THE POPULATION OF FAINT OPTICALLY SELECTED ACTIVE GALACTIC NUCLEI AT z ~ 3

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ABSTRACT

We discuss a sample of 29 active galactic nuclei (AGNs) (16 narrow-lined and 13 broad-lined) discovered in a spectroscopic survey of ~1000 star-forming Lyman break galaxies (LBGs) at z ~ 3. Reaching apparent magnitudes of ΔAB = 25.5, the sample includes broad-lined AGNs approximately 100 times less UV luminous than in most surveys to date covering similar redshifts and in the first statistical sample of UV/optically selected narrow-lined AGNs at high redshift. The fraction of objects in our survey with clear evidence for AGN activity is ~3%. A substantial fraction, perhaps even most, of these objects would not have been detected in even the deepest existing X-ray surveys. We argue that these AGNs are plausibly hosted by the equivalent of LBGs. The UV luminosities of the broad-lined AGNs in the sample are compatible with Eddington-limited accretion onto black holes that satisfy the locally determined $M_{\text{BH}}$ versus $M_{\text{bulge}}$ relation given estimates of the stellar masses of LBGs. The clustering properties of the AGNs are compatible with their being hosted by objects similar to LBGs. The implied lifetime of the active AGN phase in LBGs, if it occurs some time during the active star formation phase, is ~10^1 yr.

Subject headings: galaxies: active — galaxies: evolution — galaxies: nuclei — quasars: general

1. INTRODUCTION

Until very recently, virtually all surveys for quasars (QSOs) and active galactic nuclei (AGNs) at high redshift have been geared toward the detection of relatively “extreme” and rare objects, ranging from UV excess or color selection of QSOs (e.g., Fan et al. 2001; Boyle et al. 2000; Warren, Hewett, & Osmer 1994) to the selection of objects by their extreme radio power (e.g., White et al. 2000; Dunlop & Peacock 1990; McCarthy 1993). These surveys have been quite successful because they make use of selection techniques that can be applied over large swaths of sky, and spectroscopic follow-up for them has proved straightforward and highly efficient due to the optical brightness of the sample. There are few constraints on broad-lined AGNs drawn from the faint end of the UV/optical luminosity distribution (the faintest published survey is still that of Koo & Kron [1988], reaching the equivalent of $\Delta \sim 21$ at $z \sim 3$); these fainter objects are expected to dominate the production of photons that, together with emission from young galaxies, maintain the ionization of the intergalactic medium at intermediate redshifts ($z \sim 1-5$). Thanks to results from the Chandra X-Ray Observatory (Mushotzky et al. 2000; Barger et al. 2001b; Alexander et al. 2001), we are just beginning to learn about the high-redshift ($z > 2$) population of narrow-lined, obscured type II AGNs. These objects can be quite unobtrusive at the optical (rest-UV) or radio wavelengths used by most AGN surveys in the past. Despite their possible importance to overall AGN demographics, only a handful has been identified to date (e.g., Stern et al. 2002a; Norman et al. 2002).

At the same time, a very strong case has been developed in the local universe for a tight correlation between the properties of the stellar populations in bulges and spheroids and the mass of central black holes (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998; Merritt & Ferrarese 2001). The presence of this correlation over a very wide range of mass scales strongly suggests that the formation of the spheroid stellar populations and the central black hole are causally linked. One might then reasonably expect that the era during which the spheroid stars were formed might also be that during which the black holes were most likely to be accreting material from gas-rich environs. The “quasar era” is now known to be rather strongly peaked near $z \sim 2.5$, declining rapidly at both higher and lower redshifts (e.g., Boyle et al. 2000; Warren et al. 1994; Schmidt, Schneider, & Gunn 1995; Kennefick, Djorgovski, & de Carvalho 1995; Fan et al. 2001; Shaver et al. 1999). Since it is now possible to routinely observe star-forming galaxies near the peak of the quasar era, there is the opportunity to assess the level of AGN activity that is ongoing as the galaxies are undergoing rapid star formation.

In this paper, we present some initial results on the AGN component of a moderately large spectroscopic survey for galaxies selected by their large unobscured star formation...
rates at redshifts $z \sim 3$. The survey should contain all but
the most heavily obscured star-forming galaxies at such red-
shifts (Adelberger & Steidel 2000), and as we detail below, is
well suited for detecting active accretion power in the same
star-forming objects because of the selection criteria used
and the large number of spectra obtained. For the first time
at high redshift, it may be possible to assess the fraction of
rapidly star forming galaxies that are simultaneously play-
ing host to significant accretion power. In any case, the sur-
vey has uncovered a relatively large number of UV-selected,
relatively faint, broad-lined and narrow-lined AGNs, whose
properties we summarize.

We assume a cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and
$h = 0.7$ throughout.

2. THE AGN SAMPLE

2.1. General Properties and Sample Definitions

The full Lyman break galaxy (LBG) survey consists of 16
independent fields covering a total of 0.38 deg$^2$. The effective
volume covered by a color-selected survey depends in a rela-
tively complex way on the color, magnitude, and redshift of
objects in the targeted sample (Steidel et al. 1999; Adel-
berger 2002). We have presented some of the details of the
LBG selection function in Steidel et al. (1999); the AGNs
described in this paper satisfy precisely the same photomet-
ric criteria as the star-forming galaxies in the sample.

The complete details of the LBG photometric and spec-
troscopic survey will be presented in C. C. Steidel et al.
(2002, in preparation); here we concentrate on the small
subsample for which there is spectroscopic evidence for the
presence of AGNs.

At redshifts $z \sim 3$, the distinctive colors of Lyman break
objects depend largely on properties of the intervening inter-
galactic medium (IGM), where the mean free path of pho-
tons shortward of 912 Å in the rest frame is short, result-
ing in a pronounced drop in flux in the observed $U_v$ band,
even for objects whose spectra do not have intrinsic breaks
at the Lyman limit (e.g., Madau 1995; Steidel & Hamilton
1993). Because objects in the spectroscopic sample were
selected without regard to morphology (i.e., no attempt was
made to remove point sources from the catalog), we expect
that our spectroscopic sample should be at least as complete
for objects dominated by nonstellar emission as compared to
normal star-forming galaxies.

The complete catalog of LBG candidates in the $z \sim 3$ sur-
vey fields consists of 2440 objects in the apparent magnitude
range $19.0 \leq m_v \leq 25.5$. Simulations suggest that only
$\sim 50\%$ of objects with LBG-like intrinsic colors at $z \sim 3 \pm 0.3$ will be included in our color-selected photomet-
ric catalogs due to various sources of incompleteness (Stei-
del et al. 1999). While we attempted to obtain uniform data
in each field, variations in Galactic extinction, seeing, sky
brightness, and integration time would require each field to
be treated independently in a proper evaluation of com-
pleteness. Over the full survey, we spectroscopically ob-
erved a total of 1344 objects (55% of the photometric
sample), of which 51 are identified as Galactic stars, 988 are
high-redshift objects with $(z) = 2.99 \pm 0.29$, and 306 remain
unidentified. We classified an object as a broad-lined AGN
if its spectrum contained any emission line with
FWHM $> 2000$ km s$^{-1}$. Such objects always contained se-
veral broad emission lines, usually at least Ly$\alpha + \text{N} \text{v}$, Si $\text{iv}$
$\lambda 1397$, C $\text{iv}$ $\lambda 1549$, and C $\text{iii}$ $\lambda 1909$. Of the 13 broad-lined
AGNs identified, two show evidence for “associated”
bro wide absorption lines of high-ionization species such as
O $\text{vi}$, N $\text{v}$, Si $\text{iv}$, and C $\text{iv}$. Objects were classified as narrow-
lined AGNs if their strong Ly$\alpha$ emission was accompanied
by significant emission in C $\text{iv}$ $\lambda 1549$ and if no emission line
had FWHM $> 2000$ km s$^{-1}$. These objects usually had He $\text{ii}$ $\lambda 1640$ and C $\text{iii}$ $\lambda 1909$, and often detectable N $\text{v}$ $\lambda 1340$ and
O $\text{vi}$ $\lambda 1034$. Given the quality of the typical LBG survey
spectrum, the narrow C $\text{iv}$ emission line would have to
exceed equivalent widths of a few angstroms in the rest
frame, or line fluxes of $\sim 2 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$, to have
been recognized.

The coarse properties of the two AGN samples are sum-
marized in Table 1.

The composite spectra of both classes of AGNs, formed
by shifting each spectrum into the rest frame based on the
emission-line redshift, normalizing by the median contin-
um level in the rest-frame 1600–1800 Å range, and averag-
ing, are shown in Figure 1. The top panel of Figure 1 also
shows for comparison the composite spectrum of much
brighter QSOs (typically $V \sim 18$, from Sargent, Steidel, &
Boksenberg 1989; Stengler-Larrea et al. 1995) that would
satisfy the same LBG color selection criteria. We note the
striking similarity of the two QSO samples, which are sepa-
rated by a factor of $\sim 100$ in UV luminosity. There is clear
evidence for the Baldwin (1977) effect in the increasing
strength of the C $\text{iv}$ emission line with decreasing continuum
luminosity, and the faint QSO composite has a much more
prominent narrow He $\text{ii}$ $\lambda 1640$ emission line.

Our definition of a narrow-lined AGN, based on the
detected presence of high-ionization emission lines, is
admittedly somewhat arbitrary; however, it relies on the
fact that the vast majority of LBGs show no detectable
emission in C $\text{iv}$ and He $\text{ii}$, even when Ly$\alpha$ emission is
strong, and that it is difficult to produce significant nebular
lines of these high-ionization species without the hard ioniz-
ing spectrum of an AGN component. The line ratios
observed among the objects identified as narrow-lined
AGNs are quite similar to those of local Seyfert 2 galaxies;
in fact, for the composite spectrum shown in the bottom
panel of Figure 1, the Ly$\alpha/C$ $\text{iv}$ and Ly$\alpha/C$ $\text{iii}$ ratio are
essentially identical to a composite Seyfert 2 spectrum pre-
presented by Ferland & Osterbrock (1986). The composite
narrow-lined AGN spectrum is also strikingly similar, in both
continuum and emission-line properties, to the composite
spectrum of high-redshift radio galaxies (from Stern et al.
1999).

A separate but related issue is how the narrow-lined, UV-
selected AGNs fit in with the so-called type II QSOs discov-
dered recently in deep Chandra images. The optical spectra of

| Property | Broad-Lined | Narrow-Lined | LBGs $^a$ |
|----------|-------------|--------------|-----------|
| Number $\ldots\ldots$ | 13 | 16 | 959 |
| $(z) \pm \sigma_{z}$ | $3.03 \pm 0.35$ | $2.67 \pm 0.35$ | $2.99 \pm 0.30$ |
| $\langle m_v \rangle$ $\ldots\ldots$ | 23.3 | 24.4 | 24.6 |
| $\text{Range} \ldots\ldots$ | 20.6–24.8 | 22.6–25.4 | 22.8–25.5 |

$^a$ Excluding objects identified as AGNs.

$^b$ Mean AB magnitude at an effective wavelength of 6830 or
$\approx 1700$ Å in the rest frame at $z \sim 3$. |
faint X-ray sources detected with Chandra are quite diverse, ranging from broad-lined AGNs to objects without clear UV/optical indicators of the presence of AGNs (e.g., Barger et al. 2001b; Hornschemeier et al. 2001; Mushotzky 2002, and references therein). However, for the relatively small number of published spectra of identified Chandra sources at $z > 2$, every one would have satisfied either our broad-lined or narrow-lined AGN criteria. In particular, the spectra of the two published type II QSOs at high redshift (Stern et al. 2002a; Norman et al. 2002) both resemble our faint optically selected narrow-lined AGN spectra in their UV emission-line properties. In particular, the spectra of the two published type II QSOs at high redshift (Stern et al. 2002a; Norman et al. 2002) both resemble our faint optically selected narrow-lined AGN spectra in their UV emission-line properties. As discussed below, at present there is only limited information on the X-ray emission from objects in the optically selected samples. Clearly, optical/UV selection of AGNs will impose different selection criteria than X-ray selection, and there may well be strong X-ray emitting AGNs at $z > 2$ that would either not be detected at all in the rest UV or not be recognizable as AGNs from their UV spectra, because of heavy obscuration. Similarly, because of greater absolute sensitivity in the UV and widely varying UV/X-ray flux ratios (for whatever reason), it may be that faint-AGN selection in the UV can identify objects whose X-ray fluxes are still beyond the deepest Chandra integrations. We discuss this issue further in § 3.

2.2. Estimates of Internal Completeness of the AGN Subsample

While a more detailed analysis of the AGN selection function and a derivation of the UV luminosity function of faint AGNs are deferred to another paper (M. P. Hunt et al. 2002, in preparation), here we make some approximate
statements on the completeness of our spectroscopic AGN sample. When we could not determine a redshift from a spectrum we had obtained, it was usually due to an absence of emission lines and an inadequate continuum signal for measuring the relatively weak absorption lines that help establish redshifts for a large fraction of our galaxy sample. Since every AGN in our sample has several strong emission lines (including strong Ly\(\alpha\) emission), it is unlikely that an AGN with UV-detectable features in the target redshift range would not have been recognized, even in spectra of much lower than average quality. We can estimate an upper limit on the number of unrecognized narrow-lined AGNs (for reasons of an inadequate signal-to-noise ratio [S/N] in the spectra) among those objects identified as normal star-forming galaxies by examining high-S/N composite spectra of the LBGs (with identified AGNs excluded). The average intensity of C\textsc{iv} emission in the narrow-lined AGN sample is \(\sim20\%\) that of Ly\(\alpha\) (see Fig. 1). If we assume that this ratio is characteristic of narrow-lined AGNs that we failed to flag as such, and we use the fact that the intensity ratio of Ly\(\alpha\) to C\textsc{iv} emission in the spectral composite of non-AGN LBGs is \(\gtrsim100\) for the quartile of the LBG sample having the strongest Ly\(\alpha\) emission strength,\(^4\) then an upper limit on the fraction of AGN-like spectra to have contributed to that subsample is \(\sim5/100 = 5\%\). The corresponding limit on the fractional contribution of unrecognized AGNs to the full LBG sample would then be \(\sim(0.25)(5) = 1\%\). The true fraction with unrecognized AGN-like spectra is likely to be smaller than this limit, since in most individual spectra, we could have recognized C\textsc{iv} emission at the level seen in the composite AGN spectrum, and because low-level C\textsc{iv} emission (part of which is due to the stellar P Cygni feature) is expected in the rapidly star-forming galaxies, even without AGN excitation.

Thus, we expect that with respect to the photometric LBG sample, the spectroscopic AGN sample is close to \(N_{\text{obs.spec}}/N_{\text{phot}} = 1344/2440 \approx 55\%\) complete, i.e., that any AGN in the LBG photometric sample that was attempted spectroscopically would have yielded a redshift. We estimate that our present spectroscopic AGN sample contains only \(\sim30\%\) of the AGNs in our fields with \(2.7 \lesssim z \lesssim 3.3\) and satisfying our photometric criteria \(R \leq 25.5, G-R < 1.2\), and \(U-G > (G-R) + 1\) (i.e., the spectroscopic completeness of 0.55 is the estimated photometric completeness of \(\sim50\%\)). The mean redshift of the narrow-lined AGNs in our sample is somewhat different from that of the galaxies, probably due to a combination of the subtleties of how the emission lines have affected the broadband photometry and the redder continuum color (see below). The broad-lined AGN completeness within the photometric sample is expected to be smaller than that of galaxies at a given redshift and apparent magnitude, because at \(z \approx 3\), only about 60\% of (bright) QSO spectra have intervening optically thick Lyman limit systems at high enough redshift to produce the distinctive UV color that we depend on to identify them (see Sargent et al. 1989). Galaxies do not suffer this form of incompleteness because they are expected to have significant intrinsic Lyman limits from a combination of stellar spectral energy distributions and opacity to their own Lyman continuum radiation from the interstellar medium.\(^5\) Again, a careful treatment of these effects is deferred to M. P. Hunt et al. (2002, in preparation), but this additional source of incompleteness for broad-lined AGNs is likely to be of roughly the same order as the spectroscopic advantage that AGNs enjoy when they are observed.

With these caveats in mind, a reasonable estimate of the fraction of AGNs among objects in our LBG sample is approximately the same as the fraction of AGNs within the spectroscopically confirmed sample: 29/988, or \(\sim3\%\). This number would increase to \(\sim4\%\) allowing for the maximal incompleteness of the narrow-lined sample discussed above. The observed ratio of narrow-lined to broad-lined AGNs, \(N(\text{NL})/N(\text{BL}) = 1.2 \pm 0.4\), is consistent with the ratio of broad-lined and narrow-lined radio-loud AGNs found by Willott et al. (2000), although we emphasize that our numbers are not yet corrected for relative incompleteness.

3. X-RAY PROPERTIES OF OPTICALLY FAINT AGNs AT \(z \approx 3\)

At present, there is only a small amount of information on the X-ray properties of the optically faint AGNs in our sample. A cross-correlation of our LBG survey with the 1 Ms exposure of the Chandra Deep Field–North (the Hubble Deep Field–North [HDF-N] region) yields X-ray detections for four of the 148 candidates\(^6\) (\(\sim3\%\)) in an \(8^\prime\times8^\prime\) field centered on the deep Hubble Space Telescope (HST) pointing (Nandra et al. 2002). Of these, two have not yet been observed spectroscopically. The other two are a faint broad-lined AGN with \(R = 24.15\) and \(z = 3.406\) (HDF-oC 34=J123633.4+621418), and a narrow-lined AGN with \(R = 24.84\) and \(z = 2.643\) (HDF-MMD 12=J123719.9+620955). Both of these AGNs have rest-frame 2–10 keV luminosities (uncorrected for intrinsic absorption) of \(\sim5 \times 10^{43}\) ergs s\(^{-1}\). Our spectroscopic LBG sample also contains a clear narrow-lined AGN spectrum, shown in Figure 2, that is undetected in the deep Chandra image and thus has an unobserved X-ray luminosity of \(\lesssim5 \times 10^{42}\) ergs s\(^{-1}\) in the 2–10 keV band. Thus, while we expect that a large fraction of the optically faint AGNs in our sample would be detected in the deepest Chandra exposures, there is also likely to be a subsample that is relatively X-ray faint that would not be detected in even the deepest X-ray pointings to date. Given the overall completeness estimate of \(\sim30\%\) discussed above, we expect \(\approx20\) optically faint (\(R \approx 21–25.5\)) AGNs (of which \(\sim11\) would be broad-lined objects) over a redshift interval of \(\Delta z \approx 0.6\) near \(z = 3\) per \(17^\prime \times 17^\prime\) Chandra ACIS field.\(^7\) Ostensibly, this number is significantly larger than the number of AGNs (in a similar redshift range) identified with Chandra sources in the deep fields (e.g.,

\(^4\) This is the only subsample of the LBGs that has a mean Ly\(\alpha\) equivalent width close to that of the AGNs.

\(^5\) We cannot rule out the possibility that faint broad-lined AGNs are subject to increased internal Lyman continuum opacity compared to the bright QSOs that have been studied to date; however, the absence of detectable interstellar absorption lines in the composite broad-lined QSO spectrum does suggest that the typical H\textsc{i} column density within the host galaxies along our line of sight is significantly smaller than that for typical LBGs.

\(^6\) None of these objects is detected in the radio continuum with the VLA (Nandra et al. 2002).

\(^7\) The number 20 is just 29/(0.3)(0.38) \(\approx 250\) AGNs deg\(^{-2}\). We note, however, that the region in which four LBGs were directly detected with Chandra was only \(\sim25\%\) of the full Chandra field of view.
Barger et al. 2001b; Hornschemeier et al. 2001; Stern et al. 2002b; Crawford et al. 2002), although the numbers are small and the follow-up of optically faint Chandra sources is still underway. More complete surveys of both Chandra sources and faint optically selected AGNs in the same fields will significantly improve our understanding of the overall AGN demographics at high redshift.

4. ARE LBGs THE HOSTS OF THE OPTICALLY FAINT AGNs?

It would be interesting in the context of understanding the history and efficiency of accretion-powered luminosity in galaxies if one could verify that the AGNs in the sample are hosted by the equivalent of LBGs.8 The range of continuum apparent magnitudes (i.e., the lack of objects brighter than $r$ ~ 23) of the narrow-lined AGNs in the spectroscopic sample is similar to that of the non-AGN LBGs in the sample (Table 1). The strength of the few interstellar absorption lines that are not strongly masked by emission lines in the composite narrow-lined AGN spectrum are quite similar to those of a composite spectrum of non-AGN LBGs with Ly α seen in emission (see Fig. 3). Unfortunately, the strongest stellar feature in the spectra of the LBGs is the C IV P Cygni profile, which is badly affected by C IV emission in the composite narrow-lined AGN spectrum. We cannot say with certainty whether the continuum light of the narrow-lined AGNs is produced by stellar or nonstellar emission; making this distinction is notoriously difficult, even for nearby Seyfert galaxies (e.g., Gonzalez-Delgado et al. 1998). However, the far-UV continuum slope ($\beta = -0.4$, where $f_\lambda \propto \lambda^{\beta}$) of the composite narrow-lined AGNs is redder than all but $\sim$10% of the LBG sample and is much redder than the subsample of LBGs with similarly strong Lyα emission, as illustrated in Figure 3. If the continuum were attributed to starlight in the same manner as other LBGs, then the implied extinction would be a factor of $\sim$50 (Adelberger & Steidel 2000). At this time, only one of the narrow-lined AGNs has been observed in the K band, HDF-oMD 49 (see Fig. 2). This object has $R - K = 4.20$, making it the third reddest LBG in the observed sample of 118 (Shapley et al. 2001).

The brightest broad-lined object in the sample is more than 2 mag brighter than the brightest narrow-lined object, and there are five broad-lined AGNs brighter than the brightest narrow-lined AGN. There is some evidence for a flatter magnitude distribution for the broad-lined AGNs than for the narrow-lined AGNs, but small number statistics and numerous possible selection effects prevent us from making too much of this trend at this time. The relative absence of very UV bright narrow-lined AGNs is at least qualitatively consistent with the possibility that much of the AGN-produced UV continuum is obscured. There is considerable overlap between our survey fields and planned deep surveys with the Space Infrared Telescope Facility (SIRTF), so that it should soon be possible to measure many of these optically selected AGNs at mid-IR wavelengths, at which any bolometrically luminous obscured AGNs are expected to be quite prominent.

Assuming that the broad-lined AGNs are the less obscured versions of similar AGN activity, let us suppose for the sake of argument that the mass of putative LBG black holes scales with stellar bulge mass according to the relation established locally, $M_{\text{BH}} \sim 2 \times 10^{-3} M_{\text{bulge}}$ (e.g., Ho 1999). Adopting the range of inferred stellar masses of LBGs in our survey from Shapley et al. (2001), we expect typical black hole masses of $3 \times 10^7 M_\odot$ and a range from $2 \times 10^6$ to perhaps $2 \times 10^8 M_\odot$. If these black holes were radiating at the Eddington limit, they would be expected to have observed $\dot{M} \sim 0.0085$ and $\dot{M}/\dot{M}_{\text{edd}} = 0.66$, we find that the density of AGNs in the vicinity of narrow-lined AGNs is $0.96 \pm 0.24$ times the density of LBGs around other AGNs. The density of AGNs around broad-lined AGNs is $1.58 \pm 0.33$ times higher than the density of AGNs around other LBGs. These crude tests suggest that the narrow-lined AGNs cluster very similarly to non-AGN LBGs, and that broad-lined AGNs may be more strongly clustered than typical LBGs.

A more quantitative test of whether the AGNs and the LBGs share the same host dark matter halos comes from an evaluation of the clustering statistics of the AGNs with respect to the LBGs. We have performed tests, using methods similar to those outlined in Adelberger et al. (2002), of the density of AGNs around LBGs as compared to that of other (non-AGN) LBGs. Evaluated on scales $\delta z = 0.0085$ and $\delta z = 0.208$, we find that the density of AGNs in the vicinity of narrow-lined AGNs is $0.96 \pm 0.24$ times the density of LBGs around other AGNs. The density of AGNs around broad-lined AGNs is $1.58 \pm 0.33$ times higher than the density of AGNs around other LBGs. These crude tests suggest that the narrow-lined AGNs cluster very similarly to non-AGN LBGs, and that broad-lined AGNs may be more strongly clustered than typical LBGs.

A more in-depth treatment of these issues will be presented in M. P. Hunt et al. (2002, in preparation).

In any case, it seems plausible that the observed AGNs may be hosted by the equivalent of LBGs. If this is indeed the case, the fraction of LBGs in which obvious AGN activity is present may provide a rough timescale for near-Eddington accretion rates onto central black holes, as follows. The characteristic timescale for star formation episodes in LBGs is estimated to be $\sim$300 Myr, inferred from...
the modeling of the far-UV to optical (rest-frame) colors (Shapley et al. 2001; Papovich, Dickinson, & Ferguson 2001). If the 3% AGN activity reflects the duty cycle of significant black hole accretion in LBGs, it would imply an active accretion timescale of $\sim 10^7$ yr, broadly consistent with the expected black hole masses given the implied Eddington mass accretion rate of $\sim 1 M_{\odot}$ yr$^{-1}$. AGN lifetimes of this order have been inferred from theoretical studies of black hole growth based on mergers in hierarchical models of structure formation (e.g., Kauffmann & Haehnelt 2000) and from consideration of the QSO luminosity functions and the distribution of black hole masses in the local universe (e.g., Haehnelt, Natarajan, & Rees 1998; Yu & Tremaine 2002). Significantly longer accretion timescales of $\sim 500$ Myr have been suggested by Barger et al. (2001a) based on the observation that $\sim 4\%$ of “L* galaxies at all redshifts” are X-ray sources, but such timescales may refer to a very different, more protracted process of sub-Eddington accretion onto black holes in well-formed galaxies primarily at $z < 1$.

5. DISCUSSION

While we defer more quantitative statements to a future paper, there are several statements we can make that are unlikely to change after more careful modeling of incompleteness. First, narrow-lined AGNs that are optically identifiable using LBG color selection criteria are quite common, with a space density (at $z \sim 3$) $\sim 50$–$100$ times larger than that of the spectroscopically similar high-redshift radio galaxies (e.g., Willott et al. 2001). The implied surface density of AGNs per square degree per unit redshift at $z \sim 3$ reaches $\sim 400$. It is still uncertain, due to small number statistics and incomplete surveys, what fraction of this number would also be Chandra sources that may contribute significantly to the X-ray background. Nevertheless, we can say with some confidence that narrow-lined AGNs make a negligible contribution to the $z \sim 3$ UV background: the total 1500 Å luminosity of narrow-lined AGNs in our sample is only $\sim 20\%$ of that contributed by the broad-lined AGNs, and $\lesssim 2\%$ of that contributed by non-AGN LBGs. We do not know the narrow-lined AGN contribution to the ionizing UV background, but it is likely to be far smaller than 20\% of the broad-lined AGN background, judging by the red continuum colors and the expectation that the objects are fairly heavily obscured.

Using currently accepted parameterizations of the $z \sim 3$ QSO luminosity function (Pei 1995), $\sim 75\%$ of the AGN-produced ionizing radiation field would come from QSOs that have apparent magnitudes in the range $R = 20$–$25.5$.

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Fig. 3.—Comparison of the continua of the composite (non-AGN) LBG spectra culled from the subset with strong Ly$\alpha$ emission (red line; Shapley et al. 2002) with that of the identified narrow-lined AGNs (black line). Note that the AGN spectrum has much stronger emission lines and is considerably redder in the continuum. Note the similarity of the strength of the interstellar O$+\,\,\,\text{Si}^\prime$ feature near 1303 Å.
and only ∼7% would come from brighter QSOs. Thus, while our sample of broad-lined AGNs is fairly small, it extends far deeper than existing QSO surveys, allowing for the first time a direct measurement of the AGN contribution to the ionizing radiation field at high redshift. While it is possible that star formation in LBGs may dominate the production of Lyman continuum photons at $z \sim 3$ (Steidel, Pettini, & Adelberger 2001), broad-lined AGNs such as those in our faint sample almost certainly provide a substantial fraction of the higher energy photons that apparently reionized He II near $z \sim 3$. An accurate measurement of the AGN ionizing photon production requires careful attention to issues of photometric and spectroscopic completeness, which will be presented in M. P. Hunt et al. (2002, in preparation).

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