High-Redshift Quasars as Probes of Galaxy and Cluster Formation

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**Abstract.** Quasars at large redshifts provide a powerful probe of structure formation in the early universe. Several arguments suggest that the formation of ellipticals and massive bulges may have involved an early quasar phase. At very large redshifts, such structures are likely to be found at the highest peaks of the density field, and would thus be highly biased tracers: the earliest (massive) galaxy formation may have occurred in the cores of future rich clusters. Preliminary results from our search for clustered protogalaxies around quasars at \( z > 4 \) support this idea. Quasars at even larger redshifts may be an important contributor to the reionisation of the universe, and signposts of the earliest galaxy and cluster formation.

1. Introduction

Hy Spinrad always hated quasars (Spinrad 1979). In those paleolithic days (i.e., before 1987 or so) it was not yet obvious that a powerful quasar lurks in the heart of every one of Hy’s beloved radio galaxies, but in some sense this does not really matter: in the work of the Spinrad School of Observational Cosmology, AGN have been used simply as means to find stellar populations at large redshifts, in order to probe their formation and evolution. This is in principle a viable and sound approach.

In the simplest view, the very existence of luminous quasars at large redshifts suggests the existence of their (massive?) host galaxies, at least in the minds of a vast majority of astronomers today. At \( z > 4 \), this has some very interesting and non-trivial implications for our understanding of galaxy and structure formation (Turner 1991).

At a slightly more complex level, the observed history of the comoving number density of quasars may be indicative of the history of galaxy formation and evolution: the same kind of processes, i.e., dissipative mergers and tidal interactions, may be fueling both bursts of star formation and AGN activity. The peak seen in the comoving number density of quasars around \( z \sim 2 \) or 3 (Schmidt, Schneider & Gunn 1995) can then be interpreted in this context: the
ostensible decline at high redshifts may be indicative of the initial assembly and
growth of quasar central engines and their host galaxies; whereas the decline
at lower redshifts may be indicative of the decrease in fueling, as galaxies are
carried apart by the universal expansion, as many of the smaller pieces are being
consumed, and as the gas is being converted into stars. Qualitatively similar
predictions are made by virtually all models of hierarchical structure formation
(see, e.g., Cataneo 1999, or Kauffmann & Haehnelt 1999).

Due to their brightness, quasars are much easier to find (per unit telescope
time) than galaxies at comparable redshifts. It then makes sense to use quasars
as probes, or at least as pointers of sites of galaxy formation.

Quasars have been used very effectively as probes of the intergalactic medium,
and indirectly of galaxy formation, through the studies of absorption line sys-
tems. A vast literature exists on this subject, which is beyond the scope of this
review; for good summaries, see, e.g., Rees (1998a) or Rauch (1998).

A good review of the searches for quasars and related topics was given by
Hartwick & Schade (1990). Osmer (1999) provides a modern update. Some of
the issues covered in this review have been described by Djorgovski (1998) and
Djorgovski et al. (1999).

2. Quasars and Galaxy Formation

Possibly the most direct evidence for a close relation between quasars and galaxy
formation is the remarkable correlation between the masses of central black holes
(MBH) in nearby galaxies, and the luminosities (∼ masses) of their old, metal-
rich stellar populations, a.k.a. bulges (Kormendy & Richstone 1995, Magorrian
et al. 1998), with MBH’s containing on average ∼ 0.6% of the bulge stellar
mass. The most natural explanation for this correlation is that both MBH’s
and the stellar populations are generated through a parallel set of processes,
i.e., dissipative merging and assembly at large redshifts. Quiescent MBH’s are
evidently common among the normal galaxies at z ∼ 0, and had to originate at
some point: as they grow by accretion, their formation is the quasar activity.
Quasars may thus be a common phase of the early formation of ellipticals and
massive bulges.

Quasar demographics support this idea. Small & Blandford (1992), Chokshi
& Turner (1992), and Haehnelt & Rees (1993) all conclude that an average $L_*$-ish
galaxy today should contain an MBH with $M_\bullet \sim 10^7 M_\odot$ or so. These estimates
(essentially integrating the known AGN radiation over the past history of the
universe) are fully consistent with the actual census of MBH (quasar remnants)
in nearby galaxies.

Two other pieces of fossil evidence link the high-z quasars with the forma-
tion of old, metal-rich stellar populations. First, the analysis of metallicities
in QSO BEL regions indicates super-solar abundances (up to $Z_Q \sim 10 Z_\odot$)
in quasars at $z > 4$ (Hamann & Ferland 1993, 1999; Matteucci & Padovani
1993). The only places we know such abundances to occur are the nuclei of
giant elliptical galaxies. Furthermore, abundance patterns in the intracluster x-
ray gas at low redshifts are suggestive of an early, rapid star formation phase in
protoclusters populated by young ellipticals (Loewenstein & Mushotzky 1996).
A nearly simultaneous formation of quasars and their host galaxies, or at least ellipticals and bulges, is consistent with all of these observations, and it fits naturally in the general picture of hierarchical galaxy and structure formation via dissipative merging (see, e.g., Norman & Scoville 1988, Sanders et al. 1988, Carlberg 1990, Hernquist & Mihos 1995, Mihos & Hernquist 1996, Monaco et al. 1999, Franceschini et al. 1999, etc.).

An extreme case of this idea is that quasars are completely reducible to ultraluminous starbursts, as advocated for many years by Terlevich and collaborators (see, e.g., Terlevich & Boyle 1993, and references therein). Most other authors disagree with such a view (cf. Heckman 1991, or Williams & Perry 1994), but (nearly) simultaneous manifestations of both ultraluminous starbursts and AGN, perhaps with comparable energetics, are clearly allowed by the data. It is thus also possible that the early AGN can have a profound impact on their still forming hosts, through the input of energy and momentum (Ikeuchi & Norman 1991, Haehnelt et al. 1998).

3. Quasar (Proto)Clustering and Biased Galaxy Formation

Producing sufficient numbers of massive host galaxies needed to accommodate the observed populations of quasars at \( z > 4 \), say, is not easy for most hierarchical models: such massive halos should be rare, and associated on average with \( \sim 4 \) to \( 5-\sigma \) peaks of the primordial density field (Efstathiou & Rees 1988, Cole & Kaiser 1989, Nusser & Silk 1993). It is a generic prediction that for essentially every model of structure formation such high density peaks should be strongly clustered (Kaiser 1984). This is a purely geometrical effect, independent of any messy astrophysical details of galaxy formation, and thus it is a fairly robust prediction: the formation of the first galaxies (some of which may be the hosts of high-\( z \) quasars) and of the primordial large-scale structure should be strongly coupled.

Quasars provide a potentially useful probe of large-scale structure out to very high redshifts. The pre-1990 work has been reviewed by Hartwick & Schade (1990). A number of quasar pairs on tens to hundreds of comoving kpc scales has been seen (Djorgovski 1991, Kochanek et al. 1999), and some larger groupings on scales reaching \( \sim 100 \) Mpc (Crampton et al. 1989, Clowes & Campusano 1991), but all in heterogeneous data sets. Analysis of some more complete samples did show a clustering signal (e.g., Iovino & Shaver 1988, Boyle et al. 1998). The overall conclusion is that quasar clustering has been detected, but that its strength decreases from \( z \sim 0 \) out to \( z \sim 2 \), the peak of the quasar era, presumably reflecting the linear growth of the large-scale structure. However, if quasars are biased tracers of structure formation at even higher redshifts, associated with very massive peaks of the primordial density field, this trend should reverse and the clustering strength should again start increasing towards the larger look-back times.

The first hints of such an effect were provided by the three few-Mpc quasar pairs found in the statistically complete survey by Schneider et al. (1994), as pointed out by Djorgovski et al. (1993) and Djorgovski (1996), and subsequently confirmed by more detailed analysis by Kundic (1997) and Stephens et al. (1997). A deeper survey for more such pairs by Kennefick et al. (1996) did
not find any more, presumably due to a limited volume coverage. La Franca et al. (1998) find a turn-up in the clustering strength of quasars even at redshifts as low as \( z \sim 2 \). It would be very important to check these results with new, large, complete samples of quasars over a wide baseline in redshift.

More recently, observations of large numbers of “field” galaxies at \( z \sim 3-3.5 \) by Steidel et al. (1998) identified redshift space structures which are almost certainly the manifestation of biasing. However, the effect (the bias) should be even stronger at higher redshifts, and most of the earliest massive galaxies should be strongly clustered. A search for protoclusters around known high-\( z \) objects such as quasars thus provides an important test of our basic ideas about the biased galaxy formation.

Intriguingly, there is a hint of a possible superclustering of quasars at \( z > 4 \), on scales \( \sim 100 \, h^{-1} \) comoving Mpc (cf. Djorgovski 1998). The effect is clearly present in the DPOSS sample (which is complete, but still with a patchy coverage on the sky), and in a more extended, but heterogeneous sample of all QSOs at \( z > 4 \) reported to date. The apparent clustering in the complete sample may be an artifact of a variable depth of the survey, which we will be able to check in a near future. Or, it could be due to patchy gravitational lensing magnification of the high-\( z \) quasars by the foreground large-scale structure; again, we will be able to test this hypothesis using the DPOSS galaxy counts. But it could also represent real clustering of high-density peaks in the early universe, only \( \sim 0.5 - 1 \) Gyr after the recombination. The observed scale of the clustering is intriguing: it is comparable to that corresponding to the first Doppler peak seen in CMBR fluctuations, and to the preferred scales seen in some redshift surveys (e.g., Broadhurst et al. 1990; Landy et al. 1996). More data are needed to check on this remarkable result.

4. Quasar-Marked Protoclusters at \( z > 4 \)?

Any single search method for high-\( z \) protogalaxies (PGs) has its own biases, 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.

We are conducting a systematic search for clustered PGs, by using quasars at \( z > 4 \) as markers of the early galaxy formation sites (ostensibly protocluster cores). The quasars themselves are selected from the DPOSS survey (Djorgovski et al. 1999, and in prep.; Kennefick et al. 1995). They are purely incidental to this search: they are simply used as beacons, pointing towards the possible sites of early, massive galaxy formation.

The first galaxy discovered at \( z > 3 \) was a quasar companion (Djorgovski et al. 1985, 1987). A Ly\( \alpha \) galaxy and a dusty companion of BR 1202–0725 at \( z = 4.695 \) have been discovered by several groups (Djorgovski 1995, Hu et al. 1996, Petitjean et al. 1996), and a dusty companion object has been found in the same field (Omont et al. 1995, Ohta et al. 1995). Hu & McMahon (1996) also found two companion galaxies in the field of BR 2237–0607 at \( z = 4.55 \).

We have searches to various degrees of completeness in about twenty QSO fields so far (Djorgovski 1998; Djorgovski et al., in prep.). Companion galaxies
Figure 1. Examples of clustered companion protogalaxies in the fields of 4 DPOSS quasars at \( z > 4 \). These are deep, \( R \)-band Keck images centered on the quasars. The fields shown are 54 arcsec square. Some of the spectroscopically confirmed companions are labeled with the arrows.

have been found in virtually every case, despite very incomplete coverage. They are typically located anywhere between a few arcsec to tens of arcsec from the quasars, i.e., on scales \( \sim 100+ \) comoving kpc. We also select candidate PGs by using deep \( BRI \) imaging over a field of view of several arcmin, probing \( \sim 10 \) comoving Mpc (\( \sim \) cluster size) projected scales. This is a straightforward extension of the method employed so successfully to find the quasars themselves at \( z > 4 \) (at these redshifts, the continuum drop is dominated by the Ly\( \alpha \) forest, rather than the Lyman break, which is used to select galaxies at \( z \sim 2 - 3.5 \)). The candidates are followed up by multislit spectroscopy at the Keck, which is still in progress as of this writing.

As of the mid-1999, about two dozen companion galaxies have been confirmed spectroscopically. Their typical magnitudes are \( R \sim 25^m \), implying continuum luminosities \( L \lesssim L_\star \). The Ly\( \alpha \) line emission is relatively weak, with typical restframe equivalent widths \( \sim 20 - 30 \) \( \AA \), an order of magnitude lower
than what is seen in quasars and powerful radio galaxies, but perfectly reasonable for the objects powered by star formation. There are no high-ionization lines in their spectra, and no signs of AGN. The SFR inferred both from the Lyα line, and the UV continuum flux is typically \( \sim 5 - 10 \, M_\odot/\text{yr} \), not corrected for the extinction, and thus it could easily be a factor of 5 to 10 times higher.

Overall, the intrinsic properties of these quasar companion galaxies are very similar to those of the Lyman-break selected population at \( z \sim 3 - 4 \), except of course for their special environments and somewhat higher look-back times.

There is a hint of a trend that the objects closer to the quasars have stronger Lyα line emission, as it may be expected due to the QSO ionization field. In addition to these galaxies where we actually detect (presumably starlight) continuum, pure Lyα emission line nebulae are found within \( \sim 2 - 3 \) arcsec for several of the quasars, with no detectable continuum at all. The Lyα fluxes are exactly what may be expected from photoionization by the QSO, with typical \( L_{\text{Ly}\alpha} \sim \text{a few} \times 10^{43} \, \text{erg/s} \). They may represent ionized parts of still gaseous protogalaxy hosts of the quasars. We can thus see and distinguish both the objects powered by the neighboring QSO, and “normal” PGs in their vicinity.

The median projected separations of these objects from the quasars are \( \sim \text{a few} \times 100 h^{-1} \) comoving kpc, an order of magnitude less than the comoving r.m.s. separation of \( L_\ast \) 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 of the QSO era and the ostensible peak merging epoch. However, interaction and merging rates are likely to be high in the densest regions at high redshifts, which would naturally account for the propensity of some of these early PGs to undergo a quasar phase, and to have close companions.

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 by Madau et al. (1996) for field galaxies, and 1 or 2 orders of magnitude higher than the measurements by Steidel et al. at \( z \sim 4 \), even if we ignore any SFR associated with the QSO hosts (which we cannot measure, but is surely there). These must be very special regions of an enhanced galaxy formation in the early universe.

It is also worth noting that (perhaps coincidentally) the observed comoving number density of quasars at \( z > 4 \) is roughly comparable to the comoving density of very rich clusters of galaxies today. Of course, depending on the timescales involved, there must be some protoclusters without observable quasars in them, and some where more than one AGN is present (an example may be the obscured companion of BR 1202–0725).

5. Towards the Renaissance at \( z > 5 \): the First Quasars and the First Galaxies

The remarkable progress in cosmology over the past few years, reviewed by several speakers at this meeting, has pushed the frontiers of galaxy and structure formation studies out to \( z > 5 \). Half a dozen galaxies, two QSOs (cf. Fan et al. 1999), and one radio galaxy are now known at \( z \geq 5 \), with the most distant confirmed object at \( z = 5.74 \) (Hu et al. 1999). Remarkably, there is
no convincing evidence yet for a high-$z$ decline of the comoving star formation rate density out to $z > 4$ (Steidel et al. 1999). Moreover, the universe at $z \sim 5$ appears to be already fully reionised (Songaila et al. 1999, Madau et al. 1999), implying the existence of a substantial activity in a population of sources at even higher redshifts.

These observational results pose something of a challenge for the models of galaxy formation. Essentially in all modern models, the first subgalactic fragments with masses $\geq 10^6 M_\odot$ begin to form at $z \sim 10 - 30$, and the universe becomes reionised at $z \sim 8 - 12$ (see, e.g., Gnedin & Ostriker 1997, Miralda-Escude & Rees 1997, or Rauch 1998 and references therein). This corresponds to a time interval of only about $\sim 0.5 - 1$ Gyr for a reasonable range of cosmologies.

What is not known is what are the first or the dominant ionisation sources which break the “dark ages”: primordial starbursts or primordial AGN? This is one of the fundamental questions in cosmology today, and it dominates many of the discussions about the NGST (see, e.g., Rees 1998b, Haiman & Loeb 1998, or Loeb 1999). Optical searches for quasars at $z > 5$ have been reviewed by Osmer (1999). There are exciting new prospects of detecting such a population in x-rays using CXO (Haiman & Loeb 1999). The value of such quasars as probes of the earliest phases of galaxy and structure formation during the reionisation era at $z \sim 10 \times 2^{\pm 1}$ cannot be overstated.

Some numerical simulations suggest that an early formation of quasars, at $z \sim 8$, say, is viable in the framework of the currently popular hierarchical models with dissipation (cf. Katz et al. 1994). It is even possible that a substantial amount of QSO activity may predate the peak epoch of star formation in galaxies (Silk & Rees 1998). A catastrophic gravitational collapse of a massive primordial star cluster may be the most natural way of forming the first MBHs, but a variety of other mechanisms have been proposed (e.g., Loeb 1993, Umemura et al. 1993, Loeb & Rasio 1994, etc.). Future observations will tell whether such primordial fireworks marked the end of the dark ages in the universe.

Acknowledgments. It is a pleasure to acknowledge the work of my collaborators, R. Gal, R. Brunner, R. de Carvalho, S. Odewahn, and the rest of the DPOSS QSO search team. I also wish to thank the staff of Palomar and Keck observatories for their expert assistance during our observing runs. This work was supported in part by the Norris Foundation and by the Bressler Foundation. Ivan King and his LOC crew brought this meeting into existence; thank you all. Finally, many thanks to Hy for introducing me to the joys of low-S/N astronomy and letting me play with the big toys: it was fun (most of the time)!

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