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Measurement of [O III] Emission in Lyman Break Galaxies ¹

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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 narrow-band filters using the Near-IR Camera on the Keck I 10-m telescope. A fifth galaxy was observed spectroscopically 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 sub-solar 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 :starburst – infrared : galaxies

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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 (hereafter LBGs; c.f. 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 nearby starbursts; for example Steidel et al. (1996) compare 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 MS1512-cB58 (see Yee et al. 1996) was later obtained by Teplitz et al. (2000; hereafter T2000). At $z > 2.8$, $H\alpha$ 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 $[O III] \lambda 5007$ in a sample of five typical LBGs. Four of the objects were imaged in narrow band 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 4600-5200Å).

In section 2 the observations are presented and the data reduction techniques are explained. Section 3 outlines the observational results, and section 4 presents a discussion of their implication for understanding LBGs. The conclusions are summarized in section 5. Unless otherwise noted, a cosmology of ($H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1}, q_0=0.1, \Lambda=0$) 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 3C324 and B20902. Narrow-band fields were chosen to center on LBGs with

redshifts that place the redshifted [O III] $\lambda 5007$ line within 0.5% of $2.16 \mu\text{m}$, which is the central wavelength of the Br γ filter.

Imaging observations were taken with the Near IR Camera (NIRC; Matthews & Soifer 1994) on the Keck I telescope, on the nights of April 7-8, 1999. Broad-band K' images were taken to measure the continuum flux in the objects, and narrow-band images were taken to measure the redshifted [O III] $\lambda 5007$ flux. The narrow-band filter used for these observations was the standard Br γ filter, centered at $2.16 \mu\text{m}$ with a width $\Delta\lambda/\lambda = 0.01$. 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 3C324 fields were observed to greater depth. Both nights were photometric. In each case the broad- and narrow-band observations were taken as close in time as possible. Typically integrations were taken for 27 minutes on the broad-band, then 90 minutes narrow-band. The deeper fields were observed on both nights, but in those cases both broad- and narrow-band observations were made each night. Broad band observations were taken in 60 second exposures consisting of four coadds of 15 seconds each. Narrow-band observations were taken in single 240 second 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 broad-band images. It is difficult to calibrate narrow-band photometry onto flux units, so we measure the ratios of detected counts in the broad- and narrow-bands and then convert to narrow-band 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 narrow-band magnitude with the broad-band zeropoint so that featureless continuum objects have a broad-minus-narrow-band color that is identically zero.

The images were reduced with the same procedure described in TMM98, which will only be summarized here. We obtained images in a sequence of “dithered” exposures, offsetting the telescope between exposures in a 3×3 grid spaced by a few arcseconds. The data were reduced by dividing a twilight flat into each image and then subtracting from it a running median sky frame created from the nine other exposures taken closest in time. Objects were identified using the SExtractor (Bertin & Arnouts 1996) software.

Photometry was performed in circular apertures of 10 pixels ($1.5''$) diameter (approximately 2.5 times the seeing disk), which corresponds to 11 kpc at $z=3.3$. The size of the aperture was chosen primarily to obtain optimal signal to noise (see Thompson et al. 1995 and Howell 1989). This aperture should encompass the light from a typical LBG (Lowenthal et al. 1997). The same aperture was applied to broad and narrow-band

exposures.

Photometric errors were estimated from aperture photometry performed on random positions in the frame. The signal to noise ratio (SNR) for the individual LBGs in both bands is given in Table 2. The confidence intervals in the narrow-minus-broad band color were estimated from Monte Carlo simulations (see TMM98). These simulations generated narrow- and broad-band magnitudes for line-free objects having the Gaussian errors measured in the real data.

Emission line objects are identified as lying above the 3σ confidence interval in the narrow-minus-broad band counts. The quantity of interest, specifically, is Δm , the excess flux in the narrow-band in magnitudes. 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 γ filter in NIRC was found transmit $\sim 1/24$ of the light compared to the K' filter. Thus in measured (raw) counts, a featureless object will have $m_K - m_{n.b.} \sim -3.45$. An emission line will be seen as excess flux in the narrow band, and we can calculate the narrow-band excess, Δm , which is the difference between the raw broad-minus-narrow-band color of the object compared to the color of a featureless continuum:

$$\Delta m = m_K - m_{n.b.} + 3.45 \quad (1)$$

Since the narrow-band filter is centered at $2.16 \mu\text{m}$, with a width of 1% in wavelength, our imaging observations measure the redshifted [O III] $\lambda 5007$ line. These observations should be uncontaminated by the [O III] $\lambda 4959$ line, which is 0.96% away in wavelength. We must convert from the observed Δm to line flux. Using the standard procedure for narrow-band emission line measurements, we first calculate the equivalent width (EW) following, for example, Bunker et al. (1995). We find that

$$EW_{obs} \simeq \Delta\lambda_{n.b.} \left(10^{0.4\Delta m} - 1 \right) \quad (2)$$

where $\Delta\lambda_{n.b.}$ is the width of the narrow-band filter in \AA , and assuming that the emission line is a negligible contribution to the broad-band flux. The EW is multiplied by the observed broad-band 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; $z \simeq 3.406$) was chosen for its redshift which places [O III] and H β 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 1024×1024 pixel (ALADDIN2) InSb detector. A flat mirror in place of the Echelle grating allows lower resolution ($R \sim 2000$) 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. A 256×256 pixel (PICNIC) HgCdTe array provides simultaneous slit-viewing when filters in the $1 - 2.5 \mu\text{m}$ bands are used. The slit viewing camera (SCam) has a plate scale of $0.18''/\text{pixel}$.

The spectrum was obtained in the low resolution, long-slit mode through the $42''$ long slit. A slit width corresponding to $0.57''$ (three pixels) at the InSb detector was chosen, yielding a final resolution of $R \sim 2000$. The spectrum was obtained in three 900 seconds integrations, separated by small ($\sim 8''$) 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 ($\sim 0.35''$), 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 IRAF⁶ 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 vs. wavelength grid.

Rectification of the 2D 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

⁶IRAF is distributed by NOAO, which is operated by AURA Inc., under contract to the NSF

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 3^{rd} -order fit to the arc lines. The final rectification provided wavelength calibration good to 0.99\AA . The output pixel scale was $4.16\text{\AA}/\text{pixel}$. Unresolved Argon arc-lamp lines had $\text{FWHM} = 11.3\text{\AA}$, for a final resolution of, for example, $R = 1940$ at $2.2\ \mu\text{m}$.

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 2D 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 1D 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 continuum signal detection. However, P98 find that the equivalent widths of $[\text{O III}] \lambda 5007$ and $\text{H}\beta$ are large ($> 40\text{\AA}$ in the rest frame).

3. Results

Figure 1 plots the narrow-band excess, Δm (see section 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 narrow-band excess revealed by plotting this difference identifies an emission line object (see for example Thompson, Mannucci, & Beckwith 1996). The identification of an emission line object depends on the 3σ limits propagated from the photometric errors (section 2.1); an object above the limit is an emission line detection. The 3σ limits are plotted separately for the two deeper fields (3C324 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 depth of this survey, and are near the detection limits. However, two of them appear to show significant ($> 3\sigma$) [O III] emission as expected for young, sub-solar metallicity starforming galaxies (c.f. Kobulnicky et al. 1999; hereafter KKP99). The brightest of the LBGs shows little [O III] emission compared to the others. These narrow-band excesses are given in Table 2.

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, though 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 narrow-band 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 narrow-band LBG targets (B20902-M11), but that it lies outside the redshift range covered by the narrow band 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 non-stellar lines, such as [Ne V] $\lambda 3425\text{\AA}$, are not seen, or based on the line ratios of bright optical emission lines (see Rola, Terlevich & Terlevich 1997, who separate starbursts from Seyferts 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 MS1512-cB58, for example, the $H\beta$:[O III] $\lambda 5007$ ratio is similar to the ratio between [O III] components at 5007\AA and 4959\AA . In WESTPHAL-CC13, [O III] $\lambda 4959$ is detected with almost 3σ confidence at 0.33 times the strength of 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 2.5σ upper limit on the equivalent width (EW) is 19\AA in the rest frame, while stellar absorption has

$EW < 5\text{\AA}$.

A likely explanation for the lack of $H\beta$ in WESTPHAL-CC13 is sub-solar metallicity. A moderate range of metallicities ($\sim 0.2 - 0.9 Z_{\odot}$) 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 ($Z \sim 0.2Z_{\odot}$, the exact value depending on the ionization parameter), with decreasing metallicity the absolute lack of oxygen ions reduces the observed line emission. A “turn-around” region lies near $Z \sim 0.3Z_{\odot}$ (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 non-detection of $H\beta$ together with well established models from the literature to place an upper limit on it. Combining that limit with speculation about the difference between LBGs and modern low metallicity galaxies suggests an allowed region for the oxygen abundance of WESTPHAL-CC13.

To properly measure the oxygen abundance of WESTPHAL-CC13 we would need a measure of $[O\ II]$ emission as well as $[O\ III]$. The $[O\ III]:[O\ II]$ ratio depends on the ionization parameter, U (c.f. McGaugh 1991). For reasonable value of $10^{-4} < U < 10^{-1}$, we expect $0.1 < [O\ III]_{4959+5007} : [O\ II] < 10$ (KKP99). Using our 2.5σ lower limit for $[O\ III] \lambda 5007:H\beta \sim 3.9$, we can bound the allowed region of in the plane of metallicity vs. emission-line ratios. The oxygen abundance can be parameterized in terms of the quantity $R_{23} \equiv [I_{3727} + I_{4959} + I_{5007}]/H\beta$ (c.f McGaugh 1991). Figure 3 shows the region of allowed values for WESTPHAL-CC13.

Following KKP99, there may be an additional constraint on the metallicity. In nearby luminous galaxies there is a correlation between metallicity and luminosity (Zaritsky, Kennicutt, & Huchra, 1994). For objects more luminous than $M_B \simeq -18$, observed metallicities are $12 + \log(O/H) \gtrsim 8.3$. Since LBGs share many characteristics 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 $Z \gtrsim 0.2Z_{\odot}$ (Shu et al. 2000). So the oxygen abundance of WESTPHAL-CC13 is most likely to lie in the range of $0.25 - 0.8Z_{\odot}$.

In Figure 3, we also plot the metallicity measured for MS1512-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 (Pettini et al 2000a, in preparation).

4.2. Star Formation Rate and Dust Extinction

Balmer lines (in particular $H\alpha$, $H\beta$) have been shown to be good tracers of star formation in galaxies (c.f. 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

$$\text{SFR}(M_{\odot}\text{yr}^{-1}) = L(H\alpha)/1.12 \times 10^{41}\text{ergs s}^{-1}. \quad (3)$$

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. MS1512-cB58 is found to have a [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 a factor of order two 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 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 2.5σ .) 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 2σ discrepant. This agreement provides some evidence that trends observed in the SFRs inferred from [O III] will be born out in later observations of the Balmer lines.

The SFR may also be inferred from the UV continuum luminosity. Assuming a 10^8yr continuous star-formation model from the GISSEL96 spectral synthesis library (see Bruzual & Charlot 1993), $\text{SFR}=1 M_{\odot}/\text{yr}$ produces $L_{1500} = 8.7 \times 10^{27} \text{ ergs s}^{-1} \text{ Hz}^{-1}$ (Pettini et

al. 2000b). We can estimate L_{1500} from the measured broad-band photometry and the redshift (given in Table 4). At $z \sim 3.5$, the \mathcal{R} filter measures the rest-frame continuum near 1500\AA (see P98 for more discussion). Table 4 gives the SFR inferred from [O III] $\lambda 5007$ 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] $\lambda 5007$ rather than 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 ~ 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 some values inferred from the UV continuum slopes of LBGs (e.g. P98, Steidel et al. 1999), though 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] $\lambda 5007$ 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- \mathcal{R}) color by comparing the ratio of SFRs inferred from $H\beta$ and f_{1500} . We can make the same comparison using our SFRs (see Figure 5). In order to properly utilize the (G- \mathcal{R}) color intrinsic to each galaxy, we must correct the observed color for the intervening Lyman alpha forest blanketing. To estimate this correction, we convolve a spectra synthesis model (from GISSSEL96, see Bruzual & Charlot 1993) with the filter response and the Lyman series decrements from Madau (1995). The correction is quite large (> 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- \mathcal{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 et al. 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 $H\beta$ 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- \mathcal{R}) colors at face value (without error bars), we can ask what is the probability that a random sample would have the same appearance of a correlation. The linear correlation coefficient (c.f. Bevington, 1969)

for the 11 data points is $r = 0.70$, which implies that 2% of the time a randomly drawn population of 11 data points would exceed this correlation. The P98 points by themselves have a 5% probability of random apparent correlation, while the new points alone have 20%. Excluding the two points with the highest SFR ratio increases the probability to 22%. Thus, the trend seen in P98 still appears marginally significant.

Another approach to the same problem is to look at the SFR ratio as a function of (\mathcal{R} -K) color (see Figure 6). Although the objects lie in different relative positions on this plot, a weak trend is seen. The linear correlation coefficient indicates that there is a 5% probability of a random sample having as strong a correlation. Removing the point 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 [O 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 [O III] measurements from recent publications (T2000, I2000), we have assembled a list of [O III] measurements for LBGs that more than doubles the previous sample (P98). This combined data set is our primary result.

We have used the [O III] measurements to speculate on the nature of LBGs as a class of galaxies. From the [O 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 $0.25 - 0.8Z_{\odot}$. Future measurements of [O II] $\lambda 3727$ in LBGs will place much better constraints on this value (Pettini et al. 2000a, in preparation). The [O III] $\lambda 5007$ line is also a weak tracer of star formation. Despite uncertainties in the calibration of the SFR as a function of [O 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 sample with the advent of NIRSPEC on Keck II and ISAAC on the VLT.

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Table 1. Imaging Observations

Field Target	date	$t_{K'}$ (s)	$t_{n.b.}$ (s)
3C324-C6	1999/4/7-8	3240	11280
B20902-M11	1999/4/7	1740	6480
WESTPHAL-CC8	1999/4/7	1620	4320
WESTPHAL-CC18	1999/4/7-8	3240	12000

Table 2. Narrow-band Targets

Object	z	K^1	SNR_K	$SNR_{n.b.}$	Δm^2	$EW_{rf}^3(\text{\AA})$
3C324-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

¹Magnitude on the Vega system.

²The narrow-band excess, Δm , is the difference in magnitudes between the broad-band : narrow-band count ratio in the object and the ratio expected for a featureless continuum source (see text).

³Rest-frame equivalent width of the emission line.

Table 3. WESTPHAL-CC13

line	flux ^a
[O III] λ 5007	4.6 ± 0.9
[O III] λ 4959	1.5 ± 0.6
H β 4861	$< 0.47 (1\sigma)$

^a 10^{-17} erg cm⁻² s⁻¹

Table 4. [O III] λ 5007 flux in LBGs

Object	z	G_{AB}	\mathcal{R}_{AB}	K_{AB}^1	f_λ^2	SFR ³ ([O III])	SFR (1500Å)	Ref.
WESTPHAL-CC13	3.406	24.7	23.64	23.1	4.6 ± 0.9	$39^{+39}_{-20} \pm 8$	32	this work
3C324-C6	3.310	25.56	24.73	23.8	5.4 ± 1.5	$44^{+44}_{-22} \pm 12$	14	this work
B20902-M11	3.300	25.37	24.19	22.7	$1.25 \pm .6$	$11^{+11}_{-5} \pm 5$	22	this work
WESTPHAL-CC8	3.318	24.69	24.04	23.2	4.9 ± 3	$41^{+41}_{-20} \pm 25$	26	this work
WESTPHAL-CC18	3.304	25.83	25.08	24.0	4.1 ± 1.3	$34^{+34}_{-17} \pm 11$	10	this work
MS1512-cB58 ⁴	2.739	24.77	24.29	23.0	4.9 ± 0.3	$21^{+21}_{-10} \pm 2$	13	T2000
0000-263 D6	2.971	23.33	22.88	22.5	7.6 ± 0.7	$46^{+46}_{-23} \pm 4$	59	P98
0201+113 C6 ⁵	3.053	24.48	23.90	23.4	13 ± 2.5	$85^{+85}_{-43} \pm 16$	23	P98
0201+113 B13 ⁶	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	$53^{+53}_{-26} \pm 8$	20	P98
DSF2237+116C2	3.333	24.68	23.55	22.5	33 ± 5	$276^{+276}_{-138} \pm 42$	41	P98
HDF 4-858.13 ⁷	3.216	25.4	24.3	22.9	10.0 ± 1.1	$77^{+77}_{-38} \pm 8$	19	I2000
HDF 3-243.0 ⁷	3.233	26.7	25.6	23.8	5.7 ± 1.1	$44^{+44}_{-22} \pm 8$	6	I2000

¹The K magnitude is given on the AB system for consistency with the optical magnitudes from the literature.

²Flux in the [O III] λ 5007 line in units of 10^{-17} erg cm⁻² s⁻¹

³Errors are the systematic and random errors respectively. Systematic errors are the approximately factor of two variation in the [O III] λ 5007 : H α ratio. Random errors result from photometric and spectroscopic uncertainties.

⁴corrected for lensing magnification (c.f. Seitz et al. 1998)

⁵[O III] λ 4959 flux scaled up by the expected ratio (2.87)

⁶H α flux instead of [O III]

⁷F450W, F606W, F814W colors have been translated to G and \mathcal{R} , see text

Fig. 1.— The narrow-band excess, Δm , 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 3C324 were observed with more integration time and so reach greater depth (see text). The curved lines denote the three sigma limits above which an object is considered to have a narrow-band excess which 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 $EW_{rf} = 150\text{\AA}$, and the dot-dash line indicates $\Delta m = 0$.

Fig. 2.— The K-band spectrum of the WESTPHAL-CC13 object, obtained in 2700 seconds of integration time, is shown. Expected emission lines are indicated. The dotted spectrum shows the 1σ errors. The increases in the errors occur at the position of the night sky lines and at positions of high atmospheric extinction.

Fig. 3.— The Strong-line ratio intensity, $\log(R_{23}) \equiv \log([I_{3727} + I_{4959} + I_{5007}]/H\beta)$, as a function of oxygen abundance from KKP99, is shown. The lines indicate the limiting values from reasonable ionization parameters (McGaugh et al. 19991). The parameter space that the observed R_{23} and theoretical ionization parameter constraints allow for WESTPHAL-CC13 is shaded, with only the upper (lighter) region acceptable if the local observed metallicity-luminosity ratio is valid at $z=3.4$. The data point is the value measured for MS1512-cB58 (Teplitz et al. 2000). The arrows indicate the limits on the metallicity of three LBGs from P98; for those objects no [O II] was measured, and the direction of the arrow shows the effect of increasing [O II]:[O III]= 0.1.

Fig. 4.— The SFRs inferred from the $H\beta$ and [O III] $\lambda 5007$ fluxes in four LBGs. Object names are indicated. Errorbars are directly proportional to the errors in the flux measurement. Only random errors are plotted; that is, the systematic error in $\text{SFR}([\text{O III}])$ is not plotted. The most accurately measured object, MS1512-cB58, has its SFR adjusted downward by a factor of 30 to correct for lensing magnification. The solid line indicates a 1:1 correspondence.

Fig. 5.— Ratio of the SFRs implied by the luminosities of the optical emission lines and of the UV continuum plotted against the observed $(G-\mathcal{R})$ color, corrected for Lyman forest blanketing, assuming a 10^8 yr old continuous star formation model. Open circles indicate narrow-band [O III] detections (we exclude B20902-M11 and WESTPHAL-CC8 for which detections are less than 2.5σ); the open triangle is the NIRSPEC detection of [O III] in WESTPHAL-CC13; the open diamond is the NIRSPEC detection of [O III] in MS1512-cB58 (T2000); filled circles are P98 spectroscopic detections of [O III]; the filled square is the P98 spectroscopic detection of $H\alpha$; the * symbols are LBGs measured in narrow-band imaging by I2000.

Fig. 6.— As in Figure 5, the ratio of the SFRs implied by the luminosities of the optical emission lines and of the UV continuum plotted against the observed (\mathcal{R} -K) color. Colors are converted to the AB system.











