MEASUREMENT OF [O III] EMISSION IN LYMAN-BREAK GALAXIES

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ABSTRACT

Measurements of [O III] emission in Lyman-break galaxies (LBGs) at $z > 3$ are presented. Four galaxies were observed with narrowband filters using the near-IR camera on the Keck I 10 m telescope. A fifth galaxy was observed spectrally during the commissioning of NIRSPEC, the new infrared spectrometer on Keck II. The emission-line spectrum is used to place limits on the metallicity. Comparing these new measurements with others available from the literature, we find that strong oxygen emission in LBGs may suggest subsolar metallicity for these objects. The [O III] $\lambda 5007$ line is also used to estimate the star formation rate (SFR) of the LBGs. The inferred SFRs are higher than those estimated from the UV continuum, and may be evidence for dust extinction.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: ISM — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

Recent advances in infrared instrumentation have extended the study of high-redshift ($z > 2$) galaxies to rest-frame optical wavelengths. The Lyman-break galaxies (LBGs; cf. Steidel et al. 1996) have been well characterized from their rest-frame far-UV spectra using optical spectrographs. With the commissioning of NIRSPEC on Keck II and ISAAC on VLT, we have begun to obtain rest-frame optical spectra. The far-UV spectra of LBGs are strikingly similar to those of nearby starbursts; for example, Steidel et al. (1996) compare them directly with the Wolf-Rayet galaxy NGC 4214 (Leitherer et al. 1996). The rest-frame optical spectra of LBGs also resemble the spectra of low-redshift irregulars and starbursts. The familiar bright emission line diagnostics are present in LBG spectra ([H$\alpha$, [O III] $\lambda 5007$, H$\beta$, [O II] $\lambda 3727$]. The first rest-frame optical spectra of LBGs were obtained by Pettini et al. (1998, hereafter P98). A spectrum of the gravitationally lensed LBG MS 1512–cB58 (see Yee et al. 1996) was later obtained by Teplitz et al. (2000; hereafter T2000). At $z > 2.8$, Ha redshifts out of the $K$ band, and so the most easily observed emission line in most LBGs is [O III] $\lambda 5007$, which is a strong line in star-forming galaxies.

In this paper we present Keck measurements of [O III] in a sample of five typical LBGs. Four of the objects were imaged in narrowband filters centered on the expected wavelength of [O III] $\lambda 5007$ using the near-infrared camera (NIRC; Matthews & Soifer 1994) on the Keck I 10 m telescope. A fifth LBG was observed from Keck II with the new near-IR spectrograph (NIRSPEC), and a $K$-band spectrum was obtained (rest-frame 4600–5200 Å).

In § 2 the observations are presented and the data reduction techniques are explained. Section 3 outlines the observational results, and § 4 presents a discussion of their implication for understanding LBGs. The conclusions are summarized in § 5. Unless otherwise noted, a cosmology of $(H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.1, \Lambda = 0)$ is assumed.

2. OBSERVATIONS

2.1. Imaging

Targets were chosen from the database of spectroscopically confirmed LBGs observed by Steidel et al. (see, e.g., Steidel et al. 1996). We will use their nomenclature to refer to individual objects. Table 1 lists the imaging targets. Targets located in the so called "Groth-Westphal strip" (Groth et al. 1994), will be referred to as "Westphal-CC" or simply WCC. The other two fields from which LBGs were selected were centered on the radio galaxies 3C 324 and B20902. Narrowband fields were chosen to center on LBGs with redshifts that place the redshifted [O III] $\lambda 5007$ line within 0.5% of 2.16 μm, which is the central wavelength of the Brγ filter.

Imaging observations were taken with the near-IR camera (NIRC; Matthews & Soifer 1994) on the Keck I telescope, on the nights of 1999 April 7–8. Broadband $K'$ images were taken to measure the continuum flux in the objects, and narrowband images were taken to measure the redshifted [O III] $\lambda 5007$ flux. The narrowband filter used for these observations was the standard Brγ filter, centered at 2.16 μm with a width of $\Delta \lambda / \lambda = 0.01$. Teplitz, Malkan, & McLean (1998, hereafter TMM98) confirmed the width of the filter from standard-star observations. Table 1 lists the integration times for each observation. As shown in the
table, the Westphal-CC18 and 3C 324 fields were observed to greater depth. Both nights were photometric. In each case, the broad- and narrowband observations were taken as close in time as possible. Typically, integrations were taken for 27 minutes on the broadband, then 90 minutes narrowband. The deeper fields were observed on both nights, but in those cases both broad- and narrowband observations were made each night. Broadband observations were taken in 60 s exposures consisting of four coadds of 15 s each. Narrowband observations were taken in single 240 s exposures. The seeing varied during the nights from \( \sim 0'6 \) to \( \sim 0'8 \) (with the worst seeing at the end of the second night). UKIRT faint standard stars (Casali & Hawarden 1992) were observed periodically during the nights for photometric calibration of the broadband images. It is difficult to calibrate narrowband photometry onto flux units, so we measure the ratios of detected counts in the broad- and narrowbands and then convert to narrowband flux excess from knowledge of the width and throughput of the filter (see TMM98). Bunker et al. (1995) adopted the same approach, but have calibrated the narrowband magnitude with the broadband zero point, so that featureless continuum objects will have the same ratio of detected counts between the broad and narrow bands. This ratio depends simply on the width of the filter in wavelength and on its efficiency in transmitting light. In TMM98, the Br\( \gamma \) filter in NIRC was found to transmit \( \sim 1/24 \) of the light of the K’ filter. Thus, in measured (raw) counts, a featureless object will have \( m_K - m_{nb} \sim -3.45 \). An emission line will be seen as excess flux in the narrowband, and we can calculate the narrowband excess, \( \Delta m \), which is the difference between the raw broad minus narrowband color of the object compared to the color of a featureless continuum,

\[
\Delta m = m_K - m_{nb} + 3.45 .
\]

Since the narrowband filter is centered at 2.16 \( \mu m \), with a width of 1% in wavelength, our imaging observations measure the redshifted [O \text{ III}] \( \lambda 5007 \) line. These observations should be uncontaminated by the [O \text{ III}] \( \lambda 4959 \) line, which is 0.96% away in wavelength. We must convert from the observed \( \Delta m \) to line flux. Using the standard procedure for narrowband emission-line measurements, we first calculate its brightness in the rest-frame UV.

\[
EW_{\text{obs}} \approx \Delta \lambda_{nb}(10^{0.4 \Delta m} - 1) ,
\]

where \( \Delta \lambda_{nb} \) is the width of the narrowband filter in \( \AA \), and assuming that the emission line is a negligible contribution to the broadband flux. The EW is multiplied by the observed broadband flux. Thus, errors on the line flux stem from the photometric errors, and the error propagation is handled in the usual manner.

### 2.2. Spectroscopy

The spectroscopic target (Westphal-CC13; \( z \approx 3.406 \)) was chosen for its redshift, which places [O \text{ III}] and H\( \beta \) between the strong atmospheric OH emission lines, and for its brightness in the rest-frame UV.

The near-IR spectrum of Westphal CC13 was obtained using the NIRSPEC instrument on the 10 m W. M. Keck II telescope. The delivered spectrograph is described in detail in McLean et al. (1998, 2000). It is a cross-dispersed echelle spectrograph, with a 1024 \( \times \) 1024 pixel (ALADDIN2) InSb detector. A flat mirror in place of the Echelle grating allows lower resolution (\( R \approx 2000 \)) spectra to be taken. In this mode, each detector pixel corresponds to 0'144 in the spatial direction and 0'19 in the spectral direction.

### Table 1

| Field Target | Date       | \( t_K \) (s) | \( t_{nb} \) (s) |
|--------------|------------|---------------|------------------|
| 3C 324-C6    | 1999 Apr 7 | 3240          | 11280            |
| B20902-M11   | 1999 Apr 7 | 1740          | 6480             |
| Westphal-CC8 | 1999 Apr 7 | 1620          | 4320             |
| Westphal-CC18| 1999 Apr 7 | 3240          | 12000            |

### Table 2

| Object       | \( z \) | \( K^* \) | \( S/N_K \) | \( S/N_{nb} \) | \( \Delta m^b \) | \( EW_{\text{rf}}^c \) (Å) |
|--------------|---------|---------|-----------|-------------|--------------|------------------|
| 3C 324-C6    | 3.310   | 22.0    | 5         | 7           | 1.6          | 170 ± 50         |
| B20902-M11   | 3.300   | 20.9    | 7         | 5           | 0.2          | 10 ± 4           |
| Westphal-CC8 | 3.318   | 21.4    | 2.5       | 9           | 1.1          | 90 ± 50          |
| Westphal-CC18| 3.304   | 22.2    | 6         | 6           | 1.6          | 170 ± 50         |

\( ^* \) Magnitude on the Vega system.
\( ^b \) The narrowband excess, \( \Delta m \), is the difference in magnitudes between the broadband:narrowband count ratio in the object and the ratio expected for a featureless continuum source (see text).
\( ^c \) Rest-frame equivalent width of the emission line.
Fig. 1.—Narrowband excess, $\Delta m$, vs. $K'$ for objects in the LBG fields. Spectroscopically confirmed LBGs are circled. The different symbols indicate the field in which objects were observed according to the key. Westphal-CC18 and 3C 324 were observed with more integration time and so reach greater depth (see text). The curved lines denote the 3 $\sigma$ limits above which an object is considered to have a narrowband excess that indicates an emission-line detection. The two different lines indicate the separate observed depths. The dashed line indicates the line of constant rest-frame equivalent width $EW_{rf} < 150 \AA$, the dot-dashed line indicates $\Delta m < 0.256$

A 256 $\times$ 256 pixel (PICNIC) HgCdTe array provides simultaneous slit viewing when filters in the 1–2.5 $\mu$m bands are used. The slit viewing camera (SCam) has a plate scale of 0.18 arcsec per pixel.

The spectrum was obtained in the low-resolution, long-slit mode through the 42″ long slit. A slit width corresponding to 0.57 arcsec (three pixels) at the InSb detector was chosen, yielding a final resolution of $R \sim 2000$. The spectrum was obtained in three 900 s integrations, separated by small (8″) nods along the slit. A mechanical problem with a filter wheel reduced the throughput of the observations on this run such that the 90 minutes of integration was equivalent to 45 minutes with NIRSPEC’s usual peak performance. The seeing was very good (0.35″), so most of the light from the object should have been transmitted by the slit. The object was acquired using its known position with respect to a nearby bright star. The star was centered in the slit, with the instrument’s internal image rotator set to the position angle that allowed the star and Westphal-CC13 to be observed simultaneously (243°).

We reduced the data using custom software written for the NIRSPEC instrument in the IDL language. First, a halogen lamp flat-field image was used to remove pixel-to-pixel variations in the detector response. Known bad pixels and obvious cosmic rays are identified and fixed using an IDL version of standard IRAF routines for this purpose. The next step was to subtract a sky image, constructed from the nodded object frames. Due to the prevalence of OH lines in the spectrum, which change independently from each other with time, the sky frame had to be scaled to the sky level at the time of the individual observations. Finally, the two-dimensional spectral image was rectified onto a linear space versus wavelength grid.

Rectification of the two-dimensional spectrum was the most complicated part of the data reduction process. Raw spectral data are rotated with respect to detector pixels, and distorted by many pixels in wavelength near the edges of the frame. The wavelength scale for the final grid was determined from measurement of neon and argon arc lamp spectra taken immediately following the observations. The spatial distortion was calculated from measurement of the pixel spacing between nodded spectra of a standard star. Spatial distortion was corrected first by linearly interpolating each row of the object frame. Next, each column was independently interpolated onto the wavelength scale using a third-order fit to the arc lines. The final rectification

| TABLE 3 |
| WESTPHAL-CC13 |

| Line      | Flux* |
|-----------|-------|
| [O III] $\lambda$5007…….. | $4.6 \pm 0.9$ |
| [O III] $\lambda$4959…….. | $1.5 \pm 0.6$ |
| H$\beta$ 4861 ............ | $<0.47 (1 \sigma)$ |

* $10^{-17}$ ergs cm$^{-2}$ s$^{-1}$

9 IRAF is distributed by NOAO, which is operated by AURA Inc., under contract to the NSF.
provided wavelength calibration good to 0.99 Å. The output pixel scale was 4.16 Å per pixel. Unresolved argon arc lamp lines had FWHM = 11.3 Å, for a final resolution of, e.g., $R = 1940$ at 2.2 μm.

After rectification, the frames were registered to coadd the nodded data. The nod distance in the new spatial coordinates was recovered by fitting a Gaussian to the spectrum of the bright reference star. The final two-dimensional spectrum was a weighted mean of the registered images, with weights calculated from the integral under the Gaussian fits to the emission line. Some regions of the spectrum remain unrecoverable due to the night-sky lines. We extracted one-dimensional spectra using the stellar continuum shape to define an optimal extraction vector. This vector was used to weight each (spatial) row of the spectrum, and then the object region was summed.

Extracted spectra were divided by the atmospheric absorption spectrum. We obtained this spectrum from observation of a mostly featureless star (SAO 46659, an A0V star). The stellar data were reduced in the same manner as the spectra of Westphal-CC13, divided by a Kurucz (1993) model atmosphere. The $K$ magnitude of the star was extrapolated from optical photometry based on its stellar type. The sensitivity of the calibrated spectrum was then obtained as a function of flux density per data number per pixel per second, and this calibration was applied to the spectrum of Westphal-CC13. It is not possible to estimate the equivalent widths of the lines due to the lack of contin-

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**Fig. 2**—K-band spectrum of the Westphal-CC13 object, obtained in 2700 s of integration time. Expected emission lines are indicated. The dotted spectrum shows the 1 σ errors. The increases in the errors occur at the position of the night-sky lines and at positions of high atmospheric extinction.
uum signal detection. However, P98 find that the equivalent widths of [O III] $\lambda$5007 and H$\beta$ are large (greater than 40 Å in the rest frame).

3. RESULTS

Figure 1 plots the narrowband excess, $\Delta$m (see § 2.1), against the $K'$ magnitude for all the objects in the fields of the LBGs. The known LBGs are circled in the figure. A strong narrowband excess revealed by plotting this difference identifies an emission-line object (see, e.g., Thompson, Mannucci, & Beckwith 1996). The identification of an emission-line object depends on the 3 $\sigma$ limits propagated from the photometric errors (§ 2.1); an object above the limit is an emission-line detection. The 3 $\sigma$ limits are plotted separately for the two deeper fields (3C 324 and Westphal-CC18) and the shallower ones (B20902 and Westphal-CC8). The figure shows that no new emission-line sources are detected. The four known LBG sources are faint at the $K'$ limits and are near the detection limits.

![Table 2](https://example.com/Table2.png)

| OBJECT          | $z$ | $G_{AB}$ | $R_{AB}$ | $K_{AB}^*$ | $f_s^b$ | [O III] $\lambda$5007 | [O III] 1500 Â | REFERENCE |
|-----------------|-----|----------|----------|------------|--------|------------------------|----------------|-----------|
| Westphal-CC13   | 3.406 | 24.7 | 23.64 | 23.1 | 4.6 ± 0.9 | 39 ± 39 ± 8 | 32 | This work |
| 3C 324–C6       | 3.310 | 25.56 | 24.73 | 22.38 | 5.4 ± 1.5 | 44 ± 44 ± 12 | 14 | This work |
| B20902–M11      | 3.300 | 25.37 | 24.19 | 22.7 | 1.25 ± 0.6 | 11 ± 11 ± 5 | 22 | This work |
| Westphal-CC8    | 3.318 | 24.69 | 24.04 | 23.2 | 4.9 ± 3 | 41 ± 41 ± 25 | 26 | This work |
| Westphal-CC18   | 3.304 | 25.83 | 25.08 | 24.0 | 4.1 ± 1.3 | 34 ± 34 ± 11 | 10 | This work |
| MS 1512–cB58 d  | 2.739 | 24.77 | 24.29 | 23.0 | 4.9 ± 0.3 | 21 ± 21 ± 2 | 13 | T2000 |
| 0000–263 D6     | 2.971 | 23.33 | 22.88 | 22.5 | 7.6 ± 0.7 | 46 ± 46 ± 2 | 59 | P98 |
| 0201+113 C6     | 3.053 | 24.48 | 23.90 | 23.4 | 13 ± 2.5 | 85 ± 85 ± 16 | 23 | P98 |
| 0201+113 B13 f  | 2.168 | 23.37 | 23.43 | 22.9 | 6 ± 1 | 19 ± 3 | 19 | P98 |
| B20902–C6       | 3.099 | 24.58 | 24.13 | 22.3 | 7.7 ± 1.1 | 53 ± 53 ± 8 | 20 | P98 |
| DSF 2237+116C2  | 3.333 | 24.68 | 23.55 | 22.5 | 33 ± 5 | 276 ± 276 ± 42 | 41 | P98 |
| HDF 4–858.13     | 3.216 | 25.4 | 24.3 | 22.9 | 10.0 ± 1.1 | 77 ± 77 ± 8 | 19 | I2000 |
| HDF 3–243.0 h    | 3.233 | 26.7 | 25.6 | 23.8 | 5.7 ± 1.1 | 44 ± 44 ± 8 | 6 | I2000 |

a The $K$ magnitude is given on the AB system for consistency with the optical magnitudes from the literature.

b Flux in the [O III] $\lambda$5007 line in units of $10^{-17}$ erg cm$^{-2}$ s$^{-1}$.

c Errors are the systematic and random errors, respectively. Systematic errors are the approximately factor of 2 variation in the [O III] $\lambda$5007/H$\alpha$ ratio. Random errors result from photometric and spectroscopic uncertainties.

d Corrected for lensing magnification (cf. Seitz et al. 1998).

e [O III] $\lambda$4959 flux, scaled up by the expected ratio (2.87).

f H$\alpha$ flux instead of [O III].

* F450W, F606W, and F814W colors have been translated to $g$, $r$, and $i$.

RESULTS

Figure 2 shows the $K$-band spectrum of Westphal-CC13. The [O III] $\lambda$5007 and [O III] $\lambda$4959 lines are detected, but H$\beta$ is not, although an upper limit has been measured from the data. Table 3 lists the measured properties of Westphal-CC13. Table 4 compares the measured and inferred properties of the narrowband imaging and spectroscopic sample, together with other LBGs available in the literature. Note that in Table 4 there is a second object (B20902-C6) near one of our narrowband LBG targets (B20902-M11), but that it lies outside the redshift range covered by the narrowband filter; its flux was measured spectroscopically by P98.

4. DISCUSSION

We assume that the source of the ionization for the oxygen lines we measure are the stars in the LBGs rather than the presence of active galactic nuclei (AGNs). The rest-frame UV spectra of the LBGs show no evidence for AGN activity, such as the high ionization lines that might be expected. The possibility that a dust-enshrouded AGN could be present is unlikely, given the relatively blue continuum colors of the galaxies. Future rest-frame optical spectroscopy will rule out the possibility if other nonstellar lines, such as [Ne v] $\lambda$3425 Å, are not seen, or based on the line ratios of bright optical emission lines (see Rola, Terlevich, & Terlevich 1997, who separate starbursts from Seyfert galaxies based on the ratios of [O II] $\lambda$3727, [Ne III] $\lambda$3869, H$\beta$, and [O III] $\lambda$5007).

4.1. The Metallicity of Westphal-CC13

No H$\beta$ is detected in Westphal-CC13, which may be surprising in light of the strength of the [O III] lines. In MS 1512–cB58, for example, the H$\beta$/[O III] $\lambda$5007 ratio is similar to the ratio between [O III] components at 5007 and 4959 Å. In Westphal-CC13, [O III] $\lambda$4959 is detected with almost 3 $\sigma$ confidence at 0.33 times the strength of [O III] $\lambda$5007, agreeing within the errors with the expected fraction 1/2.87. It is unlikely that underlying stellar absorption can account for the lack of H$\beta$ emission. Our 2.5 $\sigma$ upper limit on the equivalent width (EW) is 19 Å in the rest frame, while stellar absorption has EW < 5 Å.

A likely explanation for the lack of H$\beta$ in Westphal-CC13 is subsolar metallicity. A moderate range of metallicities (~0.2–0.9 $Z_{\odot}$) produce the highest ratios of O/H emission lines. With further increasing metallicity, oxygen serves as an effective coolant, reducing the collisional excitation rates that would otherwise increase the oxygen line strengths. Below some critical value ($Z \sim 0.2 Z_{\odot}$, the exact value depending on the ionization parameter), with decreasing
metallicity the absolute lack of oxygen ions reduces the observed line emission. A “turnaround” region lies near $Z \sim 0.3 Z_\odot$ (see KKP99).

What is the metallicity of Westphal-CC13 likely to be? We cannot measure the oxygen abundance with the current data. However, we can use the nondetection of H$\beta$ together with well-established models from the literature to place an upper limit on it. Combining that limit with speculation with moderate metallicity, low-redshift starbursts, it is likely that they follow this same correlation, but it has not yet been measured. Similarly, chemical evolution models of LBGs suggest a lower limit on their metallicity of $Z \gtrsim 0.2 Z_\odot$ (Shu et al. 2000). Therefore, the oxygen abundance of Westphal-CC13 is most likely to lie in the range of 0.25–0.8 $Z_\odot$.

In Figure 3, we also plot the metallicity measured for MS 1512–cB58 (T2000), and the limits on the metallicity of three LBGs from P98 for which [O III] and H$\beta$ are measured but [O II] is lacking. We find that most LBGs appear likely to have less than solar metallicity, and yet not to lie in the extremely low Z regime seen in low-mass local galaxies. These results are in broad agreement with the results from a larger spectroscopic sample of LBGs using NIRSPEC and ISAAC over a wider wavelength range (M. Pettini et al., in preparation).

4.2. Star Formation Rate and Dust Extinction

Balmer lines (in particular H$\alpha$ and H$\beta$) have been shown to be good tracers of star formation in galaxies (cf. Kennicutt 1983). The strength of oxygen lines is substantially more complicated, being strongly dependent on the temperature of the ionized gas, which in turn depends on the metallicity of the galaxy. So far, it appears that many LBGs have roughly similar metallicities, so some correlation may exist between [O III] $\lambda$5007 strength and the star formation rate (SFR). We explore the implications with the understanding that the analysis is inherently limited by the unknown properties of the galaxies.

Kennicutt (1983) connected H$\alpha$ luminosity to the SFR by

$$SFR(M_\odot \text{ yr}^{-1}) = \frac{L(H\alpha)}{1.12 \times 10^{41} \text{ ergs s}^{-1}},$$

(3)

In order to estimate the SFR, we must assume an [O III] $\lambda$5007:H$\alpha$ ratio; this assumption is uncertain due to the unknown metallicity. MS 1512–cB58 is found to have an [O III] $\lambda$5007:H$\alpha$ ratio of unity (and $Z \sim 1/3 Z_\odot$). We will take this value as typical for this analysis. Many local, strongly line-emitting, low-metallicity galaxies are seen to vary from this value by a factor of order 2 or less in either direction (e.g., KKP99). The variation in the [O III] $\lambda$5007:H$\alpha$ ratio is also dependent on other parameters in addition to metallicity, such as the effective temperature of the gas and the ionization parameter (Kennicutt et al. 2000), so we are making a number of assumptions when we fix the value of the ratio. These complications have led to the conventional wisdom that [O III] is not the preferred indicator of the SFR (Kennicutt 1992). We proceed with this caution in mind.

We have measured [O III] in three LBGs in the present survey (we exclude B20902–M11 and Westphal-CC8, for which detections are less than 2.5 $\sigma$). In addition to these, seven other LBGs have measured [O III] $\lambda$5007 fluxes (P98; T2000; Iwamuro et al. 2000, hereafter I2000). Inferred SFRs are listed in Table 4. Of the objects with measured [O III] $\lambda$5007 fluxes, four also have measured Balmer emission line fluxes. Figure 4 compares the inferred SFRs. For three of the galaxies, the rates agree within the errors; the fourth is less than 2 $\sigma$ discrepant. This agreement provides some evidence that trends observed in the SFRs inferred from [O III] will be borne out in later observations of the Balmer lines.

The SFR can also be inferred from the UV continuum luminosity. Assuming a $10^8$ yr continuous star formation model from the GISSEL96 spectral synthesis library (see Bruzual & Charlot 1993), a SFR = 1 $M_\odot$ yr produces
FIG. 4.—SFRs inferred from the Hβ and [O iii] λ5007 fluxes in four LBGs. Object names are indicated. Error bars are directly proportional to the errors in the flux measurement. Only random errors are plotted; that is, the systematic error in SFR([O iii]) is not plotted. The most accurately measured object, MS 1512-cB58, has its SFR adjusted downward by a factor of 30 to correct for lensing magnification. The solid line indicates a 1:1 correspondence.

$L_{1500} = 8.7 \times 10^{27}$ ergs s$^{-1}$ Hz$^{-1}$ (Pettini et al. 2000). We can estimate $L_{1500}$ from the measured broadband photometry and the redshift (given in Table 4). At $z \sim 3.5$, the $R$ filter measures the rest-frame continuum near 1500 Å (see P98 for more discussion). Table 4 gives the SFR inferred from [O iii] λ5007 and the UV continuum.

From the inferred SFRs, we can see that in most cases, there is clear evidence that SFRs are higher when inferred from [O iii] λ5007 rather than from the UV. A natural explanation for this difference is the presence of dust extinction. The UV continuum appears to underestimate the SFR by an average factor of $\sim 3$. This value is highly uncertain, given the number of assumptions necessary to use [O iii] as a star formation indicator. However, this extinction is consistent with values inferred from the UV continuum slopes of LBGs (e.g., P98; Steidel et al. 1999), although it is lower than other estimates in the literature (e.g., Trager et al. 1997; Sawicki & Yee 1998). The difference may be attributable to the problems with inferring the SFR from the [O iii] λ5007 flux. On the other hand, there may be a more fundamental difference between the SFR inferred from the UV continuum and that inferred from nebular emission lines (see Bechtold et al. 1997).

P98 observed a trend in dust extinction as a function of $(G-R)$ color by comparing the ratio of SFRs inferred from Hβ and $L_{1500}$. We can make the same comparison using our SFRs (see Fig. 5). In order to properly utilize the $(G-R)$ color intrinsic to each galaxy, we must correct the observed color for the intervening Lyman forest blanketing. To estimate this correction, we convolve a spectral synthesis model (from GISSEL96; see Bruzual & Charlot 1993) with the filter response and the Lyman series decrements from Madau (1995). The correction is quite large (greater than 0.5 mag. at $z > 3$). The colors in Figure 5 have this correction applied. In addition, we have applied a small color term to translate the I2000 data points from WFPC2 colors (from the Hubble Deep Field North; see Williams et al. 1996) to $(G-R)$ colors (see Steidel & Hamilton 1993 for a description of those filters). The color term was determined by integrating under the filter curves using the spiral galaxy spectrum used initially to estimate a photometric redshift for the galaxies (see Fernandez-Soto, Lanzetta, & Yahil 1999, who used the bluest spectrum from the Coleman, Wu, & Weedman 1980 library).

We note that the trend observed in P98 from SFRs inferred using the Hβ line in comparison to the UV is still seen when using their [O iii] measurements as an SFR indicator. It is difficult to judge the trend quantitatively, given the many uncertainties in the SFR estimates (not the least of which is the systematic uncertainty in using [O iii] as an SFR indicator). However, taking the SFR ratios and $(G-R)$ colors at face value (without error bars), we can ask what the probability is that a random sample would have the same appearance of a correlation. The linear correlation coefficient (cf. Bevington 1969) for the 11 data points is
with the highest SFR ratio increases the chance of random apparent correlation to 17%, and removing the two highest points increases it to 29%.

5. SUMMARY

We have presented measurements of the flux of the $[\text{O} \text{ III}]$ $\lambda 5007$ emission line in three LBGs with no previous optical line fluxes in the literature. In one of the objects (Westphal-CC13), we have a strong limit on the strength of the H$\beta$ line, which is not seen in the spectrum. Combining these data with three other $[\text{O} \text{ III}]$ measurements from recent publications (T2000; I2000), we have assembled a list of $[\text{O} \text{ III}]$ measurements for LBGs that more than doubles the previous sample (P98). This combined data set is our primary result.

We have used the $[\text{O} \text{ III}]$ measurements to speculate on the nature of LBGs as a class of galaxies. From the $[\text{O} \text{ III}]$ $\lambda 5007$:H$\beta$ ratio in Westphal-CC18, together with similar measurements from P98 and the reasoning of KKP99, we consider it likely that LBGs tend to lie in the metallicity range 0.25–0.8 $Z_\odot$. Future measurements of $[\text{O} \text{ III}]$ $\lambda 3727$ in LBGs will place much better constraints on this value (M. Pettini et al., in preparation) The $[\text{O} \text{ III}]$ $\lambda 5007$ line is also a weak tracer of star formation. Despite uncertainties in the calibration of the SFR as a function of $[\text{O} \text{ III}]$ $\lambda 5007$, there is a clear trend that SFRs inferred from the oxygen line are higher than those inferred for the same LBGs from their rest-frame UV continuum fluxes. This difference (a ratio of ~3) is naturally attributable to dust extinction, and the value, while uncertain, is in general agreement with other estimates.

These results are a first step in the direction of using optical-line diagnostics for the study of LBGs. This new approach is now possible on larger samples with the advent of NIRSPEC on Keck II and ISAAC on the VLT.

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