HIGH-REDSHIFT QUASARS AS PROBES OF PRIMORDIAL LARGE-SCALE STRUCTURE AND GALAXY FORMATION

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Several arguments suggest that quasars at \( z > 4 \) may be in the cores of future giant ellipticals, and forming at the very highest peaks of the primordial density field. A strong bias-driven primordial clustering is then expected in these fields, which are naturally interpreted as the cores of future rich clusters. High-redshift quasars can thus be used as markers of some of the earliest galaxy formation sites. Recent discoveries of (proto)galaxy companions of \( z > 4 \) quasars, and hints of strong clustering among high-\( z \) quasars give some support to this idea. The frequency of companions is much higher than is expected for a general field, or the upper limits for comparable redshifts in the HDF. Clustering of quasars themselves at \( z > 3 \) or 4 may reflect the primordial large-scale structure.

1 Introduction

Primeval galaxies (PGs) have now been found, in a variety of forms and environments, using a variety of techniques: narrow-band Ly\( \alpha \) imaging, Lyman-break method, as DLA absorbers, as quasar companions, as gravitationally lensed objects, etc. Statistical studies of the HDF have outlined a global history of galaxy formation in the general field. Moreover, we are starting to see evidence for large-scale structure formation at high redshifts, i.e., \( z > 3 \).

However, any single discovery method may bias the sample of objects found, and formative histories of galaxies in different environments may vary substantially. For example, galaxies in rich clusters are likely to start forming earlier than in the general field, and studies of galaxy formation in the field may have missed possible rare active spots associated with rich protoclusters. Diverse and complementary paths towards discoveries of first galaxies are still very much worth pursuing. Our group is pursuing the use of quasars at \( z > 4 \) as markers of the early galaxy formation sites, by looking for PGs associated and/or clustered with quasar host galaxies themselves (\( z_{\text{gal}} \approx z_{\text{QSO}} \)).
It is now believed that galaxy formation is an extended series of processes, which may have a broad peak at \( z \sim 2 - 3 \). However, it is of a considerable importance to catch the first galaxy-size structures forming at high redshifts, i.e., the very onset of massive galaxy formation.

Any galaxies at \( z > 4 \) must be still very young, simply on account of the timing: they can be at most a few percent of the present galaxian age, or \( \sim 0.5 - 1 \) Gyr, for any reasonable cosmology. The evolutionary status of galaxies at \( z \sim 2 \) or 3 is more ambiguous, with possible physical ages up to \( \sim 2 - 3 \) Gyr, or \( \sim 10 - 20\% \) of their present age. Going to \( z > 4 \) removes this age ambiguity.

We are conducting an observational program to discover and study such protogalaxies in the earliest stages of formation, clustered with the known quasars at \( z > 4 \). This pushes beyond the territory now explored in the HDF and elsewhere, at the epochs when the universe was only a few percent of its present age.

2 Quasars as Cores of Massive Protogalaxies

There is currently very little known about normal galaxies and their progenitors at \( z > 4 \). While the current theoretical belief is that some subgalactic structures (\( M \sim 10^6 - 10^8 M_\odot \)) may start forming at \( z \sim 6 - 10 \), more massive (\( M \sim 10^{11} - 10^{12} M_\odot \)) progenitors of normal galaxies today are unlikely to be in place before \( z \sim 4 - 5 \).

Some of these first massive protogalaxies may be the hosts of quasars at \( z > 4 \). While AGNs by themselves are problematic as a probe of galaxy formation and evolution, they may still provide useful pointers to the sites of early galaxy formation. The relation between high-z AGN and galaxy formation remains unclear. The comoving density of quasars seems to track very well the inferred history of star formation in galaxies, and both follow the merger rate evolution predicted by hierarchical structure formation scenarios. The same kind of processes, dissipative merging and infall, may be an important trigger of both star formation and the AGN activity.

Indeed, most or all ellipticals and massive bulges at \( z \sim 0 \) seem to contain central massive dark objects suggestive of an earlier quasar phase. Masses of these putative “dead quasars” also correlate with the luminous old stellar mass of the host galaxy, again suggestive that they formed at about the same time and through the same sequence of early dissipative merging and starbursts.

The very existence of numerous quasars at \( z > 4 \) poses a timing problem, and it is likely that they are situated in the massive parent structures (future host galaxies) which are among the first objects to form. Furthermore, high metallicities (up to \( 10 \times Z_\odot \)) observed in \( z > 4 \) quasars are indicative of a considerable chemical evolution involving several generations of massive stars in a system massive enough to retain and recycle their nucleosynthesis products, e.g., comparable to the cores of giant ellipticals. Metallicities and abundance patterns in the intracluster x-ray gas at lower redshifts are also suggestive of an early, rapid star formation and enrichment phase in the rich cluster progenitors at high redshifts.

It is perfectly possible that every young elliptical or a massive bulge undergoes an early quasar phase as it is forming the bulk of its stars. While quasar activity can happen at any redshift if there is a central engine in place and a supply of fuel available, the situation at high redshifts is special: these objects must be young on account of the short time scales. Quasars at \( z > 4 \) can thus be naturally interpreted as being in the cores of future massive ellipticals.

In general, the most massive density peaks in the early universe are likely to be strongly clustered and thus the first galaxies may be forming in the cores of future rich clusters. It then makes sense to look for other galaxies with or without AGN, forming in the immediate vicinity of known \( z > 4 \) quasars.
3 Quasar Clustering at $z > 3$

There is a possibility that some quasar-marked protoclusters at high redshifts have already been discovered. Schneider, Schmidt & Gunn (SSG) present the results of a grism search for quasars at $2.7 < z < 4.9$, covering 61.47 deg$^2$. In this volume, they define a complete sample of 90 quasars, which they used to measure the evolution of the quasar luminosity function. However, they have found something remarkable: among their complete sample of 90 quasars, there are 3 close pairs, all at $z > 3$: PC 0951+4637 A+B: $\langle z \rangle = 3.223$, $\Delta z = 0.005$, $\Delta \theta = 410''$; PC 1314+4748 A+B: $\langle z \rangle = 3.355$, $\Delta z = 0.004$, $\Delta \theta = 364''$; and PC 1643+4631 A+B: $\langle z \rangle = 3.810$, $\Delta z = 0.041$, $\Delta \theta = 198''$.

The corresponding comoving separations are $\sim 3 - 5$ Mpc, i.e., comparable to the sizes of galaxy clusters. The volume covered by the SSG survey is huge, and for each quasar pair, the probability of a random occurrence in this volume is $\sim a few \times 10^{-5}$. The pairs are detected independently. Thus, the joint probability of finding 3 pairs this close in this survey is $P \sim 10^{-13}$. This clearly cannot be due to a chance. Assuming a standard power-law clustering with slope $\gamma = -1.8$, the implied comoving clustering length is of the order of $50h^{-1}$ Mpc, i.e., comparable to that of the richest Abell clusters today. It thus appears very likely that these quasar pairs mark sites of rich protoclusters of galaxies.

While sporadic evidence for clustering of quasars at high redshifts has been presented in the past, this was the first time that a complete and well-defined sample of quasars was available for this purpose, enabling meaningful statistical arguments. Clustering of absorbers and their companion galaxies has also been detected in several instances, and of Lyman-break galaxies as well: we know that some large scale structure is in place at $z \sim 2 - 3$.

Studies of the clustering of quasars for the entire SSG sample have been done by two groups. Both have found some evidence for clustering, which is dominated by these pairs. Previous studies of quasar clustering (typically out to $z \sim 2$ or so) have generally found that their clustering amplitude decreases with redshift, presumably reflecting the growth of the large-scale structure. Here we seem to see the reversal of this trend: a sudden (and perhaps rather dramatic) increase in the clustering strength of quasars at $z > 3$. Similar effect was also found by La Franca et al., in an analysis of a completely independent sample of objects at somewhat lower redshifts.

This can be interpreted as an evidence for biasing: these quasar pairs may be marking some of the highest peaks of the density field at that epoch, probably marking the regions which will evolve into rich galaxy clusters today.

We searched for other objects at the same redshifts in these quasar-pair fields using narrow-band imaging centered on the redshifted Ly$\alpha$ line to select star-forming galaxies and faint AGN at the same redshifts. Our preliminary spectroscopic follow-up confirmed several objects, including both Ly$\alpha$ emission galaxies, and previously unknown, faint quasars. These findings are certainly consistent with the idea that these quasar pairs may be marking sites of future rich clusters.

It then makes sense to push to even higher redshifts, and look for objects clustered with known quasars at $z > 4$.

4 New Discoveries of Quasar Companions at $z > 4$

This approach has been proven to work. The first galaxy discovered at $z > 3$ was a quasar companion (PKS 1614+051 at $z = 3.215$), and many other examples have been found since then at $z \sim 2 - 3$. This method is now starting to yield non-AGN galaxies at $z > 4$.

A galaxy companion of BR 1202–0725 at $z = 4.695$ has been discovered independently and at the same time by two groups, and confirmed spectroscopically. No high-ionization lines
detected in its spectrum, but the close proximity of this object to the QSO suggests that its strong Lyα emission may be powered by the QSO radiation field, rather than by star formation. Furthermore, a dusty companion object has been found in the same field\textsuperscript{24, 25}. Two companion galaxies were also found\textsuperscript{26} in the field of the quasar BR 2237–0607 at $z = 4.55$.

There are now several other cases. For example, we have recently found\textsuperscript{20} an apparently normal galaxy companion of the quasar PSS 1721+3256 at $z = 4.031$ (Fig. 1). It is an $R \approx 25^m$ galaxy seen 13 arcsec in projection from the QSO (corresponding to $\sim 450$ comoving kpc, or $\sim 90$ proper kpc at that redshift, for a reasonable range of cosmologies), sufficiently far as to be relatively unaffected by the QSO radiation field. Its inferred continuum luminosity is $\sim L_*$, and its spectrum (Fig. 2) shows no trace of an AGN: no high ionization lines, relatively weak Lyα (an order of magnitude less than the companion of BR1202–0725) with $W_{\lambda_{\text{rest}}} \approx 25$ Å.

The inferred star formation rate, both from the Lyα emission line and the UV continuum at $\lambda_{\text{rest}} = 1500$ Å, is SFR $\approx 4$ to 5 $M_\odot$/yr. Its properties are then exactly what one may expect from a PG powered by a mild star formation. Another possible Lyα companion galaxy in the same field (galaxy A) awaits a further spectroscopic confirmation.

Another very interesting case is PSS 0030+1702 at $z = 4.305$ (Fig. 3). The QSO has at least
one, and possibly two Lyα companion galaxies within 10 arcsec from the line of sight. Their observed parameters are similar to those of the galaxy companion of PSS 1721+3256, described above: no high-ionization lines in their spectra, relatively weak Lyα, continuum luminosity $\sim 1 - 1.5 L_*$, SFR $\sim 10 \pm 5 M_\odot/yr$ (both from the Lyα line, and the UV continuum flux). We also conclude that these objects are most likely powered by star formation.

We have also found similar cases of protogalaxy companions of quasars PSS 0117+1552 at $z = 4.275$, PSS 0248+1802 at $z = 4.465$, PSS 1048+4407 at $z = 4.45$, PSS 1057+4555 at $z = 4.12$, PSS 1253-0228 at $z = 4.01$, and GB 1713+2148 at $z = 4.01$; several other cases which require more observations at this point. Overall, the intrinsic properties of these quasar companion galaxies (their luminosities, SFR, etc.) are very similar to those of the Lyman-break selected population at $z \sim 3$, except of course for their special environments and higher look-back times.

In addition to these galaxies where we actually detect (presumably starlight) continuum, we sometimes see pure Lyα emission line nebulae within a few arcsec from the quasars, with no detectable continuum at all. One example is PSS 0030+1702. The Lyα flux from the nebula exactly what may be expected from photoionization by the QSO, with $L_{Ly\alpha} \approx 2 \times 10^{43}$ erg/s. These nebulae may be parts of still gaseous protogalaxy hosts of the quasars themselves. We can thus see and distinguish both the objects powered by the neighboring QSO, and objects which by all signs appear to be “normal” PGs in their vicinity.

5 Evidence for Protoclusters in Highly Biased Regions?

The median projected separations of these objects from the quasars are $\sim 100h^{-1}$ comoving kpc, an order of magnitude less than the comoving r.m.s. separation of $L_*$ galaxies today, but comparable to that in the rich cluster cores. The frequency of QSO companion galaxies at $z > 4$ also appears to be an order of magnitude higher than in the comparable QSO samples at $z \sim 2 - 3$, the peak merging epoch; galaxy interactions alone are thus probably not the
Figure 3: Deep $R$ band Keck image of the field of the quasar PSS 0030+1702, at $z = 4.305$. The field shown is 27.5 arcsec square. Galaxy A is an $R \approx 24''$ object at the QSO redshift; galaxy B ($R \approx 25''$) may also be at the same redshift. There is a pure Ly$\alpha$ line emission nebula on the opposite side of the quasar, probably a part of the still gaseous QSO host galaxy ionized by its UV emission.
whole story here. The implied average star formation density rate in these regions is some 2 or 3 orders of magnitude higher than expected from the limits estimated for these redshifts for field galaxies.

While this is still very preliminary, this “excess” may be an observable manifestation of biasing, i.e., the expected clustering of the highest density peaks. A generic expectation in most models of galaxy formation, including the standard CDM cosmogony, is that first objects forming at high redshifts should be strongly clustered: they would presumably form in the highest peaks of the density field, which are clustered ab initio. The same explanation applies to the redshift “spikes” at $z \sim 3 - 3.5$ found by Steidel et al. What we are finding may be even denser, and thus much rarer peaks at $z > 4$. Because they are rare, we use quasars as markers of sites where some structure is already forming, in order to increase our chances. Doing a “pure deep field” approach at these redshifts would be much harder and less likely to succeed than at $z \sim 3$. These are obviously very special (highly biased) spots in the early universe.

Quasars at $z > 4$ may thus be interpreted as being in the metal-rich cores of young, massive ellipticals, and possibly mark sites of future rich clusters of galaxies. The discoveries of their companion galaxies may support this idea: these may be “normal” PGs in the cores of future rich clusters, in the earliest stages of formation. These are obviously very special spots in the early universe, and they present a great opportunity to study galaxy and cluster formation, in an environment deliberately different from the general field (e.g., the HDF).

On an even larger scale, there may be some evidence for excess power on supercluster scales, as probed by quasars at $z > 4$ (Fig. 4). While the numbers of objects are still relatively small, we are finding an unexpectedly large frequency of QSO pairs and triplets (and even one quartet!) with typical comoving separations of $\sim 100 h^{-1}$ Mpc. The statistical significance of this effect is still difficult to quantify, due to the heterogeneity of some of the data, and the patchy sky coverage. The effect may be spurious, e.g., due to the variable depth of the QSO surveys or other selection effects, or it could be real. If it is real, it may be due to the actual clustering of quasars, or to some other physical effect, e.g., a patchy gravitational magnification by the foreground large-scale structure.

If this is a real clustering signal, its implications would be profound. It would be the first detection of a primordial large-scale structure, seen by its highest, highly biased peaks containing quasars, only a few hundred physical Mpc away from the CMBR photosphere. As the data improve, both for the QSO samples and the CMBR measurements, it would be intriguing to see if any correlation can be found between these quasar-marked structures and the CMBR fluctuations behind them.

Further work is needed in order to better establish and quantify these findings. If the evidence holds, it would represent a powerful confirmation of our basic ideas about biased galaxy formation. In any case, we are beginning to probe the earliest phases of galaxy and large-scale structure formation at high redshifts.

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Figure 4: The distribution of known $z > 4$ quasars (as of May 1998) on the northern and equatorial sky. The majority are from the uniform, but still very incomplete Palomar DPOSS survey (PSS), others are from the APM survey, from the Palomar transit surveys (PC), and a few others selected in radio, x-rays, colors, or serendipity. Several close pairs and triplets are seen, sometimes with components found by independent surveys. The dotted lines indicate the circles of equal Galactic latitude, $b = -30^\circ, 0^\circ, +30^\circ, +60^\circ$, and the cross marks the North Galactic pole.
References

1. Cowie, L., & Hu, E. Astron. J. 115, 1319 (1998).
2. Steidel, C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. Astrophys. J. Lett. 462, L17 (1996).
3. Djorgovski, S., Pahre, M., Bechtold, J., & Elston, R. Nature 382, 234 (1996).
4. Djorgovski, S., Spinrad, H., McCarthy, P., & Strauss, M. Astrophys. J. Lett. 299, L1 (1985).
5. Hu, E., McMahon, R., & Egami, E. Astrophys. J. Lett. 459, L53 (1996).
6. Franx, M., Illingworth, G., Kelson, D., van Dokkum, P., & Tran, K. Astrophys. J. Lett. 486, L75 (1997).
7. Madau, P., Ferguson, H., Dickinson, M., Giavalisco, M., Steidel, C., & Fruchter, A. Mon. Not. R. Astron. Soc. 283, 1388 (1999).
8. Steidel, C., Adelberger, K., Dickinson, M., Pettini, M., & Kellogg, M. Astrophys. J. 492, 428 (1998).
9. Miralda-Escude, J., & Rees, M. Astrophys. J. Lett. 478, L57 (1997).
10. Kormendy, J., & Richstone, D. Ann. Rev. Astron. Astrophysics. 33, 581 (1995).
11. Turner, E. Astron. J. 101, 5 (1991).
12. Hamann, F., & Ferland, G. Astrophys. J. 418, 11 (1993).
13. Loewenstein, M., & Mushotzky, R. Astrophys. J. 466, 695 (1996).
14. Kaiser, N. Astrophys. J. Lett. 284, L9 (1984).
15. Schneider, D., Schmidt, M., & Gunn, J. Astron. J. 107, 1245 (1994).
16. Stephens, A., Schneider, D., Schmidt, M., Gunn, J., & Weinberg, D. Astron. J. 114, 41 (1997).
17. Kundic, T. Astrophys. J. 482, 631 (1997).
18. Hartwick, F.D.A., & Schade, D. Ann. Rev. Astron. Astrophysics. 28, 437 (1990).
19. La Franca, F., Andreani, P., & Cristiani, S. Astrophys. J. ?, in press (1998).
20. Djorgovski, S.G., et al., in preparation (1998).
21. Djorgovski, S., Thompson, D., & Smith, J.D. in First Light in the Universe, eds. B. Rocca-Volmerange et al., Gif sur Yvette: Editions Frontières, p. 67 (1993).
22. Djorgovski, S.G., in Science with the VLT, eds. J.R. Walsh & I.J. Danziger, Berlin: Springer Verlag, p. 351 (1995).
23. Petitjean, P., Pecotial, E., Vals-Gabaud, D., & Charlot, S. Nature 380, 411 (1996).
24. Omont, A., Petitjean, P., Guilloteau, S., McMahon, R., Solomon, P., & Pecotial, E. Nature 382, 428 (1996).
25. Ohta, K., Yamada, T., Nakanishi, K., Kohno, K., Akiyama, M., & Kawabe, R. Nature 382, 426 (1996).
26. Hu, E., & McMahon, R. Nature 382, 231 (1996).
27. Efstathiou, G., & Rees, M. Mon. Not. R. Astron. Soc. 230, P5 (1988).
28. Kennefick, J.D., Djorgovski, S.G., & de Carvalho, R. Astron. J. 110, 2553 (1995).
29. McMahon, R., Irwin, M., & Hazard, C., in preparation (2001).