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THREE Lyα EMITTERS AT $z \approx 6$: EARLY GMOS/GEMINI DATA FROM THE GLARE PROJECT

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ABSTRACT

We report spectroscopic detection of three $z \sim 6$ Lyα-emitting galaxies, in the vicinity of the Hubble Ultra Deep Field, from the early data of the Gemini Lyman Alpha at Reionisation Era (GLARE) project. Two objects, GLARE 3001 ($z = 5.79$) and GLARE 3011 ($z = 5.94$), are new detections and are fainter in z' ($z'_{AB} = 26.37$ and 27.15) than any Lyman break galaxy previously detected in Lyα. A third object, GLARE 1042 ($z = 5.83$), has previously been detected in line emission from the ground; we report here a new spectroscopic continuum detection. Gemini/GMOS-South spectra of these objects, obtained using nod and shuffle, are presented together with a discussion of their photometric properties. All three objects were selected for spectroscopy via the i-drop Lyman break technique, the two new detections from the GOODS version 1.0 imaging data. The red $i' - z'$ colors and high equivalent widths of these objects suggest a high-confidence $z > 5$ Lyα identification of the emission lines. This brings the total number of known $z > 5$ galaxies within 9′ of the Hubble Ultra Deep Field to four, of which three are at the same redshift ($z = 5.8$ within 2000 km s^{-1}), suggesting the existence of a large-scale structure at this redshift.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: starburst

1. INTRODUCTION

The work of detecting and analyzing objects at very high redshift is a challenging but rapidly advancing field. In recent months, increasing numbers of galaxies have been found at redshifts of $z \approx 6$, as a result of both narrowband selection (e.g., Rhoads et al. 2003; Taniguchi et al. 2003; Hu et al. 2003) and the use of Lyman break methods (e.g., Dickinson et al. 2004; Stanway, Bunker, & McMahon 2003a, hereafter SBM03). However, until now, spectroscopic confirmation of very high redshift candidates has only been possible for objects at the bright end of the galaxy luminosity function.

Spectroscopic surveys for fainter objects are essential for shaping our understanding of the universe at these redshifts, and, with modern instrumentation and new techniques for faint-object spectroscopy, such surveys are now possible. The Gemini Lyman Alpha at Reionisation Era (GLARE) survey, described in this Letter, aims to obtain extremely deep spectra of very faint high-redshift star-forming galaxies, selected via $i - z$ color from the *Hubble Space Telescope* (*HST*) Advanced Camera for Surveys (ACS) Ultra Deep Field (UDF; Beckwith, Somerville, & Stiavelli 2003) and Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) data, using the Gemini Multi-Object Spectrograph (GMOS) on Gemini South. In this Letter, we present spectra and fluxes[12] of three Lyα emitters, two of which are new, identified in the early observation data of the GLARE project.

2. GMOS OBSERVATIONS

The spectra described in this Letter were obtained as part of the Gemini South program GS-2003B-Q-7 using the GMOS (Hook et al. 2003) and targeting sources in the region of the Hubble UDF (Beckwith et al. 2003). The goal of program GS-2003B-Q-7 was to obtain a total of 100 hr of exposure on this UDF mask. This Letter concerns the first 7.5 hr of data. Observations were made with the R150 grating at a 9000 Å central wavelength and with a custom-made 7800 Å long-pass filter ("RG780") giving a spectral range from 7800 Å up to the CCD cutoff (about 10,000 Å) and a spectroscopic resolution of 15 Å (4 pixels FWHM at 3.5 Å pixel^{-1}) with 0″.7 wide slits and a resolving power of $\lambda/\Delta\lambda_{FWHM} \approx 550$. Since the seeing disk (<0″.5 FWHM) was smaller than the slit width (0″.7), the true resolution is somewhat better for a source that does not fill the slit.

The data were taken using the "nod and shuffle" (N&S) observing mode (Cuillandre et al. 1994; Glazebrook & Bland-Hawthorn 2001; Abraham et al. 2004, hereafter GDDS1). Our N&S setup and observational scheme follow that in GDDS1, except that the slits were 2″.5 long with a 1″.5 nod. Data reduction also follows GDDS1 (Appendices B and C). Fifteen

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[12] We adopt the following cosmology: a flat universe with $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, and $H_0 = 70\ h_{70}$ km s^{-1} Mpc^{-1}. All magnitudes are quoted in the AB system (Oke & Gunn 1983).

TABLE 1
SUMMARY OF SPECTROSCOPIC AND PHOTOMETRIC PROPERTIES

Object	z	Peak (Å)	Flux 1 (ergs cm^{-2} s^{-1})	Flux 2 (ergs cm^{-2} s^{-1})	FWHM (Å)	z'	$i'-z'$	R_h (z') (arcsec)	SFR$_{UV}$ (h_{70}^{-2} $M_\odot$ yr^{-1})
1042	5.83	8309.1	0.97×10^{-17}	0.91×10^{-17} (12 σ)	16.3	25.48 ± 0.03	1.48 ± 0.09	0.09	15
3001	5.79	8252.7	0.79×10^{-17}	0.76×10^{-17} (12 σ)	20.5	26.37 ± 0.06	1.66 ± 0.20	0.14	6.0
3011	5.94	8434.0	1.0×10^{-17}	1.0×10^{-17} (25 σ)	24.5	27.15 ± 0.12	>1.68 (3 σ)	0.13	1.7

NOTES.—The wavelengths are measured in air. The error on the fluxes due to slit losses and photon noise is ≈20%. Flux 1 is taken between zero power points, and flux 2 by fitting a Gaussian line profile to the data. The FWHM of this fit is shown in the sixth column (with a spectral resolution of ≈16.5 Å). All objects are undetected at 3 σ in v ($v > 29.4$) and also resolved in the z' band (with a stellar half-light radius $R_h = 0''.05$). SFRs are calculated using the UV flux–SFR relation of Madau et al. (1998), having removed line contamination (and assuming $\beta = -1.1$).

1800 s frames were obtained in queue observing during 2003 November (19th, 24th, 28th, and 30th) during conditions of 0″.4–0″.5 seeing and high transparency. Relative flux calibration was performed using observations of a standard star, and the absolute flux calibration was done by normalizing the spectra of the mask alignment stars to their z'-band photometric fluxes. Sky lines were used for wavelength calibration.

One- and two-dimensional sky-subtracted spectra were inspected for the presence of emission lines. An advantage of the N&S data reduction technique is that lines appear in a positive-negative dipole pattern in the two-dimensional images, making them easy to distinguish from residual CCD defects and other nonastrophysical effects.

3. *HST*/ACS PHOTOMETRY AND CANDIDATE SELECTION

Spectroscopic candidates for this program were selected using the *i*-drop Lyman break technique (see SBM03 or Dickinson et al. 2004). This photometric selection method has been used by a number of authors to identify $z > 5$ galaxies (e.g., Bremer et al. 2004 and Lehnert & Bremer 2003 at $z \sim 5$, Dickinson et al. 2004 and SBM03 at $z \sim 6$). In each of these surveys, the Lyman break spectral feature is detected by means of a color-cut criterion. At $z \sim 6$, the Lyman break passes through the z' filter, and hence a cut is usually placed in the range $1.3 < i'-z' < 1.5$, with the exact value affecting the survey redshift range and low-redshift contamination.

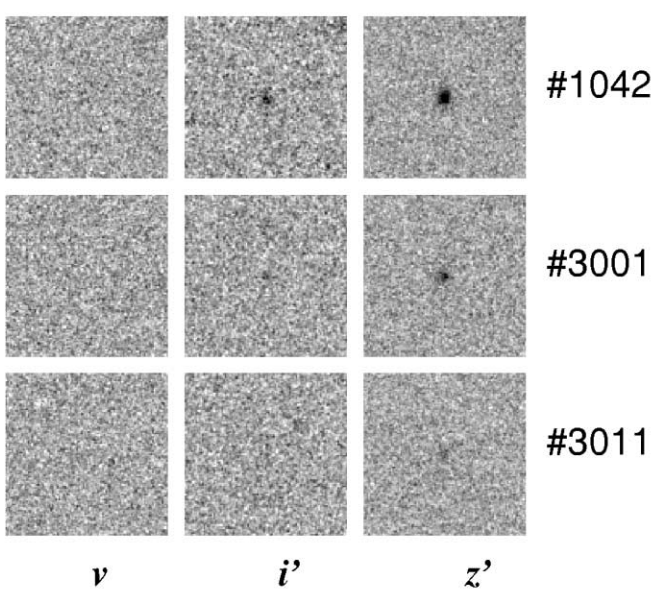

FIG. 1.—GOODS-South imaging of GLARE 1042, GLARE 3001, and GLARE 3011 in v (F606W), i' (F775W), and z' (F850LP). The panels are 3″ to a side (17 h_{70}^{-1} kpc at $z = 5.8$). North is up.

Within the UDF itself, 19 candidates were drawn from the catalog of the reddest ($i'-z'$) objects, prereleased by the UDF team[13] in order to facilitate ground-based spectroscopic follow-up and satisfy $(i'-z')_{AB} > 1.5$. The 5′.5 GMOS field is bigger than the UDF, so in the outlying region we selected objects from the GOODS-South field. The GOODS version 1.0 data release[14] comprises co-added imaging from 5 "epochs" of observations, reaching 3 σ magnitude limits $v_{lim} = 29.44$, $i'_{lim} = 28.83$, and $z'_{lim} = 28.52$. We selected candidates using $(i'-z')_{AB} > 1.3$ mag and $z'_{AB} < 27.5$ mag and identified 18 objects in the slit-mask area of which 10 were placed on the mask. The faint end of this selection reaches the magnitude limit in the i band. The rest of the mask area was used for a blank sky survey. Of the objects presented in this Letter, object 1042 was identified as a candidate in both catalogs, while objects 3001 and 3011 lie outside the UDF and were selected from the GOODS version 1.0 data.

Table 1 presents the broadband photometric properties of these objects. Magnitudes are measured in a 0″.3 diameter aperture, and an aperture correction of −0.32 mag (measured from point sources on the images) is applied to obtain a total magnitude for these compact sources. Postage stamp images in the v, i', and z' bands are shown in Figure 1. Since object 1042 lies within the UDF, more accurate photometry and morphological information should soon be available for this object. All three objects are spatially resolved with half-light radii in the range 0″.09–0″.14 (cf. stellar value of 0″.05), well detected in the z' band, faintly detected (or in the case of object 3011 undetected at 3 σ) in i', and undetected at 3 σ in the v band.

4. RESULTS

Single isolated emission lines have been identified for each of the three objects. GLARE 1042 (R.A. = $3^h32^m40^s.0$, decl. = −27°48′15″.0 [J2000]) is an *i*-drop initially selected by SBM03 and already confirmed as a $z = 5.83$ Lyα emitter (Stanway et al. 2003b; Dickinson et al. 2004). GLARE 3001 (R.A. = $3^h32^m46^s.0$, decl. = −27°49′29″.7) and 3011 (R.A. = $3^h32^m43^s.2$, decl. = −27°45′17″.6) are new. Their properties are given in Table 1. All three lines are almost unresolved given our dispersion, although 1042 is known to be highly asymmetric from published spectra (Stanway et al. 2003b; Dickinson et al. 2004).

We also detect the continuum break in the spectrum of GLARE 1042, although at a low signal-to-noise ratio (flux density ≈ 0.6×10^{-19} ergs cm^{-2} s^{-1} Å^{-1}). This is consistent with the level of continuum reported in the low-resolution ACS

[13] See http://www.stsci.edu/hst/udf.
[14] Available at ftp://archive.stsci.edu/pub/hlsp/goods/v1.

slitless spectrum of Dickinson et al. (2004) and also with the broadband colors of this object. A good continuum spectrum of this object should be obtained if GLARE does achieve a 100 hr total exposure. The spectra of the candidates are shown in Figure 2.

5. INTERPRETATION

5.1. *The Redshifts of GLARE 1042, 3001, and 3011*

The most plausible line identifications given the red $i-z$ selection are Lyα at $z = 5.83$, $z = 5.79$, and $z = 5.94$ for 1042, 3001, and 3011, respectively. Hβ λ4861.3 or [O III] $\lambda\lambda$5006.8, 4958.9 at $z \approx 0.7$ or Hα λ6562.8 at $z \approx 0.25$ are ruled out be the absence of nearby lines and because galaxies at these redshifts do not have strong $i-z$ continuum breaks.

An unresolved [O II] $\lambda\lambda$3726.1, 3728.9 doublet at redshifts $z \approx 1.2$ is a possibility for 3001 and 3011 (1042 is already known to be strongly asymmetric, thus ruling it out; Stanway et al. 2003b). The best evidence against this is the red $i-z$ color. The reddest possible color from an early-type spectral energy distribution at $z = 1.2$ is $i'-z' = 1.2$ (SBM03), and our two new objects are redder than this at 95% confidence. An [O II] identification would also imply rest-frame equivalent widths of 50–250 Å (see § 5.2), which is higher than is normally seen in $z \sim 1$ [O II] emitters (Hammer et al. 1997).

5.2. *Equivalent Widths*

The emission-line equivalent widths can be calculated from their z'-band photometry and line fluxes. However, a subtlety arises as the emission lines for these objects contribute significantly to their continuum flux in both the z' and i' filters; the calculated equivalent widths are sensitive to the detailed shape of the filter transmission curve. Accounting for these effects, we calculate equivalent widths $W^{\rm Ly\alpha}_{\rm rest} = [20, 30, 100] \pm 10$ Å for [1042, 3001, 3011] respectively, assuming that there is negligible flux shortward of the Lyα line due to absorption by the Lyα forest. From stellar synthesis models of star-forming regions (e.g., Charlot & Fall 1993), the theoretical Lyα equivalent width for a young region of active star formation is $W^{\rm Ly\alpha}_{\rm rest} \approx 100$–$200$ Å. However, observed Lyα emission from star-forming galaxies is generally weaker in continuum-selected samples at lower redshifts, which typically have $W_{\rm rest} =$ 5–30 Å (e.g., Steidel et al. 1996), or even in absorption. Our $z \simeq 6$ sample has a comparable selection, but the equivalent width of GLARE 3011 is notably larger. We note that $z \simeq 6$ narrowband-selected samples also produce higher equivalent widths with a median of 200 Å (Malhotra & Rhoads 2002; Hu et al. 2003).

5.3. *Active Galactic Nucleus or Starburst?*

Careful inspection of the spectra reveals no other lines. The only other significant line in our range is the high-ionization rest-UV line N V λ1240, which is usually prominent in active galactic nuclei (AGNs). Our flux limits at $\lambda_{\rm rest} = 1240$ Å are $f < [2.3, 2.3, 1.8] \times 10^{-18}$ ergs cm^{-2} s^{-1} (3 σ), for a 15 Å FWHM (unresolved) line. This gives lower limits of $f({\rm Ly}\alpha)/f({\rm N\,V}) > [4.3, 3.5, 5.6]$ (3 σ). Typical line ratios from composite QSO spectra are $f({\rm Ly}\alpha)/f({\rm N\,V}) = 4.0$ (Osterbrock 1989). Although our constraints are admittedly weak, the non-detection of N V λ1240 favors the interpretation that the Lyα arises from the Lyman continuum flux produced by OB stars rather than the harder UV spectrum of a QSO.

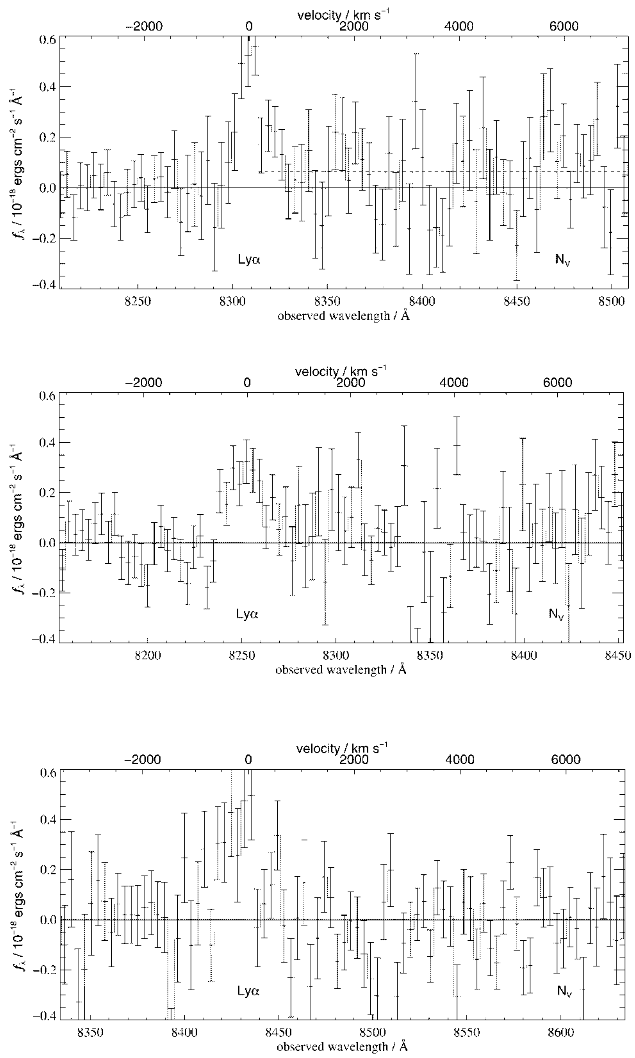

FIG. 2.—Unbinned GMOS-South spectra of GLARE 1042, GLARE 3001, and GLARE 3011 around the Lyα candidate line emission. The continuum level is indicated on 1042

None of the objects in this Letter correspond to X-ray sources in the Chandra Deep Field–South (CDF-S) 1 Ms catalog that covers this region (Giacconi et al. 2002). This allows us to place a limit on their X-ray fluxes in the 0.5–2 keV (soft) and 2–8 keV (hard) bands at $\sim 5.5 \times 10^{-17}$ and $\sim 4.5 \times 10^{-16}$ h_{70}^{-2} ergs cm^{-2} s^{-1}, respectively. The hard X-ray flux limits rule out a type II QSO like CDF-S 202 (Norman et al. 2002) but not CXO 52 (Stern et al. 2002). The soft X-ray limits would permit low-luminosity Seyfert galaxies and QSOs (Malhotra et al. 2003), but the line emission we see is not broad.

Given that an AGN interpretation for the observed emission lines is unlikely, the rest-frame UV spectra of these objects is likely to be dominated by star formation. The relation between the flux density in the rest-frame UV around 1500 Å and the star formation rate (SFR, in units of solar mass per year) is given by $L_{\rm UV} = 8 \times 10^{27}$SFR ergs s^{-1} Hz^{-1} (Madau, Pozzetti, & Dickinson 1998) for a Salpeter (1955) stellar initial mass function (IMF) with $0.1\ M_\odot < M^* < 125\ M_\odot$. The rest-frame UV at $z \approx 6$ is redshifted into the z' photometric band. The inferred SFR for the objects in this Letter, given their z' magnitudes, line contamination, and identified redshifts, are shown in Table 1.

5.4. *Overdensity at $z = 5.8$?*

The redshift of the new Lyα emitter GLARE 3001 is very similar to that of Lyα emitter SBM03 No. 3 reported by Bunker et al. (2003) and is also close to that of the reconfirmed $z = 5.83$ object (variously called GLARE 1042, SBM03 No. 1, and CDFS J033240.0−274815 in this Letter, Stanway et al. 2003b, and Dickinson et al. 2004, respectively).

The *i*-drop selection procedure used to identify candidate objects for spectroscopy is in principle sensitive to objects in the redshift range $5.6 < z < 7.0$, although the sharp falloff in the transmission of the z' filter effectively restricts detection of objects to a smaller redshift range that varies with absolute magnitude ($5.8 < z < 6.5$ for an $L^*_{z=3}$ Lyman break galaxy; see SBM03). The line centers of three of the four Lyα emitters detected in the GOODS-South field are separated by 2000 km s^{-1} (only ≈5% of the survey redshift range). The maximum angular separation of the three objects (GLARE 1042, 3001, SBM03 No. 3) is less than 11$'$.5, corresponding to a projected separation of only 4.0 h_{70}^{-1} Mpc. This suggests the interesting possibility of an overdensity of Lyα emitters at $z = 5.8$ in this field, perhaps similar to that observed at $z = 3.1$ in SSA 22 by Steidel et al. (2000).

To quantify the statistical likelihood of this happening by chance, we undertook a Monte Carlo simulation. A population uniformly distributed in the redshift range $5.6 < z < 7.0$ was considered, and the effects of the GMOS throughput (including the RG780 filter) and increased noise due to sky lines on spectroscopic detection, and intergalactic medium absorption leading to incomplete z' filter coverage on Lyman break photometric selection, were modeled. The effects of an apparent magnitude limit on the photometric selection were also calculated, using the measured luminosity function for Lyman break galaxies at $z = 3$ (Steidel et al. 1999) as an approximation for the currently unknown $z = 6$ luminosity function. Although each of these effects bias detection probability toward the lower end of the accessible redshift range, the probability of selecting three or more out of four galaxies within ± 2000 km s^{-1} of $z = 5.80$ was still small (2.1%). This suggests that we have statistical evidence of a redshift spike at $z = 5.8$ in this field, which augurs well for the future UDF observations.

5.5. *Comparison with Previous Work*

The spectroscopic properties of the three galaxies presented in this work are similar to those of other confirmed high-redshift Lyman break galaxies. Lehnert & Bremer (2003) report Lyα luminosities of 10^{42}–10^{43} ergs s^{-1} for six $z = 5$ line emitters in a sample of 12 Lyman break candidates. The fluxes for our $z = 6$ Lyα emitters fall comfortably into this range of luminosities and probe to a comparable depth. The emission-line equivalent widths of the GLARE candidates are also comparable to those of other spectroscopically confirmed Lyman break galaxies; e.g., at $z = 5.8$, $W_{\rm rest}^{\rm Ly\alpha} = 20$ Å (Bunker et al. 2003), and at $z = 6.17$, $W_{\rm rest}^{\rm Ly\alpha} = 50$ Å (Cuby et al. 2003).

6. CONCLUSIONS

In this Letter, we have presented photometry and spectra for three objects with extreme $i'-z'$ colors and line emission that may be Lyα at $z \approx 5.8$, observed as part of the GLARE project. Our main conclusions can be summarized as follows:

1. The GLARE project has detected three very high redshift objects ($z = 5.83$, 5.79, and 5.94) in the first 7.5 hr of integration time on Gemini/GMOS-South. To the best of our knowledge, the two new Lyα emitters are fainter in z' than any previous Lyman break–selected objects with a spectroscopic redshift.
2. The $i'-z'$ color selection can successfully identify objects lying at these redshifts and magnitudes, and the faint end of the galaxy luminosity function at $z = 6$ is now within the reach of 8 m telescopes.
3. We have evidence of an overdensity of $z = 5.8$ objects in a narrow redshift spike in the GOODS-South field; further observations (e.g., narrowband imaging) would be invaluable in confirming the existence of such a structure.

The work done in this Letter was based on observations obtained at the Gemini Observatory, which is operated by AURA, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: NSF (US), PPARC (UK), NRC (Canada), CONICYT (Chile), ARC (Australia), CNPq (Brazil), and CONICET (Argentina). K. G. and S. S. acknowledge generous funding from the David and Lucille Packard Foundation. The work done in this Letter was also based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the STScI, which is operated by AURA, Inc., under NASA contract NAS5-26555.

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