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Evolution of high-redshift quasars

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Abstract. The discovery of luminous quasars at $z > 6$ indicates the existence billion-solar-mass black holes at the end of reionization epoch. directly probing the early growth of supermassive black holes in the universe and the relation between the formation of early galaxies and black holes. With the advant of the Sloan Digital Sky Survey and other large area surveys, about 1000 quasars have been discovered at $z > 4$, including > 50 at $z > 5$ and nine at $z > 6$. In this proceeding, I review the recent observational results studies of the highest redshift quasars, including the evolution of quasar density and luminosity function, the evolution of spectral properties and chemical enrichment history, distribution of black hole masses and properties of quasar environment and host galaxies at high redshift.

Key words. quasars: general – quasars: emission lines; cosmology: observations

Discoveries of luminous quasars at $z > 6$ (Fan et al. 2001a, 2003, 2004, 2005) shows that active, massive black holes of the order billion solar masses existed a few hundred million years after the first star formation in the Universe (e.g. Kogut et al. 2003), at the end of the reionization epoch (Fan et al. 2002). How does the black hole population grow with cosmic time? How does the evolution of quasar density traces the accretion history of early supermassive black holes? Locally, the tight correlation between the mass of central BHs and the velocity dispersion of host galaxies implies that black hole activities and galaxy formation are strongly coupled (e.g. Gebhardt et al. 2001). How are the formation of galaxies and black hole activities related at early epochs? Finally, the detection of complete Gunn-Peterson (1965) troughs in the highest redshift quasars (Becker et al. 2001, Djorgovski et al. 2001, Fan et al. 2002, White et al. 2003) marks the reionization process ended at $z \sim 6$. What is the role of black hole accretion power played in the reionization of the Universe? Detailed observations of the highest-redshift quasars known provide crucial answers to these important questions about quasar formation, galaxy evolution and the evolution of intergalactic medium (IGM).

1. Progress in Survey of High-redshift Quasars

In the past decade, because of wide-field CCD technology and a number of new and very powerful surveys, such as the Sloan Digital Sky Survey (SDSS, York et al. 2000), the studies of highest redshift quasars entered a new era: not only can we probe the $z > 5$ universe, nearing the end of the cosmic dark ages, but also begin to collect large samples of high redshift quasars to ask detailed statistical ques-

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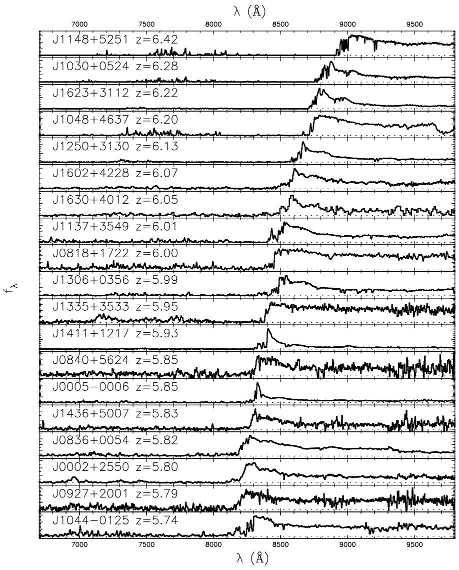

Fig. 1. Low-dispersion spectra of the nineteen SDSS quasars (as of Fall 2005) at $z > 5.7$. Note the strong Lyα absorption blueward of Lyα emission and the existence of strong metal emission lines in the spectra (Adapted from Fan et al. 2006b).

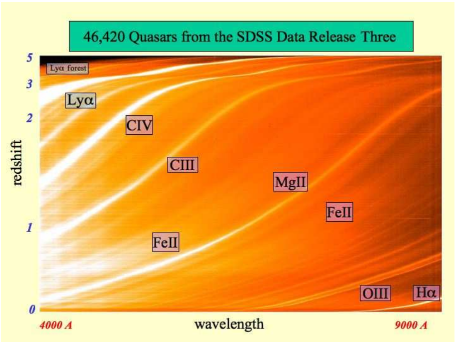

Fig. 2. A two-dimensional composite of the 46,420 quasars from the SDSS DR3 quasar catalog.

tions about their properties and their evolution. These surveys revolutionized quasar research, and gave us some first glimpse of the questions posted above.

Quasars with redshift greater than 5.7 are characterized by very red $i - z$ colors. Since 2000, we have been using the imaging data from the SDSS to select i-dropout candidates. At $z > 5.7$, all quasars have deep Lyα absorption and satisfy our color-selection criteria ($i - z > 2.2$). In a series of papers (Fan et al. 2000, 2001, 2003, 2004, 2006a), we reported the selection and identification of nineteen quasars selected from about 6600 deg^2 of SDSS imaging. The sample covers the redshift range $z = 5.74 - 6.42$, and a range of absolute magnitudes in rest-frame 1450Å, $M_{1450} = -26.2$ to -27.9. They are the most distant luminous quasars published to date (see also Mahabal et al. 2005, R. Cool et al. in preparation). We are currently extending the survey towards fainter luminosities, and expect to increase this number by another 50% at the end of the SDSS survey. Figure 1 shows the spectra of the nineteen SDSS quasars at $z > 5.7$. Note the strong and complete Gunn-Peterson troughs in the highest redshift objects, and the existence of strong metal emission lines in all quasars.

2. Evolution of Quasar Density and Luminosity Function at High-Redshift

Figure 2 is a composite 2-dimensional spectrum (as a function of both wavelength and redshift) of the 46,420 quasars in the SDSS public Data Release 3 quasar catalog (Schneider et al. 2005). We combine all the 1-dimensional spectra, order them by redshift to construct this 2-dimensional image. This figure illustrates two fundamental properties about quasar evolution:

- The strong evolution of quasar number density. The distribution along y-axis in Figure 2 indicates the evolution of quasar numbers as a function of redshift of this flux-limited sample: luminous quasars are very rare in the early universe, following the initial rise of quasar population in the early times.
- In sharp contrast to the strong density evolution is the lack of strong evolution of quasar spectral properties. The strength

of emission lines remains roughly constant through cosmic history. The immediate environment of quasars matures very early on, and are somewhat decoupled from the cosmic evolution. In other words, quasar emission looks the same even up to the highest redshift, which implies that the knowledge about quasar emission we learned from local universe can be applied to the highest redshift. We will discuss both points in more detail.

The density of luminous quasars is a strong function of redshift: it peaks at $z \sim 2-3$ and declines exponentially towards lower and higher redshift (e.g. Schmidt et al. 1995, Boyle et al. 2000). Compared to the evolution of star-formation rate in the Universe, the quasar density peaks at higher redshift, and evolves much faster. This exponential decline continues to the highest redshifts. In Figure 3, we present the density of quasars at $M_{1450} < -26.7$ found in 6000 deg^2 of SDSS data at $z \sim 6$, along with the results from lower redshift (Schmidt et al. 1995, Boyle et al. 2000, Fan et al. 2001b). The quasar density at $z \sim 6$ found here is consistent with extrapolating the best-fit quasar luminosity functions in the range $3 < z < 5$. The comoving density of luminous quasars at $z \sim 6$ is ~ 40 times smaller than that at $z \sim 3$, as we close in to the epoch of the formation of first supermassive black holes in the Universe.

The existence of these objects is amazing feat of galaxy formation process. The SDSS $z \sim 6$ quasars are among the most luminous quasars at any redshift; their apparent magnitudes are ~ 19 even at $z > 6$! They are likely powered by supermassive black holes with several billion solar masses, and reside in dark matter halo of $10^{13} M_{\odot}$. They are among the most massive black holes and galaxies at any redshifts. It is a challenge as how the universe could have formed with such massive galaxies, and in particular, have assembled such massive black holes in the first Gyr of the cosmic evolution. They are clearly the rarest and most biased systems in the early universe, and probably have started the initial assemble at redshift much higher than 10, well into the dark ages, providing important clues to the co-formation

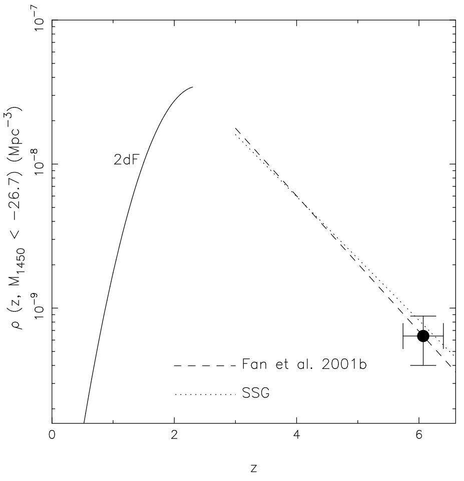

Fig. 3. The evolution of the quasar comoving spatial density at $M_{1450} < -26.7$. The filled circle represents the result from this survey. The error-bar in redshift indicates the redshift range covered by the *i*-dropout survey. The dashed and dotted lines are the best-fit models from Fan et al. (2001b) and Schmidt et al. (1995, SSG), respectively. The solid line is the best-fit model from the 2dF survey (Croom et al. 2004) at $z < 2.3$. Adapted from Fan et al. 2004

and co-evolution of the earliest supermassive black holes and galaxies (§4).

Surveys such as the SDSS only sample the brightest end of the quasar luminosity function. Does fainter quasars and AGNs evolve differently at high-redshift? We know from the 2dF quasar survey that at low-redshift, quasar luminosity function is well fit by a double power law with pure luminosity evolution, in the sense that the characteristic luminosity of quasars decreases at lower redshift. This can be understood in the sense that the black hole activities powering the quasars is downsizing towards current epoch, similar to what people found in X-ray selected samples (e.g. Cowie et al. 2003).

But at high redshift, we currently have very few direct constraints on the LF shape. The SDSS main surveys are limited to $M_B < -26$ at $z > 4$. Does the difference between X-ray and optically selected samples a true reflec-

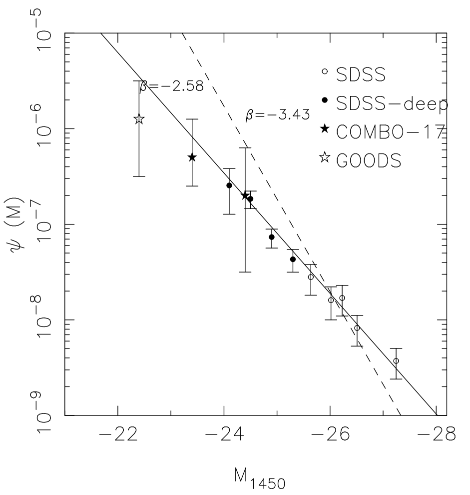

Fig. 4. The luminosity function of quasars at $z \sim 4.5$, comparing the data from the SDSS main survey, the SDSS deep survey, COMBO-17 survey and quasar candidates in the GOODS field. It is evident that quasar luminosity function at $z \sim 4$ is shallower than that at $z < 2$.

tion of the different evolution of the obscured population? Or it is simple a luminosity effect. Are we seriously biased by only looking at the luminous sources? We are currently using the repeated imaging in the SDSS deep stripe in the Southern Galactic Cap to select faint, high-redshift quasar candidates and carry out a deep quasar survey with the 300 fiber HECTOSPEC spectrograph on the MMT (Liang et al. 2006). This deep survey will reach 2 to 3 mag fainter than the SDSS main survey. We will be able to find several thousand new faint quasars, including few hundred at $z > 3$, and a reasonable number at $z \sim 6$ (depending on the unknown slope of quasar luminosity function at high-redshift), reaching AGN luminosity at $z \sim 3$ in wide area, and bridge the current SDSS wide area sample with deep pencil beam surveys such as the CDFS. Preliminary results (Figure 4) already strongly suggest a very different LF slope for high-redshift quasars: it is much flatter than at low-redshift, suggesting that the most luminous quasars grow early in the cosmic history.

What is the role quasars and AGNs played in the cosmic reionization? Fan et al. (2001b) showed that quasars could not have maintained IGM ionization at $z \sim 6$, as far as the shape of the luminosity function at $z \sim 6$ is not much steeper than that at $z < 3$. Willott et al. (2005) and Mahabal et al. (2005) present surveys of a few deg^2 for faint $z \sim 6$ quasars. Their non-detection of faint QSO at $z \sim 6$ implies that the quasar population contribution to the ionizing background is $< 30\%$ that of star-forming galaxies. Finally, Dijkstra et al. (2004) and Salvaterra et al. (2005) show if the Universe were ionized by AGNs, hard X-rays from these same sources would over-produce a present-day soft X-ray background by a large factor. A population dominated by mini-quasars could still partially ionize the IGM at $z >> 6$, but its contribution could be severely constrained if the X-ray background is further resolved into discrete sources. Most likely, the Universe was reionized by a population of star-forming galaxies at high-redshift.

3. Spectral Evolution and Black Hole Mass at High-Redshift

The spectral energy distributions of luminous quasars show little evolution out to high redshift. There is growing evidence from emission line ratio measurements that quasar broad emission line regions have roughly solar or even higher metallicities at $z > 4$ (e.g., Hamann & Ferland 1993), similar to that in low redshift quasars. Dietrich et al. (2003b) found the FeII/MgII ratio to have roughly the same value in a sample of $z \sim 5$ quasars as at lower redshift, suggesting that the metallicity of quasar emission line region remains high to even earlier epochs.

The sample of quasars at $z > 5.7$ from the SDSS provides the first opportunity to study the evolution of quasar spectral properties at $z \sim 6$, less than 1 Gyr after the Big Bang and only 700 million years from the first star formation in the Universe. Optical and infrared spectroscopy of some $z \sim 6$ quasars already indicates *a lack of evolution* in the spectral properties of these luminous quasars: Pentericci et al. (2002) show that the CIV/NV ratio in two

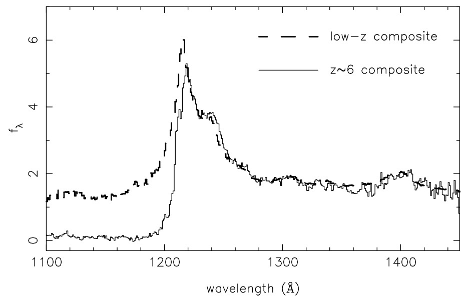

Fig. 5. The composite spectrum of $z \sim 6$ quasars (solid line).For comparison, we also plot the low-redshift quasar spectral composite from Vanden Berk et al. (2001). The effective redshift in the 1000 – 1500Å range in the Vanden Berk et al. composite is about 2. The quasar intrinsic spectrum redward of Lyα emission shows no detectable evolution up to $z \sim 6$, in terms of both the continuum shape and emission line strengths. On the blue side of Lyα emission, the strong IGM absorption at $z \sim 6$ removes most of the quasar flux. Adapted from Fan et al. (2004)

$z \sim 6$ quasars are indicative of supersolar metallicity in these systems. Freudling et al. (2003) and Barth et al. (2003). detected strong FeII emission in the spectra of four $z \sim 6$ SDSS quasars. In addition, the optical-to-X-ray flux ratios and X-ray continuum shapes show at most mild evolution from low redshift (e.g. Brandt et al. 2002, Vignali et al. 2003). Figure 5 shows the composite of our $z \sim 6$ quasar spectra: it is almost identical to the low-z composite, both in term of the spectral slope, and emission line strength. The only differences are that the Lyα forest is much stronger at $z \sim 6$ and the blue wing of Lyα is also affected.

Based on chemical evolution models, especially with diagnostic lines such as N, Fe or C, the strength of these emission lines indicate the metallicity of quasar emission line region to be supersolar. This is direct evidence of rapid chemical enrichment process through multiple generations of star formation in the immediate environment of these luminous quasars. These results, if confirmed with a larger sample, suggest that the accretion disk and photoionization structure of quasars reached maturity very early on and are probably insensitive to the host galaxy environment.

The continuum and emission line scaling relations currently provide the only viable way to estimate black holes mass of quasars at high-redshift. This method is very appealing, because the emission line measurement is relatively easy, and can be applied to the highest redshift, when no any other BH mass estimate can be applied with any accuracy. As discussed above, quasars do not show strong spectral evolution, indicating that their emission line region structure is not a function of redshift, is not affect by cosmic environment. This implies that the measurement calibrated locally can be reliably applied to high-redshift.

The black hole mass estimates of the $z \sim 6$ SDSS quasars ranging from several times $10^8 M_\odot$ to several times $10^9 M_\odot$. Assuming continuous Eddington accretion from a seed black hole of 100 $M_\odot$, the formation redshift for seed black holes must be at $z > 10$. Even with continuous accretion, black holes in the most luminous quasars barely had enough time growing. While there are various ways of accreting faster than Eddington, the fact that the highest redshift quasars sit right at the threshold of the reionization epoch simply indicate that the initial growth of those BHs have to be very efficient and very early on. Figure 6 shows the black hole mass distributions at $z > 3$ from the SDSS samples using virial relations. One intriguing feature that we noticed is the apparent lack of quasars with BH masses larger than a few times 10^10 solar masses, at all redshift.

The lack of spectral evolution in high-redshift quasars is not limited to the rest-frame UV, it is also evident in X-ray and near to mid-IR. Strateva et al. 2005 studied the evolution of $\alpha_O X$, the power law index between soft X-ray and optical, for a large sample of quasars at $z = 0 - 6$. They found that when taken into account the dependence of α_{OX} on UV luminosity, there is no any evidence of evolution in the X-ray emission of quasars. Preliminary analysis of Spitzer observations (Fan et al. in preparation) also indicates a lack of spectral evolution in the rest-frame optical to near-IR wavelength. In particular, there is no system-

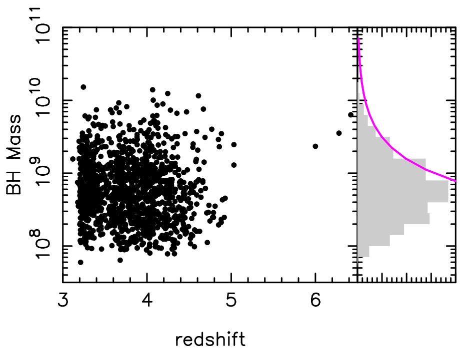

Fig. 6. Distribution of black hole masses for SDSS quasars at $z > 3$.

atic different in the onset of dust torus emission in near-IR between $z \sim 6$ quasars and their low redshift counterparts. The only noticeable difference between the SEDs of low and high redshift thus far is the detection of significant evolution in the shape of dust extinction curves (Maiolino et al. 2004). At $z \sim 6$, the age of the Universe is ~ 1 Gyr, shorter than the timescale for dust formation in AGB envelops. Maiolino et al. (2004) found evidence of dust consistent with those produced in supernova explosions along the line of sight of low-ionization BAL quasar SDSS J1048+4637 ($z = 6.20$).

4. Probing the Host Galaxy Evolution

Luminous high-redshift quasars are likely located in the densest, most extreme environment in the early Universe. Simple estimates based on their number density show that the SDSS $z \sim 6$ quasars represent 5–6 σ peaks in the density field at high redshift. We expect them to in the richest galaxy environment, with high concentration of star-forming galaxies. Recent results of deep imaging of $z \sim 6$ quasars confirmed this picture. Zheng et al. (2005) obtained deep HST/ACS image of SDSS J0836+0054 ($z = 5.82$). They shows large number of *i*-dropout galaxies, likely associated with the quasar, with a surface density $\sim$ 6 times higher than in a blank field, making is one of the highest galaxy overdensities at high redshift, which could evolve into a rich cluster at lower redshift. Similar overdensity is found in SDSS J1030+0524 ($z = 6.28$, Stiavelli et al. 2005)

However, direct imaging of the stellar light of host galaxies is extremely difficult with current technology, because of the enormous luminosity of the central quasar and the $(1 + z)^4$ dimming in surface brightness. The best way to probe the host galaxy is to look at longer wavelength where the contribution from the central AGN is not dominating. At observed far-IR to mm wavelength, the radiation of radio quiet quasars is dominated by reprocessed radiation of cool dust in the host galaxy. Combining with IR measurement such as those coming from Spitzer, which probes the hot dust heated by the AGN itself, one can then have a reliable estimate of the star formation rate in the host galaxy. ALMA, which not only has high resolution imaging in these wavelength, but also provides wealth information on various line diagnostics, will revolutionize the study of quasar host galaxies in the sub-millimeter wavelengths.

A large number of high-z quasars have been observed with either IRAM 30m or SCUBA on JCMT. Roughly 40% of the radio-quiet quasars are detected at 1mm at 1mJy level (e.g. Carilli et al. 2002, Priddey et al. 2003). The submm radiation almost certainly comes from warm dust in the quasar host galaxy. The FIR luminosity, of the order $10^{13} L_{\odot}$, is as bright as the brightest nearby ULIRGs such as Arp 220, implying a dust mass of the order $10^{8} M_{\odot}$. If the dust heating came from star burst activity, that would suggest an enormous star formation rate of several hundred, sometimes several thousand solar masses per year. The most massive black holes in the early universe likely live in the most intensive star formation sites in the early universe.

The most striking example of the possible connection between star formation and black hole activity at early epoch is the observation of the highest redshift quasar SDSS J1148+5251 at $z = 6.42$. This object is detected as a strong mm source using IRAM 30 m (Bertoldi et al. 2003), indicating a dust mass of several times $10^{8} M_{\odot}$. Subsequent observa-

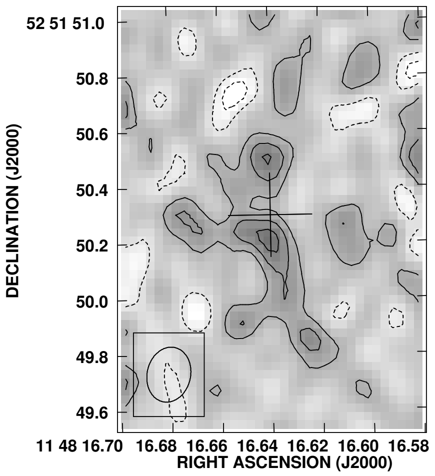

Fig. 7. VLT CO (3-2) map at 1kpc resolution in the central region of the host galaxy of SDSS J1148+5251 (z = 6.42, adapted from Walter et al. 2004). The host galaxy is clearly resolved.

tions show strong CO emission in several transitions (Walter et al. 2003), signaling a large molecular gas reservoir of the order $10^{10} M_{\odot}$. The submm and radio observations suggest an on-going SFR of 1000 $M_{\odot}$ per year.

Walter et al. (2004, Figure 7) obtained high-resolution VLA observations of the CO in this $z = 6.42$ quasar. The VLA CO 3–2 data have a resolution of 0.15", or about 1kpc at $z = 6.4$, enable us to resolve the molecular gas both spatially and in velocity space. Spatially, CO is extended to a radius of 2 kpc, with the central region showing two 2 peaks separated by 0.3", and the quasar roughly at the center of two peak. Does this suggest a disk like structure? The VLA channel map shows the velocity structure of the various components, with a velocity resolution of 60 km/s. The total gas has a line-width of 280 km/s, and the centroid of the emission shifts by 1.5 kpc over 120 km/s. This is the first time a high-z host is resolved both spatially and kinematically. Assuming the gas is bound, the estimated dynamically mass is about $10^{10} M_{\odot}$ withing a radius of 2 kpc. In other words, there just isn't a lot of mass there. If the system is living in some kind of bulge, the mass even within 20 kpc is still only $10^{11} M_{\odot}$, much smaller than the $10^{12} M_{\odot}$ one would expect from the local M-σ relation. While it is only one system, and the dynamical situation there is far from clear, it is highly suggestive that this luminous quasars at high-redshift does not live in a fully developed galaxy with a massive central bulge. Does this suggest that black hole formed before galaxy assembly? More such observations would be extremely valuable to answer this question.

5. Concluding Remarks

The last few years has witnessed the discovery of luminous quasars at $z > 6$, which are likely anchored by supermassive black holes with $> 10^9 M_{\odot}$. Furthermore, the spectral energy distribution of these quasars, across the entire electromagnetic spectrum, shows very little evolution from their low-redshift counterparts. Is the existence of luminous quasars, with massive black holes and "mature" SEDs and high metallicity a big surprise? Or this is something totally expected? What can we learn from these early, and likely extreme objects about the accretion mechanism of the first quasars, about the timescale of quasar formation, and about quasar evolution in general? These are some of the questions that future studies of these fascinating objects will have to answer.

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