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# Evidence for Early Black Hole Growth

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### Abstract
Evidence is presented that the central black-holes in distant, luminous quasars must have built up a significant fraction of their mass early and/or fast, that is before the bulk of the stars in their host galaxies.

Available spectral data of luminous, high-redshift ($1.5 < z \lesssim 6$) quasars show their central black-holes to have masses of $\sim 10^9\,M_\odot$ on average. Yet, other studies show that host galaxies of active galaxies and quasars at redshifts beyond 3 are relatively young: they have very high star-formation rates, contain large amounts of molecular gas and dust, but contain only a small fraction of what can be expected to be the final stellar mass of the galaxy.

This contribution also summarizes how the high-$z$ black hole masses are estimated and why. The results presented here are discussed in further detail by Vestergaard (2004; hereafter Paper I).

## 1.1 Motivation
It is a well-established fact that the space density of quasars rises rapidly from redshifts 1 to 2 and drops off dramatically beyond a redshift of $\sim$3 (see e.g., Figure 11.3 by Peterson 1997; note the logarithmic scale). The redshift range $2 \lesssim z \lesssim 3.5$ is known as the quasar era. If the high-$z$ drop in space density signifies the epoch at which the quasar population is being build up, one obvious question to ask is whether the fundamental properties, such as the mass of the central black hole, $M_{\rm BH}$, also change at $z \gtrsim 3.5$. During such a build-up phase one would expect the bulk of the quasars to have lower $M_{\rm BH}$ than at lower redshift ($z \lesssim 3$), assuming that quasars shine as they grow (Efstathiou & Rees 1988). Although none of the currently available quasar surveys probes the full quasar population (or even the bulk of it), especially at high-$z$, we may however hope to detect a higher fraction of quasars with lower masses relative to $z \approx 2$ quasars. In the following, black-hole masses of high-$z$ quasars are estimated and compared to those of their lower-$z$ cousins. How the properties of high redshift quasars compare to those of their host galaxies is also discussed. But first, the method used to estimate the mass is described.

A cosmology with $H_0$ = 75 km s$^{-1}$Mpc$^{-1}$, $q_0$ = 0.5, and $\Lambda$ = 0 is used throughout, although the main conclusions of this study do not depend on the specific choice of cosmology.

## 1.2 Virial Mass Estimates
Due to the strong, central glare from the active nucleus the conventional methods used to measure the mass of the central black hole in local quiescent galaxies, namely kine-

matics of stars and gas within the sphere of influence of the black hole, cannot be used for active galaxies and quasars. The possible exception is the lowest luminosity active galaxies in the nearby Universe. By utilizing the variability properties of the active nuclei, reverberation mapping does not require high spatial resolution and is the most robust method to directly measure the mass of the central black hole in active nuclei. However, luminous quasars vary on time scales of years and with smaller amplitudes (e.g., Kaspi 2001). And for high-redshift quasars, these long time scales are further increased by time dilation due to their large distances. This means that it will take *many* years to measure the mass of the central black hole in distant quasars. Practically, it is impossible to obtain a statistically significant sample of high-redshift quasar mass measurements in a human life time. However, if we can *estimate* the black-hole mass, even to within a factor of a few, we can make significant progress. This is the motivation for obtaining mass estimates based on single-epoch spectral measurements (as opposed to multiple-epoch spectroscopy required for reverberation mapping studies) and calibrating these estimates to the more accurate reverberation mapping masses (Vestergaard 2002).

The virial mass is $M_{\rm BH} = v_{\rm BLR}^2 R_{\rm BLR}/G$, where $v_{\rm BLR}$ is the velocity dispersion of the broad line region (BLR) and $R_{\rm BLR}$ is the size of the BLR (that is, the distance to the varying emission line gas). The distance, $R_{\rm BLR}$ ($= \tau c$), is determined with reverberation mapping techniques from the time delay, $\tau$, in the response of the line emission to the ionizing continuum variations. The velocity dispersion can be expressed as $v_{\rm BLR} = f v_{\rm FWHM}$, where $v_{\rm FWHM}$ is the FWHM of the emission profile of the broad-line gas and $f$ is a factor of order unity which depends on the geometry and the details of the kinematics (e.g., Peterson & Wandel 1999, 2000; Krolik 2001; McLure & Dunlop 2001). Reverberation mapping studies have shown that an empirical relation between $R_{\rm BLR}$ and the optical continuum luminosity exists across several orders of magnitude in luminosity from Seyfert 1 galaxies to quasars (Kaspi et al. 2000), $R_{\rm BLR} \propto L_\lambda(5100\text{Å})^{0.7}$. This means that the black-hole mass can be estimated given measurements of the H$\beta$ broad line width and the continuum luminosity, $L_\lambda(5100\text{Å})$. Vestergaard (2002) discusses in detail how this single-epoch mass estimate is obtained and calibrated to the more accurate reverberation mapping masses. In that work the mass scaling relationship is extended to the restframe UV using C IV line widths and UV continuum luminosity, $L_\lambda(1350\text{Å})$.

There are several reasons why such an extension is reasonable. First, most, if not all, of the broad line region gas is in virial motion around the central source. Simultaneous restframe optical and UV monitoring of NGC 5548 has shown that the broad lines measured (Si IV $\lambda$1400, C IV $\lambda$1549, He II $\lambda$1640, C III] $\lambda$1908, H$\beta$ $\lambda$4861, He II $\lambda$4686) are consistent with virial motion of the broad line region. In particular, the highest ionization lines are emitted closer to the central source (smaller time lags, $\tau$) and have larger line widths as expected if they are due to virial motion (Peterson & Wandel 1999). Second, virial motion of the broad line region is quite likely to be common to all active galaxies and quasars. For three other nearby active galaxies (NGC 3783, NGC 7469, and 3C 390.3) a test of the line width dependence on time lag is possible, and a similar behavior of the broad lines measured is observed (Peterson & Wandel 2000; Onken & Peterson 2002). For these AGNs the number of emission lines monitored is smaller than in the study of NGC 5548, but the line width − lag relationship is still secure. For these four objects the line widths span a factor of 5, the lags span a range of almost two decades, and the resulting virial black-hole mass inferred from the line widths and time lags span a factor of 40. In summary, since all the active galaxies with suitable multiple emission line measurements demonstrate a virial relationship between their line widths and variability time lags, it is fair to assume this relationship extends to most active nuclei. Third, the extension to the restframe UV is just a matter of scaling. This is because (a) the size of the C IV emitting region is about half that of H $\beta$ (Korista et al. 1995), (b) a relationship between the size of the H $\beta$ emitting region and the optical continuum luminosity is established (Kaspi et al. 2000; see above), and (c) the optical-UV continua of active galaxies and quasars are strongly correlated.

The optical relationship is (Kaspi et al. 2000; Vestergaard 2002)

$$M = 1.5 \times 10^5 \left(\frac{R_{\rm BLR}}{\rm lt-days}\right) \left(\frac{v_{\rm FWHM}}{10^3 \text{ km s}^{-1}}\right)^2 M_\odot, \tag{1.1}$$

where

$$R_{\rm BLR} = (32.9 \pm 5.5) \left[\frac{\lambda L_\lambda(5100)}{10^{44} \text{ ergs s}^{-1}}\right]^{0.7 \pm 0.1} \text{ lt} - \text{days}, \tag{1.2}$$

is the BLR size − luminosity relationship established by Kaspi et al. (see also Vestergaard 2002). The UV relationship is (Vestergaard 2002)

$$\log M_{\rm BH}/M_\odot = \log \left[\left(\frac{\rm FWHM(CIV)}{1000 \text{ km s}^{-1}}\right)^2 \left(\frac{\lambda L_\lambda(1350)}{10^{44} \text{ ergs s}^{-1}}\right)^{0.7}\right] + 6.2 \tag{1.3}$$

The 1 $\sigma$ uncertainties in the mass estimates based on these optical and UV scaling laws are a factor 2.5 and 3, respectively. The similarity of quasar spectra at all redshifts (see later) combined with photoionization modeling also argue that these scaling laws cannot yield mass estimates in error by a factor much larger than this (see Paper I). This is quite good considering that the reverberation mapping masses have uncertainties of a factor 2 or less. This is judged by the scatter around the $M_{\rm BH} - \sigma$ relationship, as established for quiescent galaxies, of the active galaxies for which the bulge velocity dispersion in the host galaxy could be measured (e.g., Ferrarese et al. 2001). Note, however, that an individual mass estimate may be in error by up to a factor $\sim$10. The power of these mass estimates is in their statistical application to large data sets.

## 1.3 Data

The mass scaling laws presented by Vestergaard (2002) and summarized above were applied to several quasar samples spanning a range of redshifts, namely, the Bright Quasar Survey (BQS; Schmidt & Green 1983) at low redshift ($z < 0.5$; 87 quasars), the well-selected samples of radio-quiet and radio-loud quasars at intermediate redshifts ($1.5 \lesssim z \lesssim 3.5$; $\sim$120 quasars) studied by Barthel, Tytler, & Thomson (1990), Vestergaard (2000), and Vestergaard, Wilkes, & Barthel (2000), and at high redshift ($3.5 \lesssim z \lesssim 6.3$), the published quasar samples from the Sloan Digital Sky Survey Early Data Release (Fan et al. 1999, 2000, 2001; Anderson et al. 2001) and the published high-quality data of 40 redshift four quasars (Constantin et al. 2001) discovered by various surveys prior to $\sim$1996.

For the BQS quasars without mass measurements from reverberation mapping studies (Wandel, Peterson, & Malkan 1999; Kaspi et al. 2000) the black-hole masses were estimated using the optical scaling law [eqs. (1.1) and eqn. (1.2)] and the spectra presented by Boroson & Green (1992). For the $\sim 270$ quasars at $z \gtrsim 1.5$, the UV scaling law (eq. (1.3)), was used to estimate their black-hole masses. Most of the radio-loud quasars in the $1.5 \lesssim z \lesssim 3.5$ sample are matched one-to-one to the radio-quiet quasars in that sample with respect to redshift and luminosity (see Vestergaard 2000 and Paper I for details).

Bolometric luminosities were estimated by applying a bolometric correction factor of 9.74 to the restframe optical continuum luminosity, $L_\lambda$(4400Å), or of 4.62 to the restframe UV continuum luminosity, $L_\lambda$(1350Å), as appropriate. These bolometric corrections were determined from the composite radio-quiet quasar spectral energy distribution by Elvis et al. (1994) corrected to account for the updates to the average X-ray spectrum presented by Elvis, Risaliti, & Zamorani (2002). Details are described in Paper I.

## 1.4 Masses of Distant Quasars

Figure 1.1 shows histograms of black-hole masses, $M_{\rm BH}$, bolometric luminosity, $L_{\rm bol}$, and Eddington luminosity ratios, $L_{\rm bol}/L_{\rm Edd}$, for the quasar samples in each of the three redshift bins $z < 0.5$, $1.5 \lesssim z \lesssim 3.5$, and $3.5 \lesssim z \lesssim 6.3$. The parameter values for the BQS are readily seen to cover larger ranges than is the case for the quasar samples at higher redshifts ($z \gtrsim 1.5$). For the latter quasars the lower limits at $M_{\rm BH} \approx 10^8\, M_\odot$ and at $L_{\rm bol} \approx 10^{46}$ ergs s$^{-1}$ are due to their selection limit. These lower limits also constrain the range of Eddington ratios, $L_{\rm bol}/L_{\rm Edd}$, observed for the higher redshift quasars. The average mass and bolometric luminosity for the $z \gtrsim 1.5$ quasars are $10^9\, M_\odot$ and $\sim 10^{47}$ ergs s$^{-1}$, respectively. Note the similar distributions of masses for the radio-quiet and radio-loud $z \approx 2$ quasars (the unmatched radio-loud quasars tend to be slightly more luminous than the other quasars in that redshift bin). In general, the $z \gtrsim 1.5$ quasars have similar distributions of $M_{\rm BH}$, $L_{\rm bol}$, and $L_{\rm bol}/L_{\rm Edd}$.

The distribution of black-hole masses, $M_{\rm BH}$, as a function of redshift is shown in Figure 1.2. It is apparent from Figures 1.1 and 1.2 that the average $M_{\rm BH}$ does not decrease beyond a redshift of $\sim$3, but these quasars are equally massive to those at lower redshifts. Clearly, we are not probing the entire quasar population or even the bulk of it but only the most luminous quasars at these great distances. However, it is noteworthy that if such massive quasars at redshift greater than 3 did not exist, we would simply not detect them. The fact that we do and in relatively significant numbers is important.

Not only is the typical black-hole mass of the most distant quasars similar to that of their lower redshift cousins, their UV spectra are also rather similar (Constantin et al. 2002; Dietrich et al. 2002), as are their properties measured at radio and X-ray wavelengths (see Paper I for a more detailed discussion). In the radio, for example, both the fractional occurrence and the radio spectra are similar to those at lower redshift (Stern et al. 2000; Carilli et al. 2001). The X-ray observations of $z \approx 4$ quasars are more sparse than what exists for less distant sources. Nevertheless, there is no strong evidence of high-$z$ quasars having significantly different X-ray properties. For example, the tendency (Bechtold et al. 2003) of the $z \approx 4$ quasars to have flatter slopes (which gets more pronounced with increasing redshift) may simply be a selection effect as different X-ray energy ranges are probed with different source redshifts. In summary, the properties of the quasars at $z \gtrsim 3.5$ are very similar to those of more nearby quasars. The quasars that we can detect at those redshifts, at least, do not exhibit properties indicating that they may go through a different stage in their (expected) evolutionary sequence compared to typical quasars at lower redshifts.

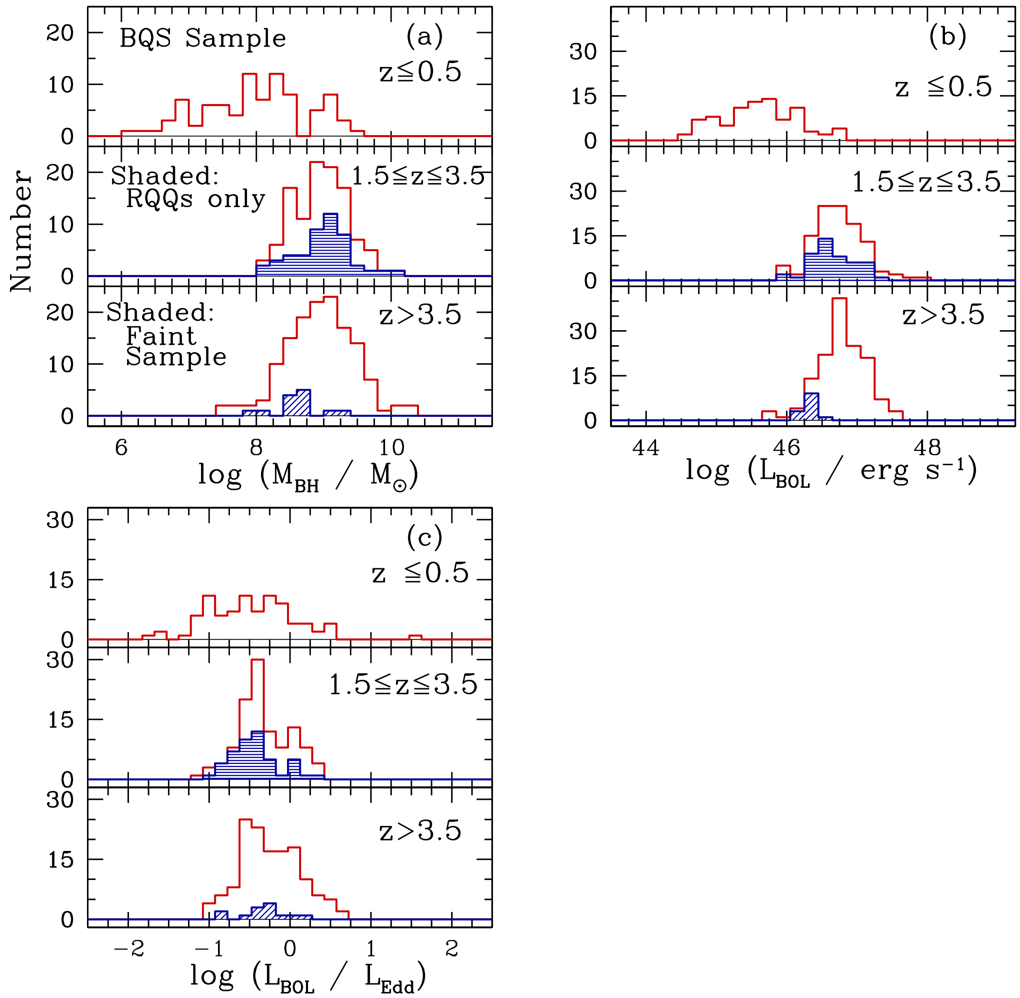


Fig. 1.1. Distributions of estimated (*a*) black-hole mass, $M_{\rm BH}$, (*b*) bolometric luminosity, $L_{\rm bol}$, and (*c*) Eddington luminosity ratio, $L_{\rm bol}/L_{\rm Edd}$ for different redshift bins. The top panel consists of Bright Quasar Survey objects only. In the middle panel, the radio-quiet quasars (RQQs) are shown shaded. The faint sub-sample (defined by Fan et al. 2001) is high-lighted with diagonal shading in the bottom panels. Although these quasars are systematically less bright than the other $z \approx 4$ quasars, they are not also systematically less massive, but show a range of masses. The lower limits in $M_{\rm BH}$ and $L_{\rm bol}$ of the high-$z$ ($z \gtrsim 1.5$) are due to the selection limit of the sample or the sensitivity limit of the SDSS quasars.

## 1.5 Properties of (Host) Galaxies at High Redshift

In the light of the results presented above, it is intriguing that the galaxies at high redshift ($z \gtrsim 3$) show ample evidence of being young and in the process of building up their stellar mass. And this seems to be the case for both quiescent galaxies and galaxies with active central black holes.

The host galaxies of $z \gtrsim 3$ quasars are most likely experiencing intense star formation

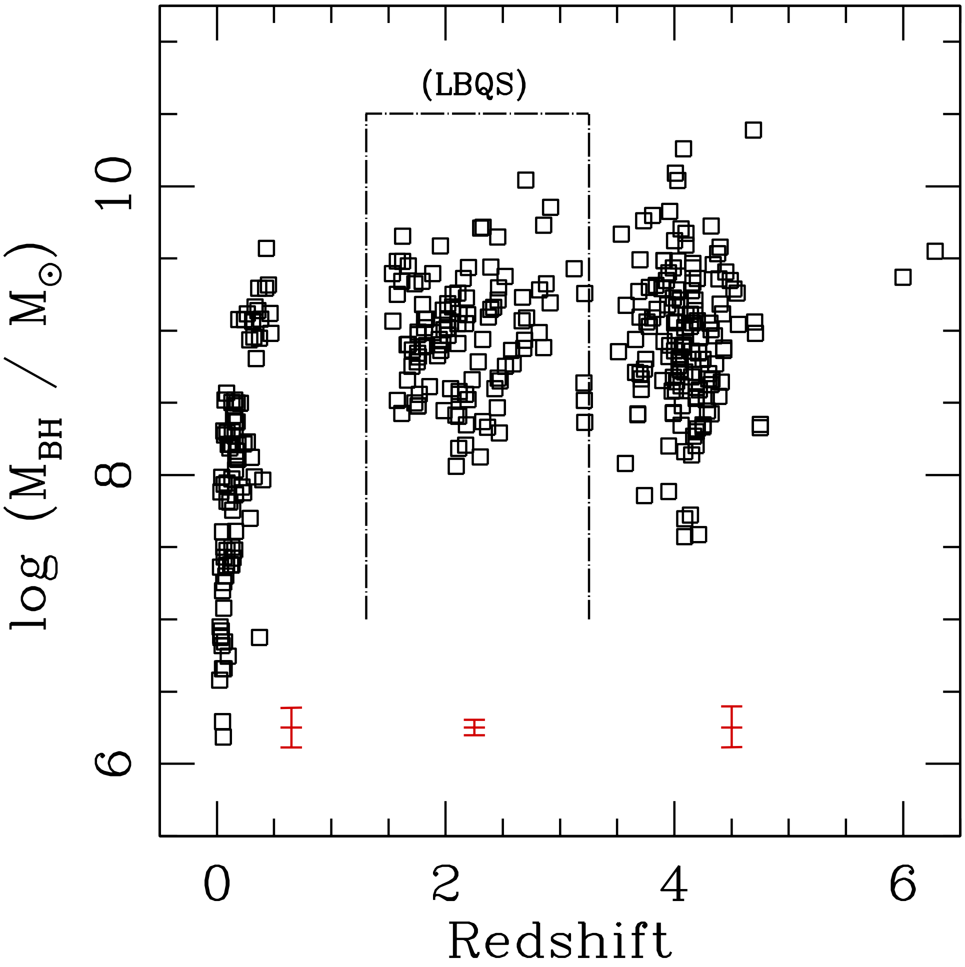


Fig. 1.2. Distribution of central black-hole masses, $M_{\rm BH}$, as a function of redshift. For each redshift bin (see Fig. 1.1) the average measurement uncertainty is indicated in the lower part of the diagram (in red). The dashed box marks for comparison the location of the black-hole masses of the quasars in the Large Bright Quasar Survey (e.g., Hewett et al. 2001) for which $M_{\rm BH}$ could be estimated using the UV scaling law (eqn. 1.3); these masses are based on a preliminary study.

(e.g., Omont et al. 2001) and may also be merging (e.g., Ridgway et al. 2001), as appears common to most galaxies at those early times (e.g., Steidel et al. 1996). Large amounts of molecular gas (a few $\times 10^{10}\,M_{\odot}$; typical of nearby IR luminous galaxies) and warm dust ($\gtrsim 10^{8}\,M_{\odot}$), heated by ongoing intense star formation, are detected in the host galaxies of known $z \approx 4$ quasars (some of which are included in the present study) in recent millimeter studies (e.g., Guilloteau et al. 1999; Omont et al. 2001; Carilli et al. 2001). From analysis of radio observations and starburst models it is evident that the far-IR emission is almost certainly thermal and consistent with emission from dust heated primarily by starbursts (e.g.,, Omont et al. 2001). Carilli et al. (2001) present millimeter data of some of the luminous $z \approx 4$ SDSS quasars, also studied here. Based thereon, one can infer the dust masses and star formation rates (Benford et al. 1999; Omont et al. 2001) in these quasar host galaxies. The ($\sim$50%) quasars with millimeter detections typically have star formation rates greater than 500 $M_\odot$/year with a few in the range of $900 - 2000$ $M_\odot$/year (and dust masses above $\gtrsim 4 \times 10^8\, M_\odot$). There is no tendency for radio-loud quasars to be differently represented among the quasars with millimeter detections and there is no correlation between radio-loudness and star formation rates (Carilli et al. 2001). While the specific star formation rate will decrease if a dust temperature higher than the typical value of $\sim$50 K is adopted, it is still evident that the detected quasar host galaxies are building up stellar mass at an immensely high rate and they are thus clearly young host galaxies. With a lower detection limit in star formation rate of 500 $M_\odot$/year, high star formation rates in the hosts of the undetected quasars cannot be ruled out.

In an *HST* study of $z \approx 3$ quasar host galaxies, Ridgway et al. (2001) found clear evidence that these hosts are more compact than low redshift host galaxies. Comparing the galaxy properties with evolutionary models, they find the high-$z$ quasar host galaxies to contain only 10% to 20% of the stellar mass of their low-$z$ counterparts. The properties of these quasar host galaxies turn out to be very similar to the Lyman Break Galaxies known at the same redshift. Lyman Break Galaxies are known to be very young, highly star-forming galaxies (e.g., Steidel et al. 1996; Shapley et al. 2001). In an independent study of the Lyman Break Galaxies in the Hubble Deep Field North, Papovich et al. (2001) also found, using stellar population synthesis models, the stellar mass of these galaxies to be a small fraction of that of $L^*$ galaxies in the local Universe.

A truly fascinating fact is that a small number ($\sim$1%) of the $\sim$1000 Lyman Break Galaxies in the survey at $z \approx 3$ by Steidel et al. (2002) emit broad UV emission lines. Based on the composite spectrum (Fig. 1.3) presented by Steidel et al. the typical C IV line width in these sources is $\sim$4700 km s$^{-1}$, similar to the average line width of the $z \approx 4$ luminous quasars in the present study! Yet, these broad-lined AGNs are rather faint, with an average magnitude of $< R > \approx 23.5$ mag. Using the UV scaling law, I obtain a ball-park mass estimate of the central black holes in these sources to be of order $10^8$ $M_\odot$. Given the faint nature of these AGNs and the fact that they are hosted by Lyman Break Galaxies (clearly very young galaxies which are far from being fully formed), the presence of such massive central black holes is a bit surprising. Along with the evidence presented and discussed above it is quite evident that black holes must build up a significant fraction of their mass before the host galaxies do. That means that black holes must form (or build up mass) fast and/or early in the history of the Universe. Rix et al. (2001) arrive at a similar conclusion based on comparisons of the relative nuclear to host galaxy luminosities at high-$z$ ($z \approx 2$) and low-$z$ ($z \approx 0.3$), allowing for some evolution in the mass to light ratio. Given the relatively short time available ($\sim$20 *e*-folding timescales) for especially $z \approx 6$ quasars to build up $\sim 10^9$ $M_\odot$ black holes, the initial accretion process must be rather efficient.

## 1.6 Conclusions

For several samples of quasars at a range of redshifts ($z < 0.5, 1.5 \lesssim z \lesssim 6.3$) the central black hole virial masses have been estimated using scaling relationships, calibrated to the more accurate masses measured by reverberation techniques among nearby active galactic nuclei. The black-hole masses of high-redshift ($z \gtrsim 3.5$) quasars, including quasars

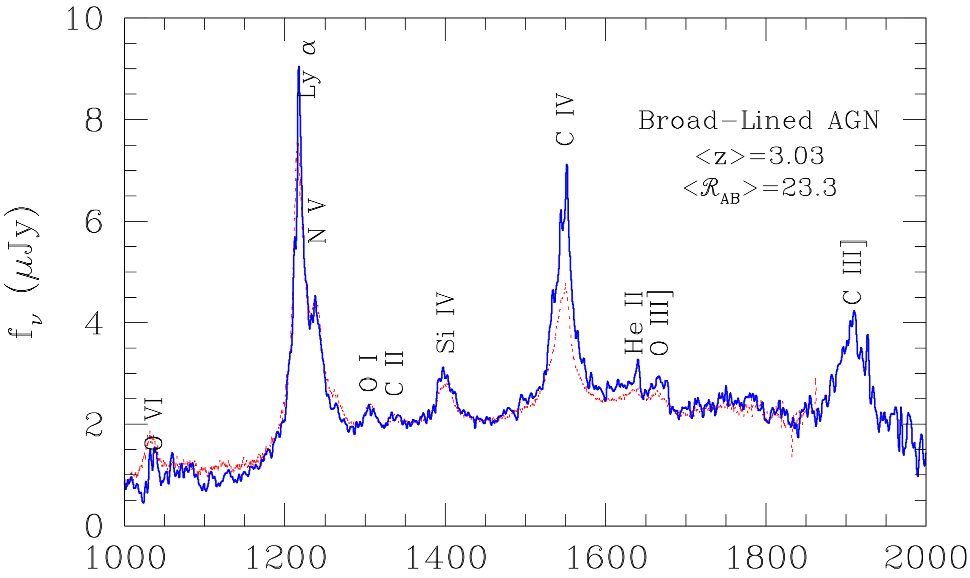


Fig. 1.3. Composite spectrum (*solid line*) of the 13 broad-lined AGNs hosted by Lyman Break Galaxies uncovered in the $z \approx 3$ survey by Steidel et al. (2002). The survey detected $\sim$1000 Lyman Break Galaxies. Note the rather broad restframe UV emission lines. The C IV line width is $\sim$4700 km s$^{-1}$, similar to the average C IV line width of the luminous $z \approx 4$ quasars in the present study. The figure is adopted from Figure 1 by Steidel et al. (2002).

from the Sloan Digital Sky Survey Early Data Release, are on average $\sim 10^9 M_\odot$. While these quasars are also the most luminous at this redshift, the lower selection limits for these quasars also show that if quasars with masses greater than $\sim 10^8 M_\odot$ did not exist at $z \approx 4$ we would not detect them! The available UV, X-ray, and radio data of $z \approx 4$ quasars show their other properties are very similar to those of lower redshift quasars. However, the host galaxies (and other more quiescent galaxies) at $z \gtrsim 3$ appear to be rather young in general: they contain huge amounts of molecular gas and dust, they are forming stars at a rapid rate, and for the $z \approx 3$ quasar host galaxies for which the stellar mass could be estimated the stellar mass is only a small ($\sim$10% to 20%) fraction of what is expected to be the final stellar mass in the galaxy at later times. Evidently, the central black holes built up a significant fraction of their mass before their host galaxies built up the bulk of their stellar mass. This conclusion is strongly supported and emphasized by the recent discovery of broad-lined active galaxies hosted by $z \approx 3$ Lyman Break Galaxies which are known to be young, star-forming galaxies at high redshift. Their very broad C IV emission lines ($\sim$4700 km s$^{-1}$) indicate the typical black-hole mass to be of order $10^8 M_\odot$ at this early stage in the evolution of these galaxies. The relatively high masses of the high-redshift black holes suggest that they may form fast and/or grow via an efficient accretion mode. This may especially be the case for the $z \gtrsim 6$ quasars.

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