A Search for Quasar Protoclusters at z > 4

J.D. Smith, D. Thompson, and S. Djorgovski
Palomar Observatory
California Institute of Technology

Introduction: In the CDM and many other hierarchical scenarios for the origins of large scale structure, the existence of luminous quasars at very high redshifts ($z > 3$ or 4) is difficult to understand, unless such objects form at the very highest peaks of the density field. One then might expect a strong clustering of quasars at large redshifts. This is a generic prediction for practically any reasonable primordial density fluctuation spectrum. For CDM, Efstathiou & Rees (1988) predicted that quasars at $z > 4$ should be clustered as strongly as the bright galaxies at $z \sim 0$. Cole & Kaiser (1989) suggest that $z > 4$ quasars might represent $\gtrsim 4\sigma$ peaks of the density field, and thus should be clustered more strongly than galaxies at $z \sim 0$.

We are performing the following experiment: A search for quasars, AGN, or other discrete objects, e.g., starforming galaxies, near *known*, $z > 4$ quasars. In other words, use the early quasars as markers of possible protoclusters. This is a fairly basic test of our understanding of the formation of galaxies, large-scale structure, and the origin of the first quasars themselves.

The Experiment: A quick and simple way to search for high-z quasars is through multicolor imaging. We obtain multicolor CCD images on and around the fields containing known $z > 4$ quasars, and use discrepant colors to select other quasar candidates near them. Such putative faint AGN may have ecsaped detection due to some selection effect (e.g., brightness, weaker lines, not being a strong radio source, etc.) The known target quasar itself provides an immediate empirical calibration as to what kind of a color discrepancy may be expected. A simple setup is to use the Gunn-Thuan *gri* bands, and look for objects where Lyα is in the r band; the line, and the continuum change between the g and i bands would leave a distinct color-color signature. This implies a redshift range $\sim 4.05 - 4.9$. Promising color-selected candidates will be followed up spectroscopically.

Whereas this method should work for AGNs where the continuum is well detectable, it may be insufficient to pick out very faint galaxies at these redshifts. Actively star-forming galaxies (which, at these redshifts, could well be identified as primeval galaxy candidates) should perhaps be even more numerous than faint AGNs. For them, the optimal detection technique may be Lyα narrow-band imaging, where they should stand out, regardless of what their continuum level is. Many high-z Lyα galaxies (but usually with active nuclei) have already been found using this method and its derivatives.

Data: So far, we have obtained multicolor images of the following quasar fields using the 4-Shooter imager at the Palomar 200-inch telescope: PC 0307+0222 ($z = 4.373$), PC 0751+5623 ($z = 4.285$), PC 0910+5625 ($z = 4.036$), PC 1158+4635 ($z = 4.733$), PC 1247+3406 ($z = 4.897$), and QSO 2203+292 ($z = 4.399$). This imaging data has been

(almost) fully reduced. Multicolor data on the following fields has also been obtained at the Palomar 60-inch telescope: PC 0104+ 0215 ($z = 4.171$), PC 0953+4749 ($z = 4.457$), PC 1233+4752 ($z = 4.447$), PC 1301+4747 ($z = 4.004$), and PC 2331+0216 ($z = 4.093$). Only the data on PC 1233+4752 has been reduced. Multicolor data on two southern quasar fields have been obtained at the CTIO 4-meter telescope and fully reduced: QSO 0000–26 ($z = 4.098$) and QSO 0051–279 ($z = 4.402$). We have also obtained one set of imaging data (PC 1233+4752) at the Palomar 200-inch telescope using the COSMIC imager which has not been reduced.

The photometry was done using *Daophot*. For the 4-Shooter, the photometry is complete down to $r \sim 24^m - 24.5^m$, and reliable detections extend even to $r \lesssim 25^m$. Typically about 2000 objects are detected in each 4-Shooter field. For the Palomar 60-inch, the photometry is complete down to $r \sim 23.5^m$ with about 350 objects detected. The CTIO data on QSO 0000–26 is complete to $r \sim 23^m$ with 650 objects detected while the data on QSO 0051–279 is complete to $r \sim 24.5^m$ with 2000 objects detected. All color-selected candidates are examined visually on a workstation. Some are resolved (galaxies), but with a strong excess in the r band; some are (quasi?)stellar in appearance. At this point, we do not discriminate against galaxies (extended objects), since we are interested in *any* objects at these redshifts. The best candidates are selected for follow-up spectroscopy.

Narrow band imaging has been obtained at the CTIO 4-meter for PC 0307+0222 and QSO 0051–279, and at the Palomar 60-inch for PC 0953+4749, and PC 1233+4752.

Results: At these redshifts, the 4-Shooter fields ($\sim$ 8.5 arcmin sq.) correspond to a comoving area of about $126 h_{75}^{-2}$ Mpc^2 (for $\Omega_0 = 1$), or about $632 h_{75}^{-2}$ Mpc^2 (for $\Omega_0 = 0$), with $\Delta z \simeq 0.8$, i.e., a depth of a few hundred Mpc. The distance moduli at these redshifts, for $H_0 = 75$ km/s/Mpc, are about about 46.9 (for $\Omega_0 = 1$), or about 48.1 (for $\Omega_0 = 0.2$). Thus, we are probing the AGN luminosity function nearly to the Seyfert 1 level. Based on *very* uncertain extrapolations of the comoving density and quasar luminosity function from lower redshifts, we estimate that the probablity of detecting another quasar (down to our magnitude limit) for each of these fields is $\sim 10^{-1 \pm 1}$. There are between 0 and 3 highly promising candidates per quasar field, and an additional half-dozen objects per field, whose spectra may be worth obtaining.

We have selected 41 objects for follow-up spectroscopy using the multicolor technique, with $\approx$ 10 of those being high-priority candidates. So far, we have obtained follow-up spectroscopy on six objects. Five of the objects have $z < 1$. However, one object in the PC 0910+5625 field has a tentative redshift of $z = 4.06$. More spectrocopy is needed on this object to confirm this result. Twelve candidates have been chosen from the narrow-band imaging but we have been unable to obtain spectra of any of them. Our Lyα flux limits achievable in $\sim$ 20 minute integrations ($\sim 10^{-17}$ erg/cm^2/s) at these redshifts correspond to unobscured line luminosities powered by star formation of $SFR \lesssim 5 M_\odot$/yr, and thus any unobscured, star-forming young galaxies in these fields should be detectable.

In the future, we hope to cover several additional fields using the multicolor technique. Most of all, we need spectra of the candidates already in hand.