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

Eilat Glikman,$^2$ S. G. Djorgovski,$^2$ Daniel Stern,$^3$ Milan Bogosavljević,$^2$ and Ashish Mahabal$^2$

Received 2007 April 30; accepted 2007 May 24; published 2007 June 28

ABSTRACT
We report the discovery of two low-luminosity quasars at $z \sim 4$, both of which show prominent N iv $\lambda 1486$ emission. This line is extremely rare in quasar spectra at any redshift; detecting it in two of a sample of 23 objects (i.e., $\sim$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 $\lambda 1486$ 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 $\lambda 1240$ 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 $\lambda 1486$ 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, $Ly\alpha$ equivalent widths, and intervening neutral hydrogen absorbers, down to the limiting magnitude of $R = 24$. Finding charts for the two N iv $\lambda 1240$ 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 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 $\lambda 1486$ emission lines, which is particularly strong in DLS 1053–0528 (e.g., in comparison with the C iv $\lambda 1549$ line). At the same time, the commonly observed N v $\lambda 1240$ 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 $\lambda 1549$ 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 $Ly\alpha$ measures an FWHM of $\sim 500$ km s$^{-1}$. Since the blue side of the $Ly\alpha$ 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 $Ly\alpha$ 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

---

1 The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

2 Astronomy Department, California Institute of Technology, Pasadena, CA 91125; eliang@astro.caltech.edu, george@astro.caltech.edu, milan@astro.caltech.edu, aam@astro.caltech.edu

3 Jet Propulsion Laboratory, Mail Stop 169-506, California Institute of Technology, Pasadena, CA 91109; stern@thisvi.jpl.nasa.gov.

4 See https://zwolfskinder.jpl.nasa.gov/stern/homepage/bogus.html.
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 Ly\_a as a proxy for C\_iv or H\_beta, and the black hole mass estimators from Dietrich & Hamann (2004) and Vestergaard & Peterson (2006), we obtain \(M_{\text{BH}} \sim (5–15) \times 10^6 M_\odot\) for DLS 1053−0528 and \(M_{\text{BH}} \sim (32–77) \times 10^6 M_\odot\) 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.

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\sigma 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 Bootes area (Elston et al. 2006). The quasar is detected at \(-5\sigma\) 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 Bootes field (Eisenhardt et al. 2004). The source is faintly (\(<5\sigma\)) detected...
with from Kinney et al. (1996, from Vanden Berk et al. (2001, 1053 parable to the quasars in our sample, but they sample the bright quasar composite from Vanden Berk et al. (2001). The quasars average quasar spectral templates show any trace of the N\textsuperscript{iv} line. The quasar population generally shows remarkable spectro-

The most striking feature in the spectra of these two faint quasars is the presence of the extremely unusual N\textsuperscript{iv} $\lambda1486$ 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\textsuperscript{iv} $\lambda1486$ 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\textsuperscript{iv} $\lambda1486$ and N\textsuperscript{iii} $\lambda1750$). 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 $\geq 0$ Å in both nitrogen lines and 33 quasars with EWs $\geq 2.0$ Å in only one of the nitrogen lines. In these quasars the N\textsuperscript{iv} $\lambda1486$ line is accompanied by similarly strong N\textsuperscript{v} $\lambda1240$ and N\textsuperscript{iii} $\lambda1750$, the latter of which is outside our wavelengths range. We fit Voigt profiles to the nitrogen lines in our spectra (as well as to Ly$\alpha$ and C\textsuperscript{IV} $\lambda1549$) to determine line fluxes, equivalent widths, and dispersion velocities (Table 2, Fig. 3). The mean N\textsuperscript{iv} $\lambda1486$ equivalent widths for the Bentz et al. (2004) sample is 3.7 Å ($\sigma_{EW} = 1.5$ Å), while the equivalent widths of N\textsuperscript{iv} $\lambda1486$ 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\textsuperscript{v} $\lambda1240$ 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).](image)

![Fig. 5.—Composite quasar spectra showing the absence of N\textsuperscript{iv} $\lambda1486$. 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\textsuperscript{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.](image)

### TABLE 1

| Name          | R.A. (J2000.0) | Decl. (J2000.0) | $z$ | $R$ (mag)$^*$ | $J$ (mag) | $K_s$ (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       |

$^*$ AB magnitudes. All other magnitudes are Vega-based magnitudes.
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 Hubble volume. One especially telling detection is in the spectrum of the other instances of this line being seen in the high-redshift universe (Fosbury et al. 2003). The line intensities in this object’s spectrum, 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 $\lambda$1240 line detection.

The second known N iv $\lambda$1486 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 Ly$\alpha$ line as well as N iv $\lambda$1486, while N v $\lambda$1240 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 $\lambda$1486 in DLS 1053−0528 as well the peculiar absence (or even absorption) of N v $\lambda$1240 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 starburst 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.

We thank the referee for helpful feedback. We are grateful to the staff of W. M. Keck observatory for their assistance during our observing runs. This work was supported in part by the NSF grant AST 04-07448, and by the Ajax foundation. The work of D. S. was carried out at Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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 Berglaffa, & 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
Vandenberg, 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
Wiitman, D. E., et al. 2002, Proc. SPIE, 4836, 73