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DISCOVERY OF TWO SPECTROSCOPICALLY PECULIAR, LOW-LUMINOSITY QUASARS AT $z \sim 4$[1]

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ABSTRACT

We report the discovery of two low-luminosity quasars at $z \sim 4$, both of which show prominent N IV] λ1486 emission. This line is extremely rare in quasar spectra at any redshift; detecting it in two of a sample of 23 objects (i.e., ~9% of the sample) is intriguing and is likely due to the low-luminosity, high-redshift quasar sample we are studying. This is still a poorly explored regime, where contributions from associated, early starbursts may be significant. One interpretation of this line posits photoionization by very massive young stars. Seeing N IV] λ1486 emission in a high-redshift quasar may thus be understood in the context of coformation and early coevolution of galaxies and their supermassive black holes. Alternatively, we may be seeing a phenomenon related to the early evolution of quasar broad emission line regions. The nondetection (and possibly even broad absorption) of N V λ1240 line in the spectrum of one of these quasars may support that interpretation. These two objects may signal a new faint quasar population or an early AGN evolutionary stage at high redshifts.

Subject headings: galaxies: evolution — quasars: emission lines — quasars: general

1. INTRODUCTION

A growing body of theoretical models backed by emerging observational evidence paints a picture of joint formation and evolution of galaxies and quasars; for reviews see, for example, the proceedings edited by Ho (2004), Djorgovski (2005), and references therein. In this picture, merger-driven buildup of massive halos trigger both vigorous star formation and fuel the central black hole igniting a quasar (Kauffmann & Haehnelt 2000; Hopkins et al. 2006). Active galactic nucleus (AGN) feedback is now believed to be an essential factor in the formation and evolution of galaxies. Understanding the AGN-starburst connection is especially interesting at high redshifts, as we probe the epoch of the initial assembly of massive galaxies. Observationally, this is challenging in the case of host galaxies of luminous type I quasars, as the AGN activity far outshines any star formation related processes. However, by observing lower luminosity type I quasars or type II (e.g., obscured) quasars, the blinding intensity of the central engine is reduced, allowing properties of the host galaxy to be studied.

In this Letter, we report the discovery of two low-luminosity type I quasars in which we could be seeing evidence for a simultaneous starburst with a top-heavy IMF, and AGN activity. Both quasars show a prominent, moderately broad N IV] λ1486 emission line, which is rarely seen in quasar spectra at any redshift.

2. OBSERVATIONS

The two objects are low-luminosity quasars at $z \sim 4$, found in a sample of 23 objects used to measure the low-luminosity end of the quasar luminosity function (QLF) at $z \sim 4$ (M. Bogosavljević et al. 2007, in preparation). The parent sample ranges in redshift from $z = 3.7$ to 5.1. The candidates for this sample were selected from the NOAO Deep Wide Field Survey (NDWFS) Boötes field (Jannuzi & Dey 1999) and the Deep Lens Survey (DLS; Wittman et al. 2002). Quasar candidates were selected based on the colors of simulated quasars in the $3.5 < z < 5.2$ redshift range, incorporating a range of spectral slopes, Lyα equivalent widths, and intervening neutral hydrogen absorbers, down to the limiting magnitude of $R = 24$. Finding charts for the two N IV] quasars are presented in Figure 1. Details of the survey and candidate selection will be presented by M. Bogosavljević et al. (2007, in preparation).

We obtained spectroscopic follow-up for our candidates on UT 2006 May 20–22 with the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I telescope. Only the red camera was used, with the 400 lines mm^{-1} grating blazed at 8500 Å. The spectra were reduced using BOGUS, an IRAF package developed by Stern, Bunker, & Stanford[4] for reducing slit mask data, modified slightly for our single-slit data. DLS 1053−0528 was discovered in a 1800 s exposure of a candidate in the DLS F4 field, and NDWFS 1433+3408 was identified from a 900 s exposure of a candidate in the Boötes field. The final spectra are presented in Figure 2, and the source parameters are listed in Table 1.

Several things are worth noting. First is the detection of the N IV] λ1486 emission lines, which is particularly strong in DLS 1053−0528 (e.g., in comparison with the C IV λ1549 line). At the same time, the commonly observed N V λ1240 emission line is entirely absent and may even be seen in absorption in DLS 1053−0528 (see Fig. 3). This latter observation is somewhat unusual since the C IV λ1549 line in this source does not show broad absorption. While broad absorption lines are seen in approximately 10% of quasars, such quasars will show broad absorption in all permitted species.

The permitted emission lines for the two N IV] quasars are narrow compared with typical quasar line widths. A single component Voigt fit to Lyα measures an FWHM of ~500 km s^{-1}. Since the blue side of the Lyα profile is absorbed, we forced symmetry in the line by mirroring the red side of the line profile over the peak wavelength. To search for a broad-line component we fit a two-component Gaussian to the Lyα profile. For DLS 1053−0528, we measure a narrow-line FWHM of 434 km s^{-1} and a broad-line FWHM of 1727 km s^{-1}. In NDWFS 1433+3408

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[4] See https://zwolfkinder.jpl.nasa.gov/~stern/homepage/bogus.html.

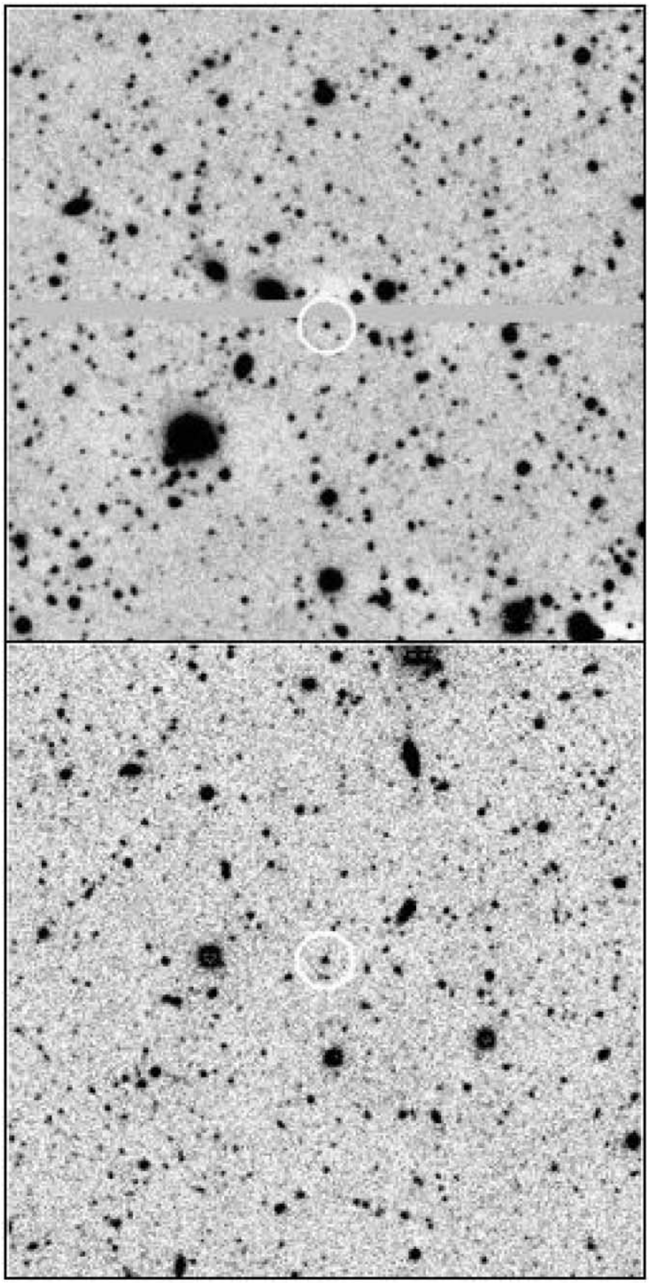

FIG. 1.—3′ × 3′ finding charts from the *R*-band images of the original survey data. DLS 1053−0528 is on the top (the gray stipe through the center of the image masks a bleed trail from a nearby saturated star) and NDWFS 1433+3408 is displayed on the bottom. In these images, north is up and east is to the left. The white circles mark the locations of the quasars.

we measure a narrow-line FWHM of 713 km s^{-1} and a broad-line FWHM of 3015 km s^{-1}. Therefore, while these objects have significant contribution from their narrow-line components (50% of the line flux in DLS 1053−0528 and 24% in NDWFS 1433+3408), their broad-line velocities of >1000 km s^{-1} place them in the quasar regime. Using the velocity widths from the broad-line component of Lyα as a proxy for C IV or Hβ, and the black hole mass estimators from Dietrich & Hamann (2004) and Vestergaard & Peterson (2006), we obtain $M_{\rm BH} \sim (5\text{–}15) \times 10^6\ M_\odot$ for DLS 1053−0528 and $M_{\rm BH} \sim (32\text{–}77) \times 10^6\ M_\odot$ for NDWFS 1433+3408. Consistent with the somewhat narrow line widths (for a broad-lined quasar) and the low luminosity, these inferred black hole masses are much lower than the masses inferred for luminous quasars.

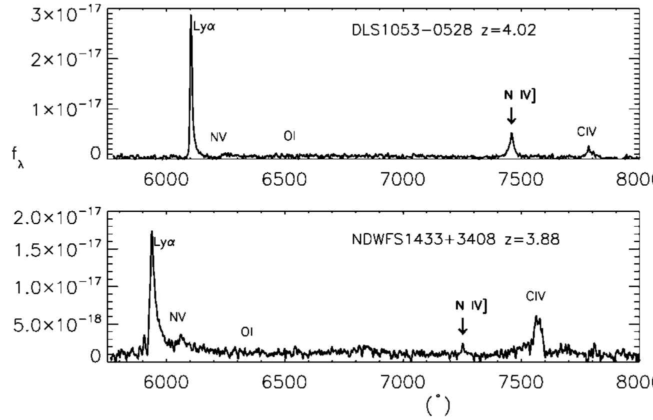

FIG. 2.—Keck LRIS spectra of the N IV] λ1486 emitting quasars. *Top*: $z = 4.02$ quasar found in the DLS field. This spectrum *lacks* N V λ1240 in emission but the line appears present as a broad absorption line. *Bottom*: $z = 3.88$ quasar found in the NDWFS Boötes field. This object shows a weaker N IV] λ1486 line and a possible weak detection of N V λ1240.

On UT 2007 January 23 we imaged DLS 1053−0528 with the Slit-viewing Camera (SCAM) of the NIRSPEC instrument on Keck II. We used the *J*-band filter and imaged the source with a nine-point dither pattern of 120 s exposures, for a total of 1080 s at the position of the quasar. The seeing was 0.7″. The data were reduced using the XDIMSUM package in IRAF. We calibrate our image to the 2MASS *J* band using a 15.26 mag point source that is detected in the field. The quasar is not detected, with a 3 σ magnitude threshold of 24.9 (Vega) mag.

NDWFS 1433+3408 was observed as part of FLAMEX, a near-infrared survey overlapping 4.1 $\deg^2$ of the Boötes area (Elston et al. 2006). The quasar is detected at ∼5 σ in both the *J* and K_s images. In addition, this quasar was observed in the IRAC Shallow Survey, an 8.5 $\deg^2$ *Spitzer* imaging survey of the Boötes field (Eisenhardt et al. 2004). The source is faintly (<5 σ) detected

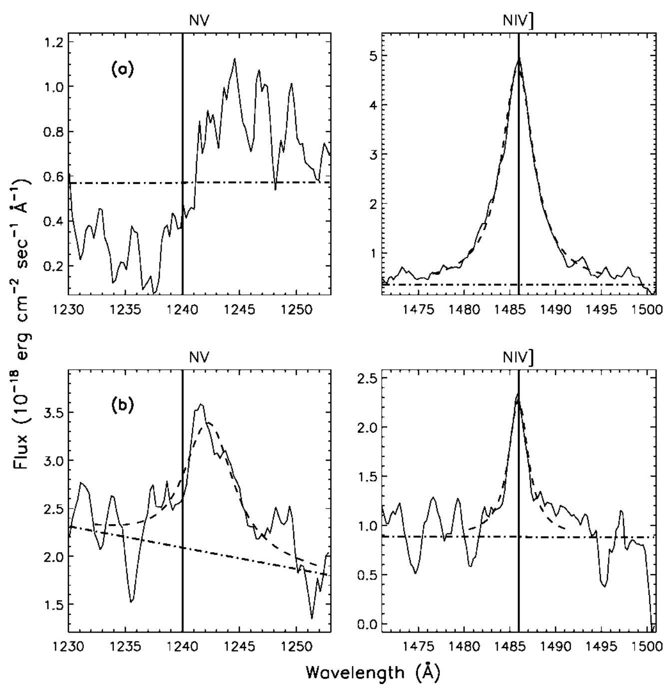

FIG. 3.—Voigt profile fits (*dotted lines*; continuum model, *dot-dashed line*) to nitrogen lines in our quasars. The line fits to DLS 1053−0528 are shown in the top panels, and the fits to NDWFS 1433+3408 are shown in the bottom panels.

TABLE 1
N IV] EMITTING QUASARS

Name	R.A. (J2000.0)	Decl. (J2000.0)	z	R (mag)[a]	J (mag)	K_s (mag)	[3.6] (mag)	[4.5] (mag)
DLS 1053−0528	10 53 46.1	−05 28 59	4.02	23.83	>26.4	...	...	...
NDWFS 1433+3408	14 33 24.5	+34 08 41	3.88	22.62	21.49	19.94	19.0	19.1

[a] AB magnitudes. All other magnitudes are Vega-based magnitudes.

at 3.6 and 4.5 μm at 19.0 and 19.1 (Vega) mag, respectively. We list the 4″ aperture magnitude from the FLAMEX catalog as well as the IRAC detections in Table 1. The quasar is not detected in the 5.8 or 8.0 μm images, whose 5 σ detection thresholds are 15.9 and 15.2 (Vega; 3″ aperture) mag, respectively. Note that the [3.6] − [4.5] colors for this object are quite blue compared to typical mid-infrared colors of AGNs (e.g., Stern et al. 2005). The result is not unexpected: at $z \sim 4$, Hα emission is shifted into the shortest wavelength IRAC band, causing AGNs at this redshift to have blue [3.6] − [4.5] colors.

Figure 4 plots the spectral energy distributions (SEDs) of both objects, using all available photometry. We compare this SED with the Sloan Digital Sky Survey (SDSS) composite spectrum (Vanden Berk et al. 2001) as well as the starburst template from Kinney et al. (1996) with $E(B-V) < 0.1$, both shifted to $z = 3.88$. Significant deviations are seen, especially at long wavelengths where both objects appear much bluer than the average quasar and starbusrt spectra. The SED of NDWFS 1433+3408 seems more consistent with the starburst spectrum, at least in the rest-frame ultraviolet, but DLS 1053−0528 deviates strongly from both.

3. DISCUSSION

The most striking feature in the spectra of these two faint quasars is the presence of the extremely unusual N IV] λ1486 emission line. The quasar population generally shows remarkable spectroscopic similarity out to the highest observed redshifts, with no obvious signs of evolution (e.g., Fan 2006). *None* of the published average quasar spectral templates show any trace of the N IV] λ1486 line (Fig. 5). The top spectrum (*solid line*) is the SDSS quasar composite from Vanden Berk et al. (2001). The quasars that contribute to this part of the spectrum are at redshifts comparable to the quasars in our sample, but they sample the bright end of the quasar luminosity function. The bottom spectrum (*dotted line*) is the *HST* UV composite spectrum from Telfer et al. (2002). The objects contributing to this part of the spectrum are low-redshift quasars ($z < 1$).

The only strong detection of this line in a quasar that we are aware of is in the nitrogen quasar Q0353−383 (Osmer & Smith 1980). This object has been analyzed by Baldwin et al. (2003), who derive an overabundance of nitrogen by a factor as high as 5–15 times solar in this object. A sample of apparently nitrogen-rich quasars was compiled by Bentz et al. (2004) from the 6650 quasars in the SDSS DR1 database with $1.6 < z < 4.1$ (allowing for the detection of N IV] λ1486 and N III] λ1750). Bentz et al. (2004) estimate that "nitrogen-enriched" quasars make up at most 0.2%–0.7% of quasars. Their sample has luminosities in the range $M_i = -28.07$ to -24.63. We found two such objects in a sample of 23 quasars (8.7%) that are concentrated at $z \sim 4$ and are 0.7 mag deeper than the SDSS sample. They found 20 quasars with equivalent widths ≥2.0 Å in both nitrogen lines and 33 quasars with EWs ≥2.0 Å in only one of the nitrogen lines. In these quasars the N IV] λ1486 line is accompanied by similarly strong N V λ1240 and N III] λ1750, the latter of which is outside our wavelengths range. We fit Voigt profiles to the nitrogen lines in our spectra (as well as to Lyα and C IV λ1549) to determine line fluxes, equivalent widths, and dispersion velocities (Table 2, Fig. 3). The mean N IV] λ1486 equivalent widths for the Bentz et al. (2004) sample is 3.7 Å ($\sigma_{EW} = 1.5$ Å), while the equivalent widths of N IV] λ1486 for our quasars are 280.2 Å for the DLS source and 24.5 Å for the Boötes source. This, combined with the nondetection (and possible absorption) of N V λ1240 in the DLS source, suggests that these quasars may be of a different ilk than the "nitrogen-enriched" population.

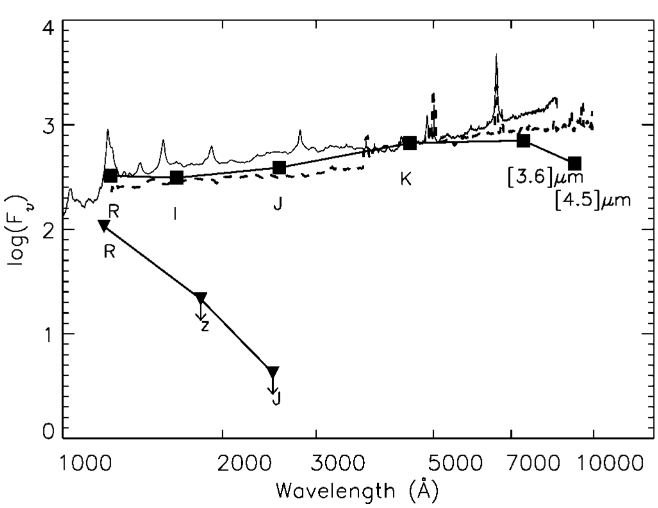

FIG. 4.—Rest-frame SED for NDWFS 1433+3408 (*squares*) and DLS 1053−0528 (*triangles*) compared with the SDSS quasar composite spectrum from Vanden Berk et al. (2001, *solid line*) and an unobscured starburst template with $E(B-V) < 0.1$ from Kinney et al. (1996, *dashed line*).

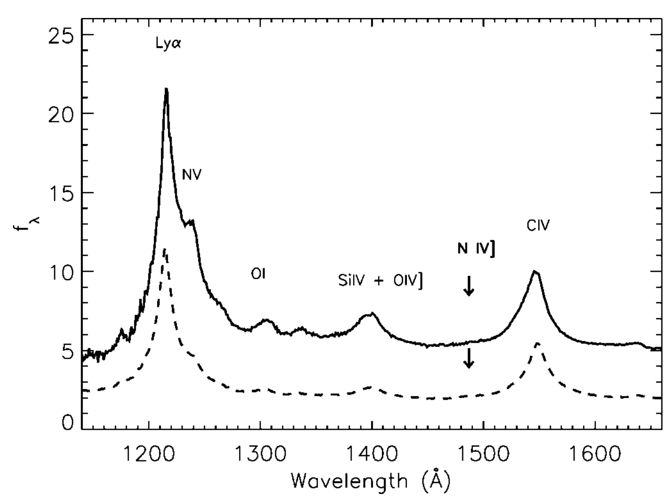

FIG. 5.—Composite quasar spectra showing the absence of N IV] λ1486. The top spectrum (*solid line*) is the SDSS quasar composite from Vanden Berk et al. (2001). The quasars that contribute to this part of the spectrum are highly luminous high-redshift quasars. The bottom spectrum (*dashed line*) is the *HST* UV composite spectrum from Telfer et al. (2002). The objects contributing to this part of the spectrum are low-redshift ($z < 1$) quasars. The absence of N IV] in both composite spectra suggests that it is necessary to probe deep into the QLF at high redshifts to witness the interaction of star formation with AGN activity.

TABLE 2
QUASAR LINE PROPERTIES

Line	Line Flux (10^{-16} ergs cm^{-2} s^{-1})	Rest-Frame EW (Å)	FWHM (km s^{-1})
DLS 1053−0528			
Lyα	2.92 ± 0.08	762.1	1726.8[a]
N v	…	…	…
N iv]	1.048 ± 0.008	280.2	807.5
C iv	0.55 ± 0.02	91.1	1101.5
NDWFS 1433+3408			
Lyα	3.8 ± 0.3	244.6	3015.6[a]
N v	0.25 ± 0.18	11.6	1086.9
N iv]	0.21 ± 0.07	24.5	524.9
C iv	1.3 ± 0.3	91.1	1334.0

[a] These line widths are from the broad component of a two-component Gaussian fit to the Lyα line. See § 2 for details on the fitting procedure.

In galaxies with no AGN signature, we are aware of only two other instances of this line being seen in the high-redshift universe. One especially telling detection is in the spectrum of the Lynx arc, a gravitationally lensed H ii galaxy at $z = 3.357$ (Fosbury et al. 2003). The line intensities in this object's spectrum, strong N iv] λλ1483, 1487, O iii] λλ1661, 1666, and C iii] λλ1907, 1909, as well as the absence of N v λ1240, favor a hot (80,000 K) blackbody over an AGN as the ionizing source. The Fosbury et al. (2003) modeling of the spectrum suggests a top-heavy IMF, which is especially interesting since such an IMF is now believed to be characteristic of early, metal-poor star formation, e.g., Population III stars. Alternatively, Binette et al. (2003) suggest an obscured AGN as the photoionizing source of the Lynx arc. Their model invokes dense absorbing gas near a central AGN that filters the power law and mimics the hot blackbody suggested by Fosbury et al. (2003) This model does require at least a weak N v λ1240 line detection.

The second known N iv] λ1486 emitter is a $z = 5.55$ galaxy in the GOODS survey (Vanzella et al. 2006; Fontanot et al. 2007). Similar to the Lynx arc, this object shows an extremely strong Lyα line as well as N iv] λ1486, while N v λ1240 is absent. No detailed analysis has been published on this source as yet.

An alternative possibility is that we are witnessing an evolutionary effect in the quasar broad emission line region. This is suggested by the traditional broad-line shape of N iv λ1486 in DLS 1053−0528 as well the peculiar absence (or even absorption) of N v λ1240 in its spectrum. Detailed modeling of such effects is beyond the scope of this Letter.

The detection of such a rare emission line in two of 23 $z \sim 4$ quasars in our sample (i.e., ~9% of the sample) suggests that it occurs more commonly in low-luminosity quasars at high redshifts, a regime that we are now exploring systematically for the first time. At these luminosities we are probing deep into the QLF where the effects of a luminous starbursts can be detected more easily; if there is an evolutionary trend, such phenomena may be present at high redshifts, and not in the better studied quasar samples at $z \sim 0$–2. As the sample sizes of comparably faint AGNs at these redshifts increase, we will be able to determine whether this is indeed a systematic evolutionary effect related to the early stages of coformation and coevolution of galaxies and AGNs.

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REFERENCES

Baldwin, J. A., Hamann, F., Korista, K. T., Ferland, G. J., Dietrich, M., & Warner, C. 2003, ApJ, 583, 649
Bentz, M. C., Hall, P. B., & Osmer, P. S. 2004, AJ, 128, 561
Binette, L., Groves, B., Villar-Martín, M., Fosbury, R. A. E., & Axon, D. J. 2003, A&A, 405, 975
Dietrich, M., & Hamann, F. 2004, ApJ, 611, 761
Djorgovski, S. G. 2005, in The Tenth Marcel Grossmann Meeting., ed. M. Novello, S. Perez Bergliaffa, & R. Ruffini (Singapore: World Scientific), 422
Eisenhardt, P. R., et al. 2004, ApJS, 154, 48
Elston, R. J., et al. 2006, ApJ, 639, 816
Fan, X. 2006, NewA Rev., 50, 665
Fontanot, F., Cristiani, S., Monaco, P., Nonino, M., Vanzella, E., Brandt, W. N., Grazian, A., & Mao, J. 2007, A&A, 461, 39
Fosbury, R. A. E., et al. 2003, ApJ, 596, 797
Ho, L. C., ed. 2004, in Coevolution of Black Holes and Galaxies (Cambridge: Cambridge Univ. Press), 496
Hopkins, P. F., Hernquist, L., Cox, T. J., Di Matteo, T., Robertson, B., & Springel, V. 2006, ApJS, 163, 1
Jannuzi, B. T., & Dey, A. 1999, in ASP Conf. Ser. 191, Photometric Redshifts and the Detection of High Redshift Galaxies, ed. R. Weymann et al. (San Francisco: ASP), 111
Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576
Kinney, A. L., Calzetti, D., Bohlin, R. C., McQuade, K., Storchi-Bergmann, T., & Schmitt, H. R. 1996, ApJ, 467, 38
Oke, J. B., et al. 1995, PASP, 107, 375
Osmer, P. S., & Smith, M. G. 1980, ApJS, 42, 333
Stern, D., et al. 2005, ApJ, 631, 163
Telfer, R. C., Zheng, W., Kriss, G. A., & Davidsen, A. F. 2002, ApJ, 565, 773
Vanden Berk, D. E., et al. 2001, AJ, 122, 549
Vanzella, E., et al. 2006, A&A, 454, 423
Vestergaard, M., & Peterson, B. M. 2006, ApJ, 641, 689
Wittman, D. E., et al. 2002, Proc. SPIE, 4836, 73