB1428 + 4217 was first observed on 1996 July 16 on the 4.2-m WHT and then again on 1995 July 19 at a redder

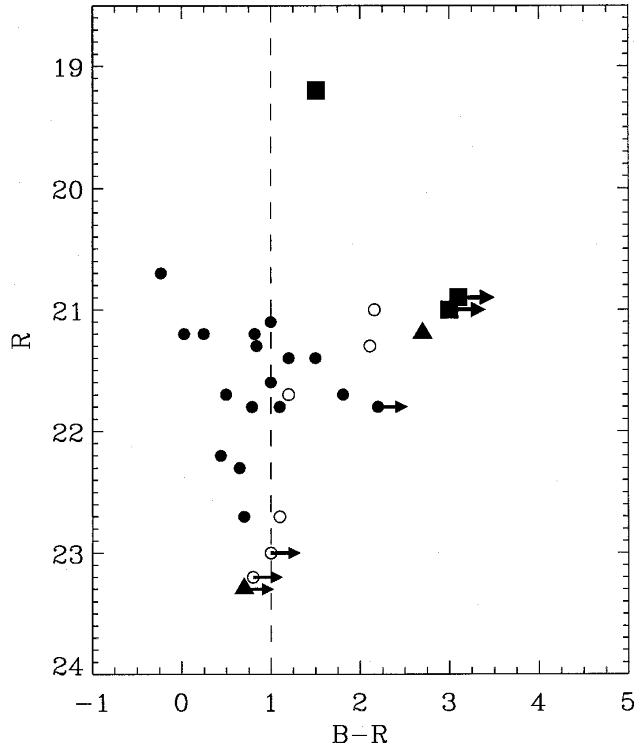

Figure 1. Colour–magnitude diagram from INT CCD identifications for the $S_{5\,GHz} > 0.2$ Jy flat-spectrum radio sample. Filled circles show unresolved sources; open circles represent galaxies. The squares show spectroscopically confirmed $z > 3$ quasars. The dashed line indicates the boundary used for the spectroscopic subsample. The filled triangles show the two objects in that sample for which a spectrum has yet to be obtained (see text).

[1]The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

[2]IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

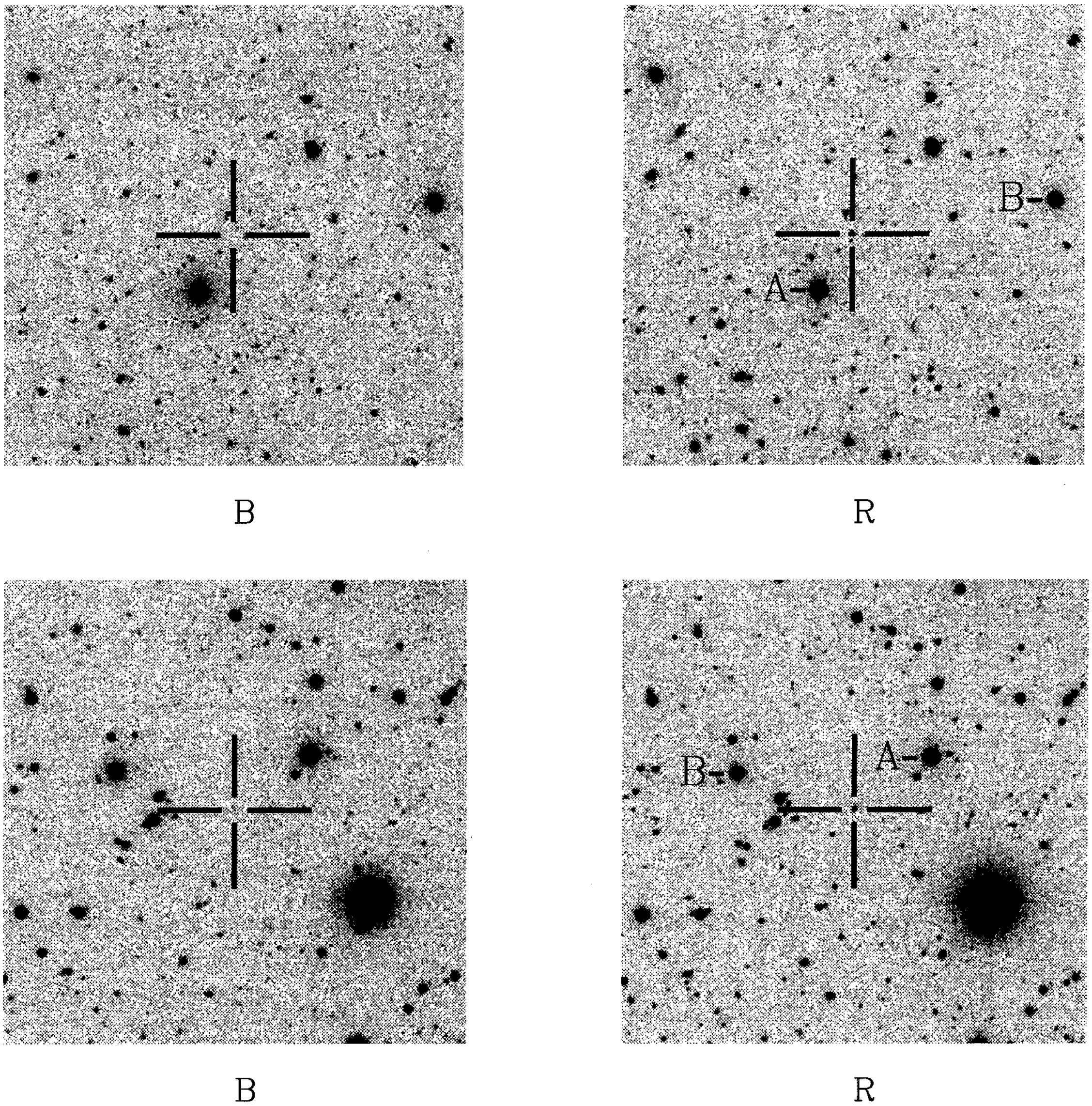

Figure 2. *B*- and *R*-band images, obtained at INT, of the two $z > 4$ quasars. The upper panels show GB1428 + 4217 and the lower panels show GB1713 + 2148. The central cross is 1 arcmin across. North is at the top, west to the right. The offsets ($\Delta\alpha$, $\Delta\delta$) in arcsec from the stars marked A and B to the quasars are as follows (positive $\Delta\alpha$ represents a move to the east from the offset star to the quasar, and positive $\Delta\delta$ represents a move to the north): GB1428 + 4217: from A to quasar (− 13.6, 22,3), from B to quasar (80.7, − 12.7); GB1713 + 2148: from A to quasar (30.2, − 19.9) from B to quasar (− 46.0, − 14.6).

wavelength grating setting in order to detect the C IV emission line. Broad emission lines of Lyα, N V, Si IV/O IV] and C IV are visible in the spectrum (Fig. 3). The observed centroids and equivalent widths are given in Table 1.

The Lyα line is visibly asymmetric because of absorption and it is therefore impractical to measure the line centroid. If one assumes that the absorption is the result of intervening H I, the blue edge of the line provides a lower limit to the redshift. The peak of the blue edge occurs at 6974 Å. The correction for instrumental resolution effects is ~3 Å, so assuming a value of 6971 Å for the Lyα edge gives a redshift of 4.734. It is quite common to observe velocity shifts between the emission lines in quasars and this redshift difference corresponds to a blue shift of 1420 km s^{-1} of C IV with respect to Lyα. This is significantly higher than the mean shift of 138 km s^{-1} derived by Tytler & Fan (1992) in their analysis of a sample of 160 quasars. We take the redshift of GB1428 + 4217 to be the mean of the three estimates.

On the night of 1996 July 19, both narrow and wide slit (7 arcsec) spectrophotometric observations of GB1428 + 4217 were obtained. The flux standard G138 − 31 (1625 + 0919; Filippenko & Greenstein 1984) was observed both prior to and immediately after the observations of GB1428 + 4217. These observations give a continuum flux at a rest wavelength of 1500 Å ($\lambda_{obs} = 8550$ Å) of 6.3×10^{-28} erg cm^{-2} s^{-1} Hz^{-1}. The corresponding continuum apparent magnitude and absolute magnitude on the AB system (Oke & Gunn 1983) are 19.4 and − 26.7 respectively. For comparison, from Hubble Space Telescope (HST) observations of the

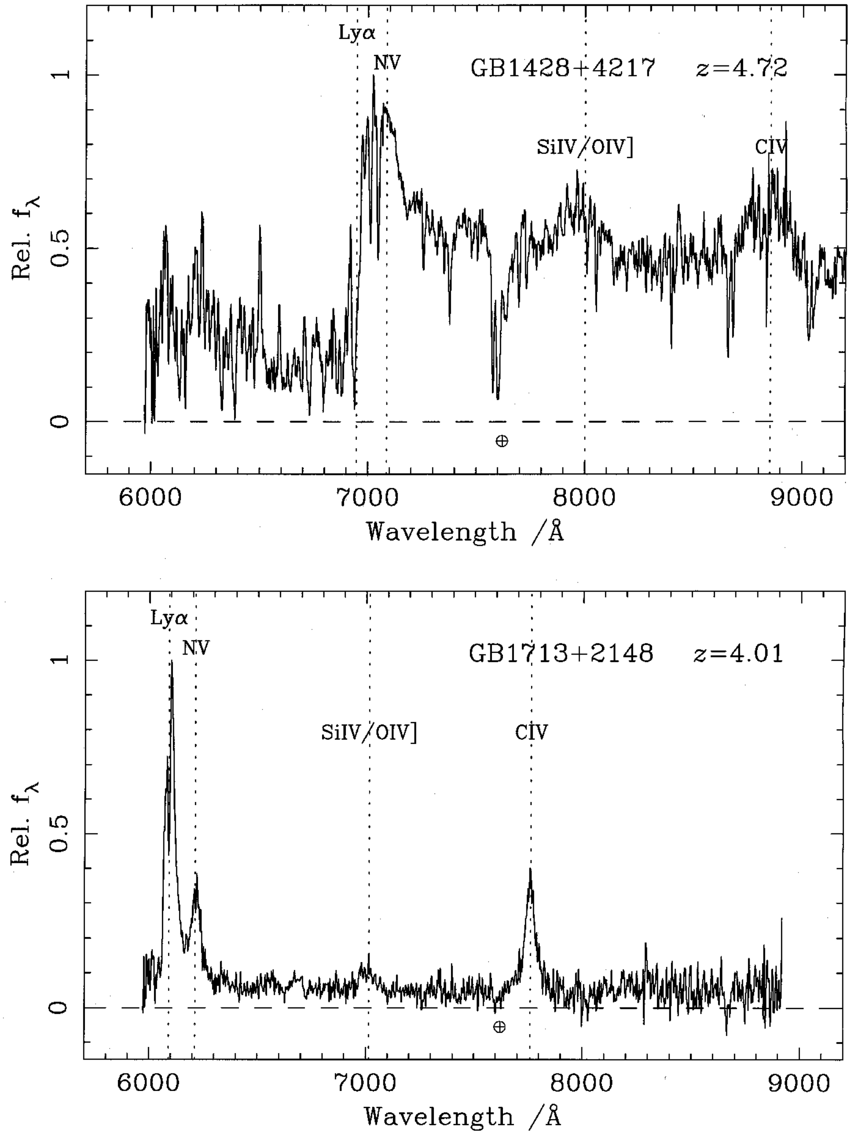

Figure 3. Optical spectra of the two $z > 4$ quasars.

Table 1. Properties of the new $z > 4$ quasars. Redshifts were measured as described in the text, assuming rest frame wavelengths for the emission lines as follows. Lyα: 1215.7; C IV: 1549.1; N V: 1240.1; S IV/O IV]: 1397.8 (see Tytler & Fan 1992). The radio fluxes are from Gregory & Condon (1991). The *R* and *B* magnitudes are accurate to 0.07 mag (rms) or better. * = Observed equivalent width measured for the Lyα–N V combination, *p* = wavelength measured from the peak rather than the centroid of line.

Name	Optical position α (B1950) δ	R mag	B − R mag	S_{5GHz} mJy	Feature	λ_{obs} Å	W_λ Å	z	$< z >$
GB1428+4217	14 28 26.74 +42 17 52.6	20.9	>3.40	259 ± 31	Lyα	6971^p	98*	4.734	
					NV				
					SiIV/OIV]	7972	48	4.707	
					CIV	8841	74	4.703	
									4.715±0.010
GB1713+2148	17 13 13.66 +21 48 51.4	21.0	>2.90	327 ± 44	Lyα	6098^p	536*	4.016	
					NV	6216^p		4.013	
					SiIV/OIV]	6999	94	4.008	
					CIV	7758	640	4.008	
									4.011±0.005

archetypal radio-selected quasar 3C273 ($z = 0.158$) (Bahcall et al. 1991) we find the continuum luminosity to be $M_v(1450) = -26.4$.

GB1713 + 2148 ($z = 4.011 \pm 0.005$)

The discovery spectrum of GB1713 + 2148 was obtained at the Lick 3-m telescope on UT 1996 May 23. It was re-observed at the WHT on 1996 July 16 for 1800 s to obtain a higher signal-to-noise spectrum, shown in Fig. 3. Broad emission lines of Lyα, N V, Si IV/O IV] and C IV are visible in the spectrum. Again, the Lyα line has visible absorption.

4 DISCUSSION

GB1428 + 4217 is the most distant radio-loud object known and the third highest redshift quasar known (behind PC1247 + 3406 at $z = 4.897$ and PC1158 + 4635 at $z = 4.73$; Schneider, Schmidt & Gunn 1989, 1991b).

GB1428 + 4217 has a tentative detection in the *ROSAT* All Sky Survey (Brinkman et al. 1997) and an archival PSPC pointing (WGACAT, the WGA catalogue of *ROSAT* PSPC point sources: White, Giommi & Angelini 1994). The extremely high apparent X-ray luminosity of this object and the possibility that the object is beamed are discussed in another letter (Fabian et al. 1997). In Fig. 4 we compare the equivalent widths of Lyα + N V for the four known $z > 4$ radio-selected quasars with other samples of $z > 4$ quasars. GB1428 + 4217 is notable in that it is among the lowest equivalent width objects. This is consistent with a scenario in which the continuum region is beamed. In addition, in contrast to the other three radio-loud $z > 4$ quasars, the emission lines are relatively broad.

After our INT and WHT observations, two of the 38 POSS-APM blank fields are quasars with $z > 4$, and 23 are ruled out as being at $z > 4$ quasars (either based on spectroscopic observations, or deduced from their blue $B - R$ colours or extended appearance on the CCD images). 10 are still unidentified and a further three of the CCD identifications still need conclusive spectra (one of these has an inconclusive WHT spectrum and two were not attempted). Clearly, it is important to determine the redshift status of these remaining 13 sources. Thus in an effective sub-area of 0.73 sr containing 302 sources, 97 per cent (all but 10) are optically identified and 96 per cent (all but 13) can be classified as being $z > 4$ quasar or otherwise.

Therefore we can derive a lower limit to the space density at $z > 4$ based on our sample, independently for any assumptions about the form of evolution. In an area of 0.73 sr, two objects with $z > 4$ were found among the CCD identifications. In our previous work we have found one $z > 4$ quasar among POSS-I identifications in an area of 3.66 sr (Hook et al. 1995) which scales to 0.2 objects in 0.73 sr. Thus a total of 2.2 ± 1.4 objects were effectively discovered in an area of 0.73 sr (where the uncertainties are from Poisson statistics).

At $z = 5$ the flux limit of our sample, $S_{5\,\mathrm{GHz}} = 0.2$ Jy, corresponds to a limiting radio power of 5.8×10^{26} W Hz^{-1} sr^{-1}, assuming a radio spectral index $\alpha = 0.0$. For objects brighter than this limit we derive a space density between $z = 4$ and $z = 5$ of $1.4 \pm 0.9 \times 10^{-10}$ Mpc^{-3}. If any of the 13 objects above are found to lie at $z > 4$, this space density estimate would be increased, hence it should be considered a lower limit.

This can be compared to the value at $z = 2$ from Dunlop & Peacock (1990) for flat-spectrum sources of the same luminosity. By integrating their models 1–5 over radio powers greater than 5.8×10^{26} W Hz^{-1} sr^{-1}, we derive $2.9 \pm 0.2 \times 10^{-10}$ Mpc^{-3}. The study by Shaver et al. (1996b) deals with somewhat stronger sources ($P \geq 1.1 \times 10^{27}$ W Hz^{-1} sr^{-1}) and since they show space densities normalized to $z \sim 3$, it is not possible to compare results directly.

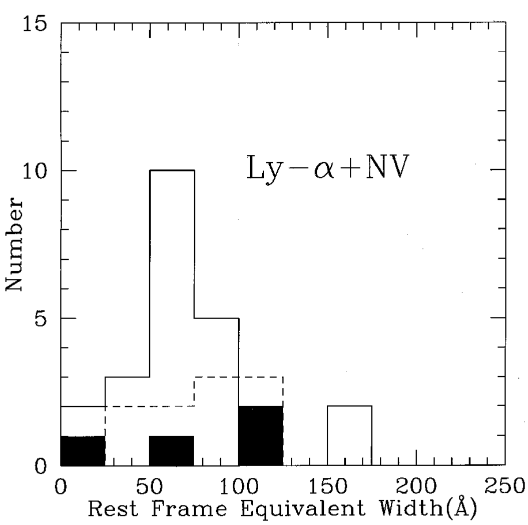

Figure 4. Rest frame Lyα + N V equivalent width distribution for $z > 4$ quasars. The solid line is for 23 colour-selected APM *BRI* quasars from Storrie-Lombardi et al. (1996). The dotted line is for the 10 grism-selected quasars from Schneider, Schmidt & Gunn (1991a). The solid bins are for radio selected $z > 4$ quasars including both those presented here and GB1508 + 5714 and PKS1251 − 407 (Shaver, Wall & Kellerman 1996a).

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