Searches for Quasars at $z > 5$

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**Abstract.**  
Quasars continue to be the most luminous objects known in the universe but no longer have the largest redshift. I review current techniques for finding quasars at $z > 5$ and the status of current optical surveys. I compare the spectra of known quasars with $z \approx 5$ with the spectra of some recently discovered galaxies with $z > 5$ to see what we may expect in the future from surveys for high redshift quasars and galaxies. The prominent emission lines of quasars should make them easier to detect and confirm spectroscopically than the $z > 5$ galaxies discovered so far.

1. Introduction and Background

I am grateful to the Organizing Committee for the opportunity to speak on searches for high-redshift quasars at this meeting. Although I have not worked directly with Hy, we have known each other for many years, and I have admired his research. I think three qualities stand out: 1) his determination and persistence at pushing telescopes and instruments to their limits, 2) his evident success at finding and studying successively more distant galaxies, and 3) his cheerfulness and optimism, which I think inspired his students and collaborators to be so successful over the many years of his career. I have also heard that Hy never liked quasars very much, so I feel honored that the topic made it on the program. Maybe the organizing committee decided it was safe to do so, now that galaxies have overtaken quasars as the objects of highest known redshift since 1997, when they displaced quasars for the first time since 1965.

Turning to the subject of this paper, the goals of surveys for high-redshift quasars include the observational determination of:

- The epoch of quasar formation
- The role of dust obscuration
- The relation of quasars to galaxy formation and evolution
- The contribution of quasars to the ionization of the intergalactic medium at high redshifts

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1As of the time of the meeting, June, 1999. New discoveries since then are discussed in the update section at the end of this article.
According to the picture that quasars are powered by the accretion of matter onto massive black holes in the nuclei of galaxies, the formation and evolution of black holes, quasars, and galaxies are closely related. The evolution of the space density of luminous quasars shows a strong peak at lookback times of 0.8 to 0.85 (Fig. 1). The evolution of galaxies is very much under debate, as we are hearing at this meeting, but it appears to extend over a broader range of redshift.

Among the questions we would like to address are: Which formed first, galaxies (or at least parts of galaxies), or quasars? What roles do interactions and mergers play in the fueling of quasars? and How do we account for the chemical abundances in high-redshift quasars, whose emission-line spectra look very similar to those at lower redshift?

We now have the observational capabilities to map the evolution of both quasars and galaxies to redshifts beyond 6, when the universe was 5% or less of its present age. Hubble Space Telescope and 8 - 10-m ground-based telescopes have already enabled us to discover more objects at $z > 5$ than seemed possible just a few years ago. Now the challenge is to carry out sufficiently large, systematic, and quantifiable surveys to answer the questions posed above.

In this paper I will discuss how to search for quasars at $z > 5$, concentrating on optical methods. Next I will review the status of current surveys and then compare the spectra of the quasars and galaxies with $z > \approx 5$ that have been found to date. I will close by making some speculations based on the current results and considering what we may expect in the future.
2. How to Search for Quasars at \( z > 5 \)?

Since the discovery of the first quasar with \( z > 4 \) in 1987 (Warren et al. 1987), more than 150 such objects have been found (G. Djorgovski and R. McMahon, private communications), and several search techniques are by now well developed. They include:

- Multi-color imaging
- Slitless Spectroscopy
- Deep Radio Surveys
- Deep X-Ray Surveys

The multicolor technique pioneered by Warren et al. (1987) and now applied to several surveys (see, e.g., Warren et al. 1991, Irwin et al. 1991, Kennefick et al. 1995, Djorgovski 1999) has contributed the majority of the known \( z > 4 \) quasars. It uses the large \( B - R \) color of quasars as a discriminant; the presence of Ly\( \alpha \) emission in the \( R \) filter band combined with the continuum depression caused by intervening Ly\( \alpha \) absorption in the \( B \) filter band makes quasars stand out from cool stars and yields an effective search criterion. The addition of \( I \) band photometry, which is an indicator of the continuum level longward of Ly\( \alpha \), aids in distinguishing high-redshift quasars from late-type stars. The multicolor technique was first used with photographic plates and Schmidt telescopes. The subsequent development of large format CCD cameras is now enabling wide-angle surveys to significantly fainter magnitudes, as discussed in more detail below.

At higher redshifts, e.g. \( z > 5 \), the same principle applies, with Ly\( \alpha \) shifting into the \( I \) band. However, as we shall see below, it is critical to have observations in the \( Z \) band, which is in the continuum longward of Ly\( \alpha \), to separate quasars from late-type stars.

The slitless spectroscopy technique is an effective way to discover high-redshift quasars through the direct detection of Ly\( \alpha \) emission in low-resolution slitless spectra (Smith 1975, Osmer 1982) and has been used by Schmidt, Schneider, and Gunn (SSG, 1995 and references therein) in their Palomar Grism Surveys. The selection effects and survey efficiencies are more straightforward to model for slitless spectroscopy in many cases than they are for the multicolor technique. The SSG survey is one of the cornerstones of our knowledge of the evolution of optically selected quasars at \( z > 3 \).

Deep radio surveys offer a different way to discover high-redshift radio galaxies and quasars. A key property of radio-selected objects is that they are significantly less affected by surrounding or intervening dust that blocks optical radiation. Although radio-loud quasars in general constitute about 10% of the total quasar population, the availability of deep radio surveys that cover a significant fraction of the sky offers the opportunity to find significant numbers of radio-loud quasars and radio galaxies at high redshift.

Current radio searches for high-redshift quasars make use of deep surveys for flat-spectrum sources (e.g. Hook and McMahon 1998) while searches for high-redshift radio galaxies focus on steep-spectrum sources (e.g. van Breugel
et al. 1999, also this volume). In both cases, subsequent selection concentrates on optically faint objects to help weed out objects of lower redshift. Hook and McMahon (1998) select objects that are red in $B - R$ to enhance the selection of high-redshift objects. van Breugel et al. (1999) make use of the well-defined $K - z$ diagram for radio galaxies and concentrate on objects with faint $K$ magnitudes. The discoveries of the radio-selected quasar of highest known redshift, $z = 4.72$ by Hook and McMahon (1998) and the radio galaxy of highest known redshift, $z = 5.19$ by van Breugel et al. (1999) demonstrate the power of their approaches.

It may be argued that X-ray emission is the key defining property of the global quasar/AGN population and should be the primary search criterion for discovering them. However, until recently, X-ray observatories have not had sufficient sensitivity to reach the objects of highest redshift. The ROSAT Deep Survey (Hasinger et al. 1998) is an indicator of the advances we may expect from CHANDRA (e.g., Mathur, this volume) and XMM as they come into operation; it has yielded the X-ray selected quasar of highest known redshift, $z = 4.45$ (Schneider et al. 1998). The requirements are a limiting X-ray sensitivity of $\approx 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ (0.5 – 2keV) and high accuracy, $\approx 1$ arcsec positions (to avoid confusion with foreground objects). Then follow-up optical imaging and spectroscopy, presumably concentrating on faint, red objects, should be an effective way of isolating high-redshift objects.

To summarize, all approaches to find $z > 5$ quasars need to cover a wide area on the sky to faint limiting sensitivities because the objects are so rare. Optical surveys need to have wavelength coverage extending to 0.9$\mu$m; indeed all approaches benefit from such coverage. Searches at even higher redshifts will push the requirements into the infrared ($\lambda > 1\mu$m).

3. Status of Current Optical Surveys

I would like to give a status report on two multicolor surveys my collaborators and I are carrying out: the BTC40 and the BFQS. I will also describe two other major optical surveys, CADIS and SDSS, and note the important contributions they are making to the search for quasars at $z > 5$.

The BTC40 is a large collaborative effort led by E. Falco and is aimed at finding gravitational lenses and distant galaxy clusters as well as high-redshift quasars. It is an optical, multicolor survey that makes use of the BTC camera and the CTIO 4-m telescope. Julia Kennefick is leading the quasar survey team, whose other members include Alberto Conti, Richard Green, Pat Hall, Eric Monier, Malcolm Smith, and myself. BTC40 has imaging data at high galactic latitude for 40 deg$^2$ in the $B, V, I, Z$ bands and reaches to $\approx 25$th magnitude at its deepest limit. All the imaging data are in hand and are being analyzed. The goal is to select $z > 5$ quasar candidates to $I = 22$.

The BFQS survey is being led by Pat Hall in collaboration with the other team members mentioned above. It also uses the BTC camera and reaches to $m_{lim} = 26.7$ over 7 deg$^2$. It uses the $B, R, I$ bands and is aimed at quasars with $3.3 < z < 5$ down to $L^*$ luminosities. The BFQS imaging data are also in hand and are being analyzed.
Together, the BTC40 and BFQS surveys extend the multicolor technique to fainter magnitudes and wider areas than have been covered before.

The CADIS (Calar Alto Deep Imaging Survey, Meisenheimer et al. 1998) survey extends the multicolor concept to higher spectral resolution and broader wavelength coverage by using 13 medium-band filters over the 0.39 to 0.93\(\mu\) range and 3 broad-band filters, including \(K'\). The filters are designed to give both improved sensitivity to the quasars being sought and improved rejection of non-quasars, such as emission-line galaxies (the veto filter concept). CADIS plans to cover 9 fields, each 10' × 10' in area. To date the CADIS team (Wolf et al. 1999) have shown the effectiveness of their approach by finding 6 quasars with 2.2 < \(z\) < 3.7 to \(R = 22\) mag in one field, about 6 times the expected number. The CADIS technique is more powerful than the original multicolor approaches because of its increased spectral resolution and greater number of filters. On the other hand, it requires more observing time per unit area on the sky to reach a given limit in sensitivity. Thus, it is a complementary and valuable addition to techniques for finding high-redshift quasars. It will be very important to see if the initial CADIS results on the surface density apply to the additional fields in their survey. Previous surveys have been subject to considerable field-to-field fluctuations, and it will be very interesting to see how the CADIS results come out. Our knowledge of the luminosity function of quasars to 22nd magnitude and fainter is still rudimentary.

The SDSS (Sloan Digital Sky Survey, Gunn & Weinberg 1995) will be the definitive survey for high-redshift quasars (and also for quasar clustering) down to 20th magnitude because of its large area coverage, 10,000 deg\(^2\). SDSS is expected to yield \(10^5\) quasars when completed. Already the initial results are very exciting. Fan et al. (1999) report the discovery of 15 quasars with \(z > 3.6\) in 140 deg\(^2\), including quasars with \(z = 4.9\) and \(z = 5.0\). They extend the high-redshift record for quasars for the first time since 1991\(^2\).

### 3.1. The Importance of the Z band

Initial spectroscopic results from the BTC40 survey confirm the importance of using the Z band for isolating \(z > 5\) quasar candidates. Unlike the situation at 4 < \(z\) < 5, where quasars can be selected with reasonable efficiency solely on their large values of \(B - R\), the analogous approach using \(V - I\) does not work for \(z > 5\) quasars. Julia Kennefick found that samples selected on the basis of large \(V - I\) are overwhelmed by late-type stars. The Z band is necessary because it is a measure of the continuum level at wavelengths longward of the Ly\(\alpha\) emission, and the behavior of late-type stars and \(z > 5\) quasars is significantly different in, for example, the \((I - Z)\) vs. \((V - I)\) two-color diagram, as Kennefick’s simulations show (Fig. 2, left). We are now in the process of selecting \(z > 5\) candidates for follow up with spectroscopic observations.

The importance of the Z band is amply demonstrated in the SDSS results (Fig. 2, right), where Fan et al. (1999) illustrate the stellar locus in the \((i^* - z^*)\) vs. \((r^* - i^*)\) plane and the location of their \(z > 4.5\) quasars, which are well

\(^2\)After the meeting, Fan et al. (2000a) reported the discovery of a quasar at \(z = 5.03\).
separated from the stars. Their results confirm that we now have well established
techniques for finding the most distant quasars.

4. The Spectra of $z \approx 5$ Quasars Compared to $z > 5$ Galaxies

It is of interest to note that the spectra of the $z \approx 5$ quasars discovered to date (Fig. 3) show the characteristically strong emission features of Ly$\alpha$, C IV, NV and Si IV + O IV] seen in quasars at lower redshift and look remarkably similar to them. Furthermore, the spectra provide information on the chemical abundances in the broad-line region that have important implications for the evolutionary history of the host galaxies of quasars (see review by Hamann & Ferland 1999).

On the other hand, the spectra of the galaxies found so far at $z > 5$ are very different from those of quasars (Figs. 4 and 5). For example, the Dey et al. (1998) galaxy at $z = 5.34$ has a very strong but narrow Ly$\alpha$ emission line on a weak continuum. The Weymann et al. (1998) galaxy at $z = 5.60$ and the van Breugel et al. (1999) radio galaxy show Ly$\alpha$ emission that is considerably weaker, while the Spinrad et al. (1998) galaxy pair at $z = 5.34$ has very weak, if any, emission and is distinguished primarily by a break in the continuum.

Let us consider for a moment the faintness of these galaxies and the large amount of spectroscopic observing time that has been dedicated by several groups of observers with the Keck telescopes to searching for faint galaxies at high redshift. It is surely impressive that galaxies with $z > 5$ are being found. The numerous discoveries exceed what I thought only a few years ago would occur. But the weakness of the spectral features of the galaxies shown in Figs. 4 and 5 compared to the strength of quasar emission lines in Fig. 3 do make one wonder if quasars/AGNs with broad-line spectra are truly very scarce at $z > 5$. 
Figure 3. Spectra of PC1247+3406, $z = 4.9$ (Schneider et al. 1991) and the SDSS $z = 5$ quasar (Fan et al. 1999).

Figure 4. Spectra of the Dey et al. (1998) galaxy at $z = 5.34$ (left) and the Weymann et al. (1998) galaxy at $z = 5.60$ (right).
Figure 5. Spectra of the van Breugel et al. (1999) radio galaxy at $z = 5.19$ (left) and the Spinrad et al. (1998) galaxy pair at $z = 5.34$ (right).

Their spectra are much easier to identify than those of the galaxies seen to date. What is their absence telling us?

Of course, it may just be too early to tell, and we must pursue the spectroscopic follow up of the $z > 5$ surveys described above. In any case, the observational opportunities that we now have to study the universe at $z > 5$ are very exciting, and we may expect continued important discoveries in the near future. Let’s meet again on the occasion of Hy’s 70th birthday to see what we have learned.

5. Update, May, 2000

Between June, 1999, when the meeting was held, and May, 2000, more quasars with $z > 5$ have been discovered, including ones at $z = 5.27$ (Zheng et al. 2000), at $z = 5.5$ (Stern et al. 2000) and at $z = 5.8$ (Fan et al. 2000b). The $z = 5.5$ object, which has $I_{AB} = 23.8$, is the faintest known quasar at high redshift. The one at $z = 5.8$, with $z^* = 19.2$ on the AB system, is very luminous. All have the strong emission lines characteristic of quasars at lower redshifts, and all have strong Ly$\alpha$ forest absorption at wavelengths shortward of their Ly$\alpha$ emission lines. However, the universe is still highly ionized at $z = 5.8$. Fan et al. (2000b) report that they have covered 600 deg$^2$ so far in their work on the Sloan Digital Sky Survey and that the discovery of the $z = 5.8$ quasar is consistent with the expectations of the Schmidt et al. (1995) parameterization of the decline of the quasar luminosity function with increasing redshift. They also note that for $z > 5.5$ it is difficult to distinguish quasars from very cool stars and brown dwarfs on the basis of the SDSS filters alone. Observations in the near infrared, where the cool objects have redder energy distributions than the quasars, aid in the selection of the quasars.
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