UNBIASED SEARCHES FOR QUASARS BEYOND A REDSHIFT OF 3.5

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1. INTRODUCTION

Nearly a decade elapsed between the discovery by Wampler at al. (1973) that the QSO OQ172 has a redshift of 3.53 and the discovery by Peterson et al. (1982) that the QSO Pks 2000-330 has a redshift of 3.78. During that time, radio and optical searches were vigorously pursued to find QSO's with redshifts greater than 3.5, but none were found. In this paper, we discuss selection effects in optical and radio searches and show how these selection effects have limited the redshift range of previous surveys. We propose a combination of radio and optical techniques that may be used to find high redshift QSO's and provide us with an undistorted view of the Universe beyond a redshift of 3.5.

2. RADIO SELECTION EFFECTS

Fig. 1 shows a schematic radio spectrum of a source with an extended power law component and a compact component. The characteristic synchrotron self absorption peak is marked as ν_m. Below this frequency, the synchrotron source is opaque, and above this frequency it is optically thin. In Fig. 2, all the known radio sources with redshifts greater than 3 are shown. Each of these sources has a spectrum that shows a synchrotron self absorption peak ν_m and each source has a steep spectrum at frequencies greater than ν_m. If these sources were seen at higher redshifts, their observed spectra would be shifted to the left toward lower frequencies and down toward lower flux densities. They would then appear as weak radio sources with steep spectra between 2.7 and 5 GHz.

Fig. 3 gives the number magnitude distributions of complete samples of flat and steep spectrum QSO's from the survey of Fanti et al. (1979). The number of steep spectrum QSO's increases right up to the plate limit. The flat spectrum QSO's in this sample show an apparent magnitude cut-off and we interpret this to be caused by the

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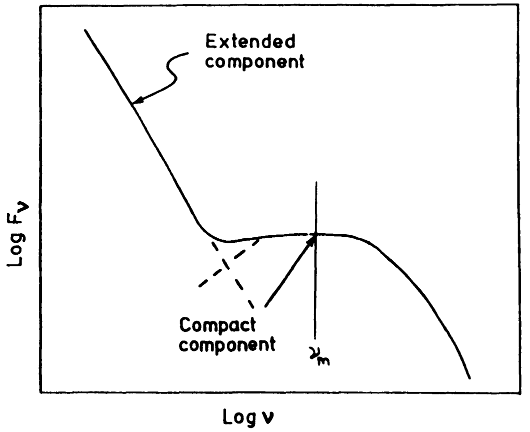

Figure 1 Schematic spectrum of a radio source with both extended and compact components.

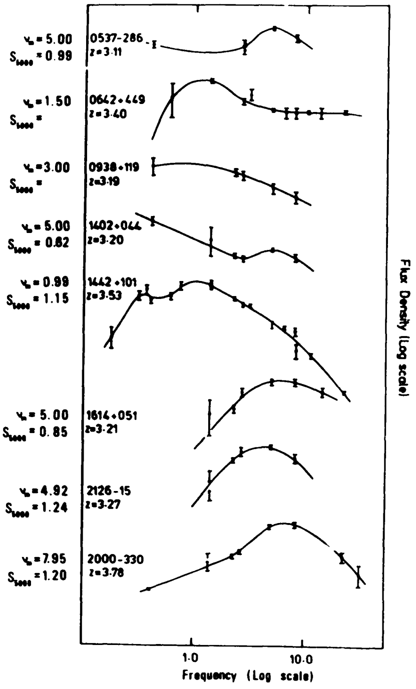

Figure 2 Radio spectra for all the known radio sources with Z > 3, showing pronounced synchrotron self absorption peaks.

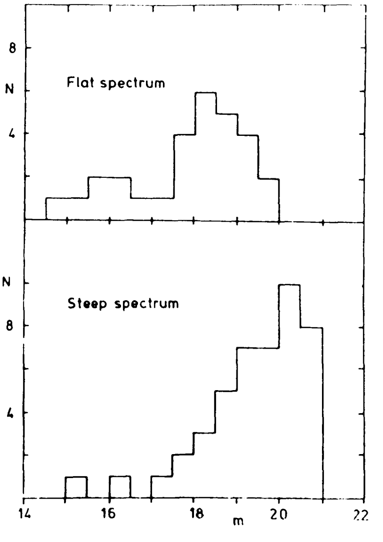

Figure 3 Number magnitude distributions for complete samples of flat and steep QSOs (Fanti et al. 1979), the N(m) for the steep spectrum QSOs continues to rise to the plate limit, while that for the flat spectrum QSOs peaks at $18^{m}.5$.

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change in the form of the radio spectrum from flat to steep as the redshift increases. In our interpretation the missing faint, flat spectrum QSO's are at high redshifts and are observed as weak steep spectrum radio sources in the 2.7 to 5 GHz radio frequency window. The peak optical magnitude of the flat spectrum radio sources is found to be independent of the flux limit of the radio samples. Thus efforts to identify weak flat spectrum sources in deeper radio surveys will not find higher redshift QSO's, but will only sample the low luminosity portion of the luminosity function.

Spectral index distributions of complete samples of sources selected at 5 GHz (Condon and Ledden 1981) are shown in Fig. 4. The samples of strong sources (S_5 > 600mJy) show a double peaked spectral index distribution. The narrow peak at $\alpha = 0.75$ is characteristic of the electron energy distribution in optically thin synchrotron sources. The broad peak at $\alpha = 0.00$ is due to the "flat" synchrotron self absorbed sources. The samples of weak sources (S_5 > 15mJy) will be a mixture of sources at all redshifts, but among them may be some sources at large redshift. At high redshift the peak in the synchrotron self absorption spectrum is shifted to lower frequencies and the source is observed as an optically thin source with $\alpha = 0.75$. Thus the lack of weak flat spectrum sources in high frequency samples can be attributed to the radio spectrum shape at high redshifts, however spectral index distributions between 408 MHz - 5 GHz also show decreasing numbers of flat spectrum sources at low flux densities (Wall and Benn 1981) and the selection effect hypothesized here may only have a small effect.

3. OPTICAL SELECTION EFFECTS

Fig. 5 shows the (redshift independent) velocity widths (FWHM) of Ly α emission lines as a function of redshift for optically selected QSO's (●) (MacAlpine and Feldman 1982) and for 5 of the high redshift radio QSO's in Fig. 2 (▼). It can be seen that the Ly α emission line is becomming increasingly narrower at high redshift. We interpret this as due to increasing numbers of Ly α absorption lines cutting into the short wavelength side of the Ly α emission line. Our examination of the observed equivalent widths of the Ly α emission lines of the optically selected QSO's in Fig. 2 showed that in the redshift interval 1.8 to 2.8, the observed equivalent widths increased nearly as 1+Z, corresponding to an almost constant emitted Ly α flux for the QSO's found optically in this redshift range. However in the redshift range 2.8 to 3.2, the emitted Ly α flux dropped, consistent with Ly α absorption by intervening clouds which increases rapidly with increasing redshift (Peterson 1978, 1983). If the unabsorbed Ly α flux follows the relation shown by the line in Fig. 5, then the unabsorbed Ly α flux emitted by QSO's seen at a redshift of 4 would be 0.65 mag less than the unabsorbed Ly α flux emitted by QSO's seen at a redshift of 3, and the higher redshift QSO's would be systematically harder to identify

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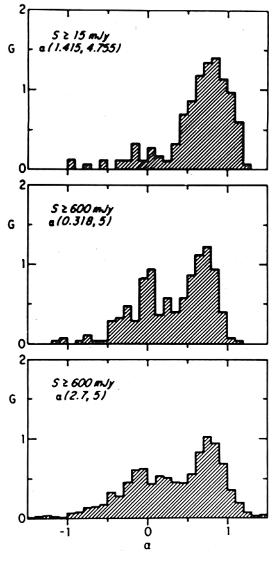


Figure 4 Spectral Index distributions of complete samples of sources at 5 GHz (Condon and Ledden 1981) showing the decrease in flat spectrum sources as the survey flux limit is decreased. These effects (Fig 3 and Fig 4) could be due to the shape of radio spectra of the high Z radio QSOs.

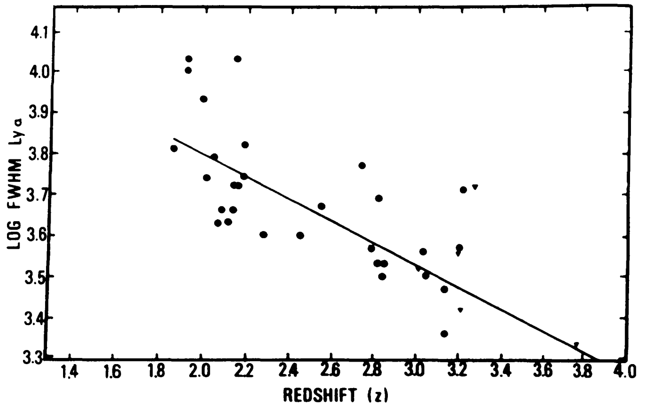


Figure 5 Redshift independent velocity widths (FWHM) of Ly α as a function of Z for some optical (●) (MacAlpine and Feldman 1982) and radio (▼) QSOs. The velocity widths of Ly α decreases by a factor of 2 for a redshift change from Z = 3 to Z = 4.

on prism plates.

Figures 6a and 6b show the optical spectra of two QSO's; (a) is a QSO with a redshift of 2.44, (b) is Pks 2000-330 with a redshift of 3.78. The prism spectrum insert on both of these figures is reproduced from objective prism spectra obtained with the UK Schmidt Telescope. Fig 6a was taken with the low dispersion prism (2200 A/mm) and has a resolution of 60 A. The IIIa-J emulsion covered a wavelength range of 3200 to 5400 A. Fig 6b was taken with the medium dispersion prism (2000 A/mm) and has a resolution of 50 A. The IIIa-F emulsion and filter combination covered the wavelength range 5700 to 6900 A. The emulsion sensitivity with wavelength is given for each emulsion. It can be seen that the sensitivity response of the IIIa-F emulsion is not smooth, and that the response drops by 0.5 mag between 6000 A and 6500 A. In addition the contrast of the IIIa-F emulsion drops by 30% from a peak at 6050 A to a low at 6900 A (Emerson, private communication).

The Ly α emission feature of the high redshift QSO (Fig 6b) is nowhere near as prominent as that for the low redshift QSO (Fig 6a). The observing conditions are the same for both QSO's except for emulsion type.

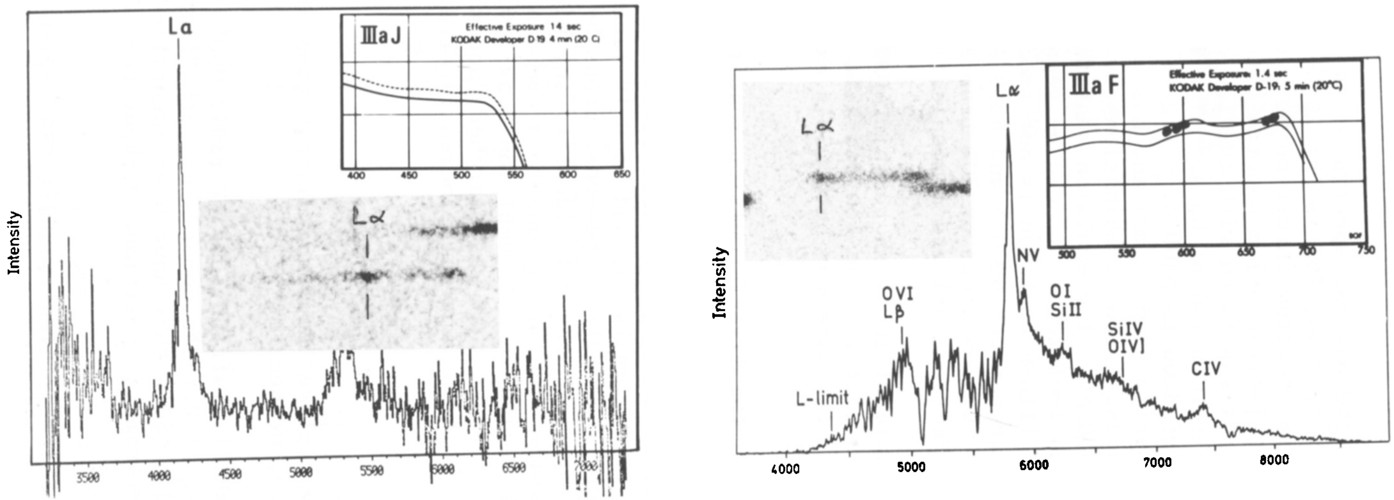
In Fig 6b, the spots on the IIIa-F emulsion sensitivity curve correspond to the wavelengths of the C IV 1549 emission lines used to identify the high redshift QSO's found in the CTIO 4m grism survey (Osmer 1982). The wavelengths of these lines are near the sensitivity peaks of the IIIa-F emulsion, and no C IV lines were detected in the range where the emulsion response drops by 0.5 mag. The failure of the CTIO 4m grism survey to identify any high redshift QSO's by their Ly α emission line may be due to a combination of the restricted wavelength region of peak emulsion sensitivity (and hence the smaller volume of space that was searched) and the systematic weakening of the flux in the Ly α line with increasing redshift.

4. CONCLUSIONS

In order to properly explore the space distribution of QSO's at redshifts greater than 3.5, we need to

(i) Investigate the redshift distributions of radio QSO's drawn from a 100 mJy sample at 2.7 GHz comprising both "flat" and "steep" spectrum radio QSO's that have been identified from accurate radio interferometer positions without regard to their optical morphology.

(ii) Conduct optical searches for high redshift QSO's with a sensitive wide field detector that has uniform wavelength sensitivity in combination with a grism that has 50 A resolution.



Figures 6(a) and (b) Optical spectra of two QSOs (a) SGP 0048−298 Z = 2.44 (b) PKS 2000−330 Z = 3.78. The prism spectra from the UKST objective prism plates are inserted. Ly α is not easily seen in the prism spectrum of PKS 2000−330 due to the variation in sensitivity response of the IIIa-F emulsion with wavelength and the loss of Ly α emission line flux due to increasing numbers of Ly α absorption lines.

5. REFERENCES

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DISCUSSION

Shklovsky: Part of the form of the spectra of QSOs can be explained by means of the relativistic Doppler effect (Scheuer and Readhead). In this case your argument must be changed.

Savage: Since we find that half of the high redshift quasars have peaked spectra, at least for these sources, relativistic beaming does not smooth out the spectra. VLBI observations of peaked spectrum sources indicate that they generally are double sources with nearly equal component flux densities and no evidence for superluminal motion. Perhaps flat spectra sources consist of components with peaked spectra which are spread out by Doppler shifts.

Thompson: Automatic measuring machines such as COSMOS have the ability to remove wavelength sensitivity from photographic objective prism surveys. Since the optical selection effects which you discuss can be partially removed by correcting for the wavelength sensitivity, do you plan to employ such automated techniques to analyze any of your survey data?

Savage: There is "automatic quasar detection" software written for COSMOS by Clowes, Cooke and Beard (see their poster paper at this symposium for recent results) which has already been used to select quasars from the UK Schmidt telescope low dispersion objective prism plates taken on the IIIa-J emulsion. Parameters are input to allow for the variation of emulsion sensitivity variation with wavelength. Thus, this program can easily be used to search the UK Schmidt medium dispersion objective prism plates which are taken on IIIa-F emulsion. We hope to start such a search this October.

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Baldwin: The radio selection effect you describe certainly affects a number of sources, but I think the number is very small at low flux densities. In a 20-MJy sample at 5 GHz of 100 sources, for which spectra extend down to 150 MHz, the number which show this effect is perhaps only one.

Savage: The survey you refer to is over a small area of 25 square degrees. The recent VLA mapping at 1415 MHz and 5 GHz of the PKS 2700 MHz deep survey regions (200 square degrees, 600 sources to 100 MJy) referred to by Peacock should give us a clearer picture of the percentage of "peaked" spectra sources in such a survey.