

The Evolution of Quasars at High Redshift and Their Connection with Galaxies

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Abstract.

I review recent observations on the evolution of quasars, describe new surveys for quasars at $z > 5$ and for quasars with $z > 3.3$ down to luminosities corresponding to L^* galaxies, and note the possible connection between the evolution of the star formation rate in young galaxies and the evolution of quasars.

1. Introduction

I appreciate the opportunity to give the first talk at this meeting and commend the Scientific Organizing Committee for bringing together researchers on both quasars and galaxies. I wish to mention some of the connections between the two fields that may be valuable for present and future research. Indeed, if quasars are powered by supermassive black holes at the centers of galaxies, the fields are not distinct. Instead, they are concerned with different stages of the formation of galactic-sized objects in the universe.

In the case of quasars at $z > 3$, for example, we may be seeing the results of the initial collapse of material at the center of a galaxy and its fueling by the infall of additional matter. The steep decline in the space density of quasars from $z \approx 2$ to the present may be caused by the decline in the fueling rate. As galaxies complete their formation, as their interaction rate presumably declines, and as the universe continues to expand, the amount of matter falling to the centers of galaxies likely declines, thus reducing quasar activity. Alfonso Cavaliere will describe his work on this model later this morning.

In the meantime, the repair of HST, the advent of the Keck telescopes, and the work on many different surveys have revolutionized observational research on the formation and evolution of galaxies. The abilities to discover, to obtain images with resolutions near 0.1 arcsec, and to do spectroscopy of galaxies with redshifts greater than 3 and down to 25th magnitude are truly changing our views of the universe.

At the same time, I think we quasar researchers are feeling rather distressed by all the excitement and developments with young galaxies. Not only have galaxy researchers pushed into the realm formerly occupied exclusively by quasars, but Franx et al. (1997) have reached beyond the highest known quasar redshift to become the current recordholders in the most-distant-known-object in the universe sweepstakes! We will hear from Marijn Franx about the lensed galaxy at $z = 4.92$ on Tuesday. Perhaps losing the redshift record will spur

quasar researchers to new depths, so to speak. More seriously, the pursuit of both galaxies and quasars at high redshift is important because it will tell us the epoch at which highly luminous objects first appeared in the universe.

In this talk, I wish to discuss three topics:

1. Recent observational results on the evolution of quasars
2. Current surveys my collaborators and I are carrying out for high-redshift quasars
3. The connection between the luminosity density of quasars and the star formation rate in high-redshift galaxies

As we shall see, the results of 1) provide motivation for 2), while 3) is of interest because of the similarity of the evolution of the quasar space density with redshift to the evolution of the star-formation or metal-enrichment rate in young galaxies (Madau et al. 1996, Connolly et al. 1997)

I will concentrate on optically selected quasars. Subsequently Isobel Hook will describe the recent results for radio-selected quasars and Stefano Cristiani will discuss his surveys for optical quasars.

2. Recent Observational Results on the Evolution of Quasars

When plotted on a linear scale against cosmic lookback time, τ , the space density of quasars shows a striking distribution with a peak near $\tau \approx 0.85$ ($q_0 = 0.5$) and a width at half maximum of ≈ 0.1 the age of the universe (Fig. 1). This plot continues to demand questions such as: Was $\tau \approx 0.85$ the main epoch of quasar formation? If so, why does the peak occur at that time and why does it have such a narrow width? Here I wish to concentrate on the observational issues.

In Figure 2 I plot the logarithm of the luminosity density for various quasar surveys against redshift. I choose the luminosity density in this case both for the comparison to be made in section 4 and because this parameter characterizes how the integrated energy output of quasars varies with redshift.

To illustrate the current observational state of quasar evolution, Fig. 2 shows the parameterization from the AAT survey (Boyle, Shanks, and Peterson 1988, Boyle 1991) for $0 < z < 2.2$ together with results from the Large Bright Quasar Survey (LBQS, Hewett, Foltz, and Chaffee 1993), the Edinburgh survey (Goldschmidt and Miller 1997), and the Homogeneous Bright Quasar Survey (HBQS, La Franca and Cristiani 1997).

One of the major recent observational questions at low redshift and bright magnitudes has been whether the Schmidt and Green (1983) results and the Boyle parameterization under-represent the true population. As we see in Fig. 2, the LBQS and Edinburgh surveys do indicate a significant correction is needed; the HBQS, less so. My assessment is that a correction on the order of a factor of several is now indicated at $z \approx 0.4$ and thus the Boyle parameterization should be modified for these redshifts and luminosities. Note that this correction is important, but it does not change the qualitative view of Fig. 1 because the space density of quasars at $z \leq 0.5$ is still down by two orders of magnitude from the peak.

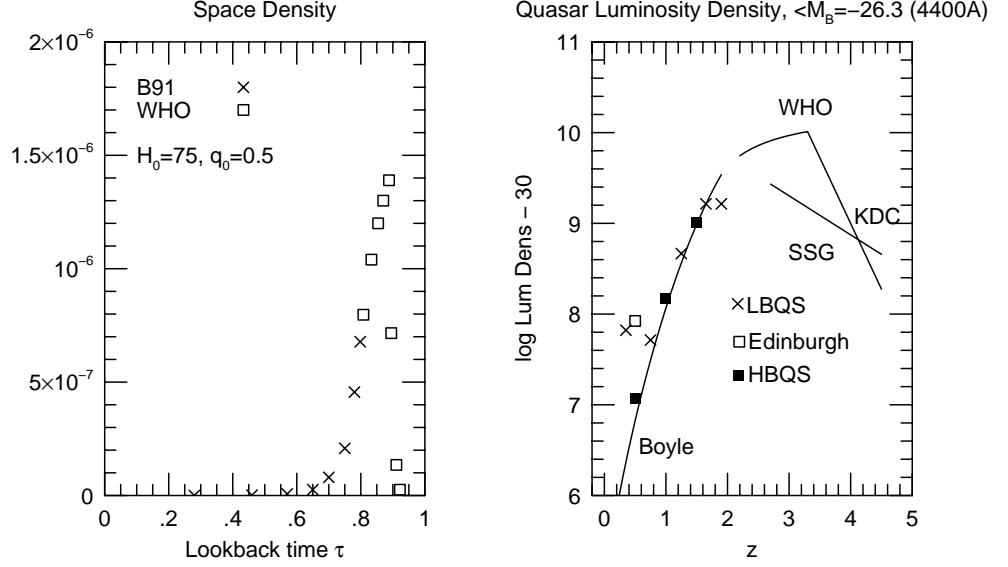


Figure 1. (Left) Quasar space density, from Warren et al. (1994) and Boyle (1991). Figure 2. (Right) Quasar luminosity density for different surveys

At intermediate redshifts, $2 \leq z \leq 3$, we see from Fig. 2 that the quasar luminosity density reaches its peak. The calibrated surveys of Warren, Hewett, and Osmer (1994, WHO) and Schmidt, Schneider, and Gunn (1995, SSG) provide the main data in this interval. WHO find the peak to be at $z \approx 3.3$, while SSG's results in combination with Boyle's indicate that the peak is closer to $z \approx 2$. I believe additional work is needed to resolve this issue, which can be done with surveys aimed particularly at the $2 < z < 3$ interval. Again, the uncertainty does not change the qualitative look of Fig. 1, but it does indicate that the uncertainty in the location of the peak is ≈ 0.07 times the age of the universe.

At higher redshifts, $z > 3$, we see in Fig. 2 that the WHO, SSG, and KDC (Kennefick, Djorgovski, and de Carvalho 1995) surveys all show good agreement at $z \approx 4.3$. This provides, I think, persuasive evidence that the apparent space density of optically selected quasars, which are the bulk of the population, does decline for $z > 3$.

However, Fig. 2 also shows that the WHO and SSG parameterizations are markedly different in the slope of the decline, with WHO being much steeper. This occurs for two reasons, the different evolutionary decline with increasing redshift *and* the different slopes of the luminosity function at the bright end. When projected to $z > 5$, the WHO and SSG results give predictions for the number of quasars that differ by more than an order of magnitude. Clearly, additional surveys over the interval $3 < z < 5$ are needed to place the quasar space density and the slope of its decline with redshift on firmer ground.

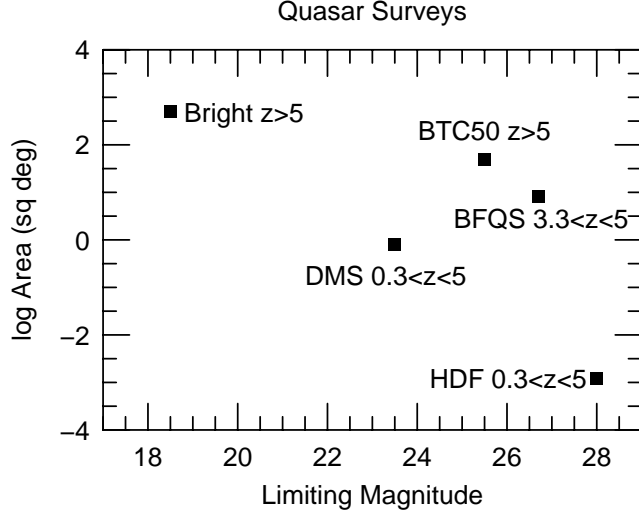


Figure 3. Area and limiting magnitude of current surveys for quasars

3. New Surveys for High-Redshift Quasars

With the success of the multicolor technique for finding quasars at high redshift (WHO, KDC, Irwin, McMahon, and Hazard 1993, IMH) and the development of multi-CCD cameras, it is now possible to carry out surveys that will either find quasars at $z > 5$ or set significant upper limits on their space density. Because we do not know well either what the slope of the luminosity function is at such redshifts or the evolutionary decline with redshift, it is important to survey a wide range of surface area and limiting magnitude. Here I will describe the surveys being done by our groups; other groups are also doing large programs, for example, Hewett and Warren; Schmidt, Schneider, and Gunn; Irwin and McMahon, the Sloan Digital Sky Survey.

To aid in visualizing the relation of the different surveys, Fig. 3 shows a plot of the log of their area *vs.* limiting magnitude. The range in area is from 500 deg^2 with the Curtis and Burrell Schmidts (in conjunction with the 2nd Palomar Sky Survey) to 4.4 arcmin^2 in the Hubble Deep Field (HDF). The range in limiting magnitudes is roughly 18 to 28. The main properties of the surveys are described below:

3.1. Deep Multicolor Survey (DMS)

P. Hall, J. Kennefick, P. Osmer, R. Green, and S. Warren are the investigators. This survey covers 0.83 deg^2 in U,B,V,R,I75,I86 to limiting magnitudes of 22.1 to 23.8 (5σ). To date 55 quasars with $0.3 < z < 4.3$ have been confirmed spectroscopically, along with 43 compact narrow emission-line galaxies (Hall et al. 1996a,b, Kennefick et al. 1997). A catalog of 21,375 stellar objects with positions, magnitudes in all six bands, and error estimates for the magnitudes is being prepared for publication.

3.2. Bright $z > 5$ Survey

This is being carried out by J. Kennefick, M. Smith, P. Osmer, R. de Carvalho, A. Athey, and P. Martini. It combines existing data from the Digitized Palomar Sky Survey (DPOSS) with new data taken at the Curtis and Burrell Schmidts in

the $z(0.9\mu)$ band to find $z > 5$ quasars to a limiting magnitude of $i \approx 18$. Ly α emission in $z > 5$ quasars will make them very red in $g - i$, and the z band data help in eliminating late-type stars. To date, data have been taken for 500 deg², and spectroscopic observations have been made of candidates selected from 300 deg². No $z > 5$ quasars have yet been confirmed.

3.3. BTC50 Survey

E. Falco, P. Schechter, C. Kochanek, R. Green, M. Smith, J. Kennefick, P. Osmer, P. Hall, and M. Postman are the investigators for this survey, which is making use of the BTC camera at CTIO to search for $z > 5$ quasars, gravitational lenses, and distant galaxy clusters. The goal is to cover 50 deg² in B,V,I, to limiting magnitudes of 25 to 26 in B and V and 24 in I. Already 20 deg² of data are in hand.

3.4. Big Faint Quasar Survey (BFQS)

P. Hall, J. Kennefick, P. Osmer, R. Green, and M. Smith are also using the BTC camera to cover 8 deg² in B,R,I to limits of 26.7, 25.7, and 24.6 to search for quasars with $3.3 < z < 5.0$ down to luminosities equivalent to those of L* galaxies. This survey will also be very useful for studies of the evolution of field galaxies.

3.5. Quasars in the Hubble Deep Field (HDF)

A. Conti, J. Kennefick, P. Martini, P. Osmer, R. Pogge, and D. Weinberg are searching for quasars and AGNs in the HDF by making use of the U,B,V,I images. From numerical simulations, we find the limiting magnitudes for classifying objects with the crude combine images to be 25.2, 27.0, 26.8, and 25.8. No clear $z > 4$ candidates have been found so far. One known emission-line galaxy with $z = 3.37$ has been independently recovered; it serves as a check on our modeling procedures. In addition, there are two possible UVX candidates.

4. Quasars at $z > 5$?

To date, I believe approximately 10³ deg² of sky have been surveyed at brighter magnitudes ($I \approx 18$) by our group and by Hewett and Warren, so far with negative results for quasars at $z > 5$. While the spectroscopy is not finished, we do have about 120 M-type stars, which should yield a significant improvement in determining the lower end of the stellar luminosity function. In the meantime, Franx et al. (1997) have discovered a lensed galaxy at $z = 4.92$. Are we hitting the wall on distant quasars?

In the spirit of Fig. 1 and 2, I show in Fig. 4 the currently known space density of $z > 5$ quasars, both in a log N vs. z and N vs. τ format. Obviously, we need to fill in the diagram for the first 7% of cosmic time to understand when quasars first became visible.

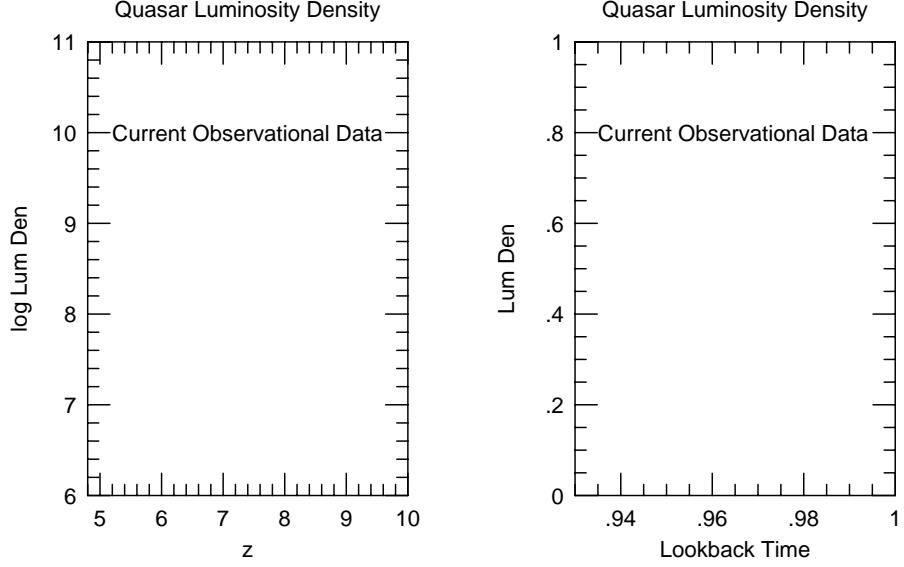


Figure 4. Currently known space density of $z > 5$ quasars. *Left.* Log of space density vs. redshift. *Right.* Linear plot of space density vs. lookback time.

5. The Connection between Quasars and Galaxies

The results of Madau et al. (1996, 1997) on the evolution of the star-formation history of galaxies show evidence for the star-formation rate (SFR) to increase with redshift by an order of magnitude from $z = 0$ to $z = 1$ and then decline toward higher redshift. The behavior is reminiscent of but not identical to the evolution of the space density of quasars. The SFR peaks at a lower redshift and has a broader distribution. Is there a connection between the SFR in galaxies and quasar evolution?

It is worthwhile to investigate the possible connection. The same processes responsible for the fueling of quasars may well trigger star formation in the host galaxies. Such processes include galaxy interactions and instabilities. Although the energy sources for stars and quasars are different, the integrated ultraviolet luminosity density reflects the SFR for young stars in the case of high-redshift galaxies and the fueling rate in the case of quasars. In addition, both luminosity densities are directly observable quantities, and both have impacts on the ionization state of the interstellar and intergalactic media at high redshift.

To illustrate the connection, I use two forms. The first, Fig. 5 (left), is the log of the quasar luminosity density, adapted from Fig. 2, and the log of the luminosity density for the 2800\AA emission of galaxies, adapted from Connolly et al. (1997), *vs.* redshift. We see that the luminosity densities of the two classes of objects are within an order of magnitude of each other. When we consider that the stellar values have been integrated over a Schechter luminosity function to represent the entire population of objects, while the quasar values are only for luminous ($M_B < -26$) quasars, the total quasar luminosity density may

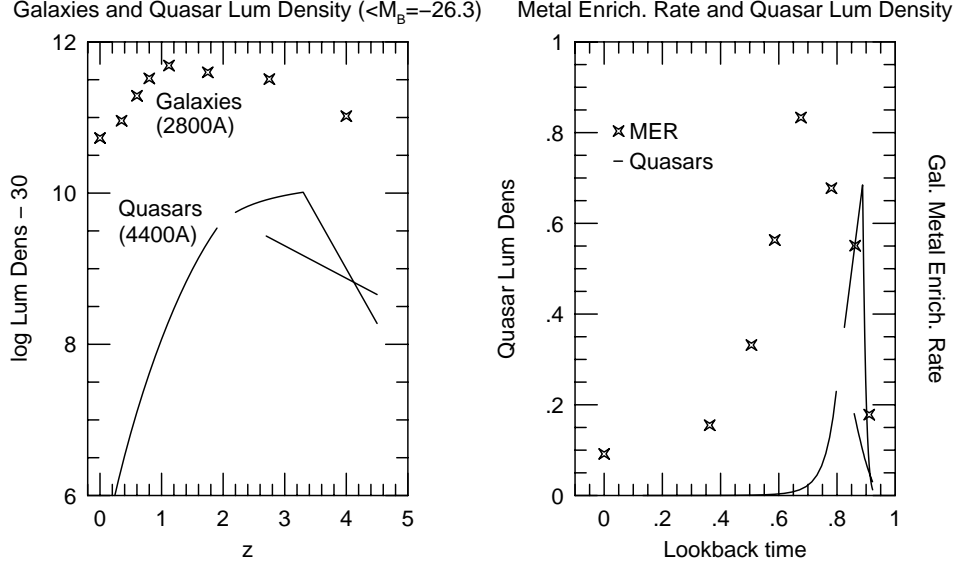


Figure 5. *Left.* A comparison of the luminosity density of galaxies (2800Å) and luminous quasars (4400Å). *Right.* A linear plot of the metal enrichment rate and the quasar luminosity density (arbitrary scale) vs lookback time.

approach and even exceed the stellar luminosity density. The second form, Fig. 5 (right) shows a linear plot of the metal enrichment rate (MER) and quasar luminosity density *vs.* lookback time. The MER is shown because it is less sensitive than the inferred star formation rate to assumptions about the slope of the initial mass function (Madau et al. 1996). This form shows more directly the offset in cosmic time, 0.25 of the age of the universe, and the greater breadth of the MER relative to quasars¹.

Although there are still uncertainties in the determination of the SFR and MER for young galaxies and in the nature of quasar evolution, Fig. 5 does provide a framework for observational mapping of the star formation history and the evolution of nuclear activity in young galaxies. Continued observational work in turn should lead to improved understanding of how galaxies form and evolve.

6. Summary and Future Work

1. The main observational properties of the evolution of optically selected, bright ($R \leq 20$) quasars are reasonably well established for $0 < z < 4.5$. However, we still need to determine better the redshift at which

¹Subsequent to the meeting, Boyle and Terlevich (1997) independently noted this connection and discussed it in terms of the starburst model for quasars.

the evolution peaks and especially the slope of its decline toward higher redshift.

2. We now have the observational tools to observe both quasars and galaxies to $z > 5$ and to magnitudes ≥ 25 . Thus, we have the capability to map observationally their evolution down to L^* luminosities at $z \approx 5$ and $0.1 L^*$ at $z = 2$. The data will be important to improving our theoretical understanding of galaxy formation and evolution.
3. There is reason to expect the discovery of galaxies and quasars at $z > 5$ (the increment in cosmic time is only 0.001 of the age of the universe compared to the most distant object now known ($z = 4.92$)).

Do quasars exist at $z > 5$? Perhaps we will have an answer by the time of the next meeting on this topic. In any case, exploring the properties and evolution of both galaxies and quasars at high redshift will be one of our grandest adventures.

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