DIRECT METHOD GAS-PHASE OXYGEN ABUNDANCES OF FOUR LYMAN BREAK ANALOGS*

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Received 2014 June 10; accepted 2014 July 18; published 2014 August 26

ABSTRACT

We measure the gas-phase oxygen abundances in four Lyman break analogs using auroral emission lines to derive direct abundances. The direct method oxygen abundances of these objects are generally consistent with the empirically derived strong-line method values, confirming that these objects are low oxygen abundance outliers from the mass-metallicity (MZ) relation defined by star forming Sloan Digital Sky Survey galaxies. We find slightly anomalous excitation conditions (Wolf–Rayet features) that could potentially bias the empirical estimates toward high values if caution is not exercised in the selection of the strong-line calibration. The high rate of star formation and low oxygen abundance of these objects is consistent with the predictions of the fundamental metallicity relation, in which the infall of relatively unenriched gas simultaneously triggers an episode of star formation and dilutes the interstellar medium of the host galaxy.

Key words: galaxies: active – galaxies: high-redshift – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

Identifying and quantifying correlations between fundamental parameters provides insight into the physical processes governing the evolution of the objects under investigation. In the ΛCDM paradigm, galaxies accrete mass primarily via hierarchical mergers with other galaxies. This formulation reproduces the physical properties of galaxies which we observe in the nearby universe (Kauffmann & Haehnelt 2000; Hopkins et al. 2006). Thus, the mass of a galaxy reveals the gross characteristics of its history. Similarly, the metallicity of a galaxy is a fundamental characteristic which is intimately related to its formation and subsequent chemical evolution. Studying how the mass and metallicity of galaxies correlate across a wide range of physical parameters informs us about how today’s galaxies coalesced and evolved over cosmic time.

The relation between a galaxy’s mass and gas-phase oxygen abundance (the MZ relation) was first investigated by Lequeux et al. (1979). Subsequent studies often focused on the more readily measured correlation between luminosity and oxygen abundance (the LZ relation; e.g., Garnett & Shields 1987; Skillman et al. 1989; Zaritsky et al. 1994). With data from the Sloan Digital Sky Survey (SDSS; York et al. 2000) for a very large number of galaxies, Tremonti et al. (2004) showed that the MZ relation persists across at least three orders of magnitude in mass and an order of magnitude in oxygen abundance. This trend was extended 2.5 orders of magnitude lower in mass and another order of magnitude lower in oxygen abundance by Lee et al. (2006). There have been a number of subsequent studies that have investigated possible variations in the MZ relation as a function of redshift (e.g., Erb et al. 2006), star formation rate (SFR; e.g., Andrews & Martini 2013), morphology and environment (e.g., Ellison et al. 2008a, 2008b), or a combination of these factors (e.g., Mannucci et al. 2010; Lara-López et al. 2010).

While general trends between galactic parameters are both interesting and useful, objects that deviate from the observed relations offer a unique perspective, as it is these objects which allow for the direct identification of the important physical mechanisms driving galactic evolution. The “Lyman break analogs” (LBA) project (Heckman et al. 2005) identified a class of galaxies which appear to deviate from the local galaxy population and more closely resemble high-redshift Lyman break galaxies (LBGs; for a review see Giavalisco 2002). These objects were initially identified as nearby (z < 0.3), compact (I_{FUV} > 10^{9} L_{⊙} kpc^{-2}), and UV bright (I_{FUV} > 10^{10.3} L_{⊙}) objects, mimicking the physical conditions in LBGs seen at much higher redshifts. Thus, if LBAs are true analogs of LBGs, then they provide us with an opportunity to study a mode of star formation that may have been dominant in the early universe in a much more detailed way than the very distant LBGs allow. After the identification of LBAs, subsequent work (Hoopes et al. 2007; Basu-Zych et al. 2007; Overzier et al. 2008, 2009, 2010; Gonçalves et al. 2010) used the Hubble Space Telescope (HST), Spitzer, Very Large Array, SDSS, Galaxy Evolution Explorer, and the Keck II telescope to investigate the physical properties of these systems, as well as the degree to which they may resemble LBGs.

The gas-phase oxygen abundance of these objects was estimated by Overzier et al. (2009, 2010) using the N2 and O3N2 empirical calibrations from Pettini & Pagel (2004, hereafter PP04). After applying the N2 relation to SDSS galaxies and LBAs, Overzier et al. (2010) showed that the offset of the LBAs from the MZ relation of local star forming galaxies is inversely correlated with mass, with the least massive LBAs falling ≳0.2 dex below the locus of SDSS galaxies. Low metallicity objects are of particular interest, as they offer a view of how the earliest stars and galaxies formed (e.g., Kunth & Östlin 2000; Skillman et al. 2013). Fortunately, the empirical abundance calibrations incorporate many low mass, low metallicity blue compact galaxies in the hope of extending the calibrations.
to the lowest metallicities possible. However, we have no a priori reason to expect that a locally calibrated empirical abundance relation ought to apply to a class of exotic objects experiencing an episode of relatively extreme, concentrated star formation, as is found in the centers of these LBAs.

Typical LBAs exhibit SFRs an order of magnitude higher than local dwarf galaxies. Additionally, most LBAs have morphologies and kinematics consistent with recent interactions (Overzier et al. 2009, 2010; Gonçalves et al. 2010). Clearly, these objects depart from the physical parameter space occupied by the local H II regions and dwarf galaxies used to calibrate the empirical relations. Are the empirically estimated oxygen abundances of LBAs being systematically affected by their extreme physical conditions? For instance, Pilyugin et al. (2010) showed that many of the line ratios used in the typical strong-line abundance indicators (Pagel et al. 1979; Alloin et al. 1979) are complex functions of electron temperature. They show that deriving an abundance calibration from a sample of relatively cool H II regions and applying it to relatively hot H II regions could yield erroneous abundance estimates. Alternatively, if locally calibrated empirical relations return reliable abundance estimates when applied to LBAs, then this would also be of interest, as this is not immediately obvious given the extreme physical nature of these objects.

Fortunately, we are not required to rely on empirical calibrations alone for these objects. With a measure of the electron temperature ($T_e$), we can determine the oxygen abundance directly using the $T_e$ or “direct” method (Dinerstein 1990). The electron temperature can be determined from temperature-sensitive intensity ratios of collisionally excited forbidden lines. Generally speaking, as metallicity increases, the temperature of the nebula decreases, as there are more ions available to cool the gas. In relatively low metallicity nebulae, a measure of the electron temperature is typically obtained using the $[\text{O} \text{III}] \lambda 4363/\lambda \lambda (4959 + 5007)$ line ratio. However, somewhat problematically, the auroral oxygen line $[\text{O} \text{III}] \lambda 4363$ is intrinsically faint, making it notoriously difficult to measure in distant and/or faint objects (though see Hoyos et al. 2005; Kakazu et al. 2007; Amorín et al. 2010, 2012 for instances of the direct method being applied at relatively high redshifts).

We have measured $[\text{O} \text{III}] \lambda 4363$ in four of the objects from the Overzier et al. (2009) sample using the newly commissioned Multi-Object Double Spectrograph 1 (MODS1) on the 8.4 m Large Binocular Telescope (LBT). We use the $[\text{O} \text{III}]$ line fluxes to determine an electron temperature, yielding a gas-phase oxygen abundance measurement which we can compare to the values derived via empirical techniques.

In Section 2, we describe the observations and data reduction. Section 3 describes the analysis of the data, including the subtraction of the underlying stellar continuum. In Section 4, we present the results of our analysis. Finally, in Section 5, we discuss where LBAs fit in the bigger picture of galaxy formation and evolution. Section 6 provides a summary. Throughout this paper, we assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.7$, and $\Omega_{M_0} = 0.3$. With these cosmological parameters, a redshift of $z = 0.2$ corresponds to an age of the universe of $\sim 11$ Gyr.

2. OBSERVATIONS AND REDUCTION

2.1. Observing Procedures

We observed four of the LBAs identified in Overzier et al. (2009) using MODS1 on the LBT (Pogge et al. 2010) between 2011 September and 2013 January. All targets were observed in longslit mode with a 1”0 slit imaged onto two 3072 × 8192 format e2v CCDs with 152μm pixels. MODS1 uses a dichroic that splits the light into separately optimized red and blue channels at $\sim 5650$ Å. The blue CCD covers a wavelength range of $\sim 5200$–$5650$ Å with a 400 nm$^{-1}$ grating (spectral resolution of 2.4 Å), while the red CCD covers a wavelength range of $\sim 5650$–10000 Å with a 250 nm$^{-1}$ grating (spectral resolution of 3.4 Å).

Each target was observed with three 600s exposures for a total of 1800 s, with the exception of J005552, which was observed with four 1200 s exposures for a total of 4800 s. The position angle of the slit approximated the parallactic angle at the midpoint of the observation so as to minimize slit losses due to differential atmospheric refraction. If the arc lamp or flat field data was not available on the night of the observation, then we used the calibration data obtained within one to two days of our observations. Given the stability of MODS1 over the course of an observing run, this is sufficiently recent to provide accurate calibrations. We obtained bias frames and $Hg(Ar)$, Ne, Xe, and Kr calibration lamp images, which we used for wavelength calibration. Night sky lines were used to correct for the small ($\sim 1$ Å) residual flexure. Standard stars were observed with a 5” × 60” spectrophotometric slit mask used for flux calibration. The standard stars are from the HST Primary Calibrator list, which is composed of well observed northern-hemisphere standards from the lists of Oke (1990) and Bohlin et al. (1995).

Target selection was done such that priority was given to the objects from Overzier et al. (2009) with the lowest oxygen abundance estimates, and hence the most offset from the MZ relation, which were visible at the time of observation. Our final sample has a mean redshift ($z$) = 0.205 with standard deviation $\sigma_z = 0.053$.

2.2. Data Reduction

The basic two-dimensional data reduction was performed in Python using the modsCCDRed suite of programs. We used modsCCDRed to bias subtract, flat field, and illumination correct the raw data frames. We then coadded the frames and removed cosmic rays with L.A. Cosmic (van Dokkum 2001), taking extra care to ensure any emission features were not misidentified as cosmic rays.

We performed sky subtraction and one-dimensional extraction using the modsIDL pipeline. This pipeline has been developed specifically for MODS and makes use of the XIDL packages. Figure 1 shows our reduced spectra compared with spectra from the SDSS. The MODS1 spectra achieve a higher signal-to-noise ratio (S/N) than the SDSS spectra across a wider wavelength range. The inset shows a zoomed view of the metallicity sensitive $[\text{O} \text{III}] \lambda 4363$ auroral emission line. For each target, the MODS1 spectra show a high significance detection of the line. In some cases, the effects of stellar absorption near the Balmer lines can be seen. Note the lack of detection of the auroral nitrogen emission line, consistent with the previously estimated low metallicity of these objects from empirical bright line methods.

\footnotesize{http://www.astronomy.ohio-state.edu/MODS/Software/modsCCDRed/}
\footnotesize{http://www.astro.yale.edu/dokkum/lacosmic/}
\footnotesize{http://www.astronomy.ohio-state.edu/MODS/Software/modsIDL/}
\footnotesize{http://www.ucolick.org/~xavier/IDL/}
3. ANALYSIS

3.1. Stellar Continuum Subtraction

Many of the emission lines are blended with underlying stellar absorption features. To obtain accurate line flux measurements, it is necessary to remove the underlying stellar component before extracting line fluxes.

Prior to modeling the underlying stellar component of the LBAs, we correct for foreground Galactic extinction using the dust maps from Schlegel et al. (1998) and the reddening law from O'Donnell (1994) with $R_V = 3.1$. We then shift each spectra to the rest frame using the redshifts from the SDSS and resample our spectra to 1 Å pixel$^{-1}$.

We model the underlying stellar component of each target using the STARLIGHT stellar population synthesis code.
STARLIGHT uses a Markov Chain Monte Carlo approach to fitting a combination of spectra from a stellar library to an observed spectrum. We adopted the stellar library from Bruzual & Charlot (2003) and assumed a Chabrier initial mass function (Chabrier 2003). We chose base spectra that cover a wide range in both metallicity ($0.0004 \leq Z \leq 0.03$) and age ($1 \text{ Myr} \leq \tau \leq 10 \text{ Gyr}$). In general, our galaxies lack any strong stellar absorption features which could be used to place strong constraints on the underlying stellar population. However, we are able to model the general shape of the continuum as well as remove any absorption features near our metallicity-sensitive lines. In particular, the $\text{[O III]} \, \lambda 4363$ line lies in close proximity to $H\gamma$, and so we need to take extra care to make sure the $\text{[O III]} \, \lambda 4363$ flux is not degraded by Balmer absorption. In general, we find that our galaxies are best fit with a young ($\tau \lesssim 20 \text{ Myr}$) stellar population of roughly solar metallicity, with a velocity dispersion $\sigma \sim 200 \text{ km s}^{-1}$. We regard this strictly as a qualitative assessment; our targets
can be equally well fit with a wide range of ages, metallicities, and kinematics. In general, we find the effects of our detailed model fit on the strengths of the stellar absorption features to be minimal. Accounting for stellar absorption, we find, on average, that model fit on the strengths of the stellar absorption features to be equally well fit with a wide range of ages, metallicities, and kinematics. We fit a library of atomic lines to each spectrum using MPFIT7 (Markwardt 2009), an IDL implementation of the robust non-linear least-squares fitting routine MINPACK-1. We assume that the electrons in the H II region follow a Maxwell–Boltzmann equilibrium energy distribution. In the low density Boltzmann regime, [O III] \(\lambda 4363/\lambda 4369 (4959 + 5007)\) is governed by the relative level populations of the [O III] ion, and, due to the spacing of the energy levels, the relative level population is very sensitive to the electron temperature of the ionized region. Since the derived ionic abundances are a strong function of electron temperature, a measurement of [O III] \(\lambda 4363/\lambda 4959 + 5007\) allows us to compute the total oxygen abundance directly, rather than having to rely on empirical methods.

The assumption of a Maxwell–Boltzmann distribution of electron energies has recently come into question. Specifically, even different temperature-sensitive line ratios used to directly measure the electron temperature (e.g., \([\text{O III}] \lambda 4363/\lambda 4369, 5007, [\text{S II}] \lambda 6716, 31, [\text{N II}] \lambda 6548, 84, \text{and} [\text{O III}] \lambda 7318, 24/\lambda 3726, 9\) sometimes yield inconsistent results. Nichols et al. (2012) proposed that these discrepancies could be explained if the distribution of electron energies follows a \(\kappa\) distribution, rather than a Maxwell–Boltzmann distribution. However, we are only concerned with relative comparisons for a given electron temperature measurement method. Thus, we do not expect systematic effects arising from our assumed energy distribution to significantly influence our results.

Osterbrock & Ferland (2006) describes how to compute \(T_e\) and \(n_e\) in ionized nebulae. In this paper, we measure the electron temperature \(T_e\) and density \(n_e\) using the im_tenden IDL routines from the Moustakas code repository.8 This set of routines uses well-known line ratios to compute the electron temperature and/or electron density of a given region. We assume a three-zone ionization region composed of a high ionization region (with \(T_e = T_{3} \equiv T_{e}(\text{[O III]})\)), an intermediate ionization region (\(T_e \equiv T_{e}(\text{[Ar III]})\)), and a low

| Ion          | J092600 | J040504 | J020556 | J005527 |
|--------------|--------|--------|--------|--------|
| [O III] \(\lambda 3727\) | 1.576 ± 0.044 | 1.662 ± 0.044 | 2.684 ± 0.063 | 2.082 ± 0.111 |
| He I \(\lambda 3820\)     | 0.005 ± 0.009 | 0.008 ± 0.007 | 0.006 ± 0.014 | 0.016 ± 0.010 |
| [Ne II] \(\lambda 3869\) | 0.468 ± 0.016 | 0.485 ± 0.018 | 0.315 ± 0.012 | 0.308 ± 0.015 |
| H\(\gamma\) \(\lambda 4340\) | 0.480 ± 0.016 | 0.472 ± 0.022 | 0.481 ± 0.015 | 0.468 ± 0.018 |
| [O III] \(\lambda 4363\) | 0.076 ± 0.005 | 0.073 ± 0.017 | 0.025 ± 0.007 | 0.022 ± 0.004 |
| [He II] \(\lambda 4686\) | 0.015 ± 0.005 | 0.008 ± 0.004 | 0.004 ± 0.001 | 0.016 ± 0.005 |
| H\(\beta\) \(\lambda 4861\) | 1.000 ± 0.037 | 1.000 ± 0.044 | 1.000 ± 0.033 | 1.000 ± 0.056 |
| [O III] \(\lambda 4959\) | 1.831 ± 0.060 | 1.939 ± 0.076 | 1.193 ± 0.038 | 1.179 ± 0.053 |
| [O III] \(\lambda 5007\) | 5.338 ± 0.169 | 5.825 ± 0.220 | 3.496 ± 0.104 | 3.509 ± 0.141 |
| H\(\alpha\) \(\lambda 6563\) | 2.927 ± 0.094 | 2.878 ± 0.117 | 2.930 ± 0.096 | 2.861 ± 0.128 |
| [N II] \(\lambda 6583\) | 0.119 ± 0.014 | 0.105 ± 0.021 | 0.246 ± 0.016 | 0.431 ± 0.027 |
| [S II] \(\lambda 6717\) | 0.161 ± 0.014 | 0.158 ± 0.023 | 0.308 ± 0.018 | 0.232 ± 0.024 |
| [S II] \(\lambda 6731\) | 0.121 ± 0.014 | 0.107 ± 0.024 | 0.226 ± 0.017 | 0.198 ± 0.023 |
| [O II] \(\lambda 7320\) | 0.022 ± 0.009 | 0.049 ± 0.026 | 0.022 ± 0.023 | 0.035 ± 0.005 |
| [O II] \(\lambda 7330\) | 0.017 ± 0.009 | 0.013 ± 0.032 | 0.008 ± 0.027 | 0.030 ± 0.004 |

Note. Units are such that H\(\beta\) = 1.

This is well above the S/N typically required to obtain an electron temperature from [O III] \(\lambda 4363\) (e.g., Croxall et al. 2009). We assume that the electrons in the H II region follow a Maxwell–Boltzmann equilibrium energy distribution. In the low density Boltzmann regime, [O III] \(\lambda 4363/\lambda 4369 (4959 + 5007)\) is governed by the relative level populations of the [O III] ion, and, due to the spacing of the energy levels, the relative level population is very sensitive to the electron temperature of the ionized region. Since the derived ionic abundances are a strong function of electron temperature, a measurement of [O III] \(\lambda 4363/\lambda 4959 + 5007\) allows us to compute the total oxygen abundance directly, rather than having to rely on empirical methods.

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\[ R_2 = I_{(\text{O III})_\alpha, \lambda 3727, 29} / I_{H\beta} \]
\[ R_3 = I_{(\text{O III})_\lambda 4959, 5007} / I_{H\beta} \]
\[ R_{23} = R_2 + R_3 \]
\[ P = R_3 / R_{23} \]

for the principal diagnostic emission line ratios.

### 3.3. Abundance Determination

We detect [O III] \(\lambda 4363\) in each of the galaxies, with the minimum detection at S/N = 8.8 and an average S/N = 15.9;

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7. http://purl.org/net/mpfit

8. https://github.com/moustakas/impro
ionization region (with $T_e = T_2 = T_{\text{e}}([\text{O}\text{ II}])$). We measure $T_3$ from $[\text{O}\text{ III}] \lambda 4363/\lambda(4959 + 5007)$ and compute $T_2$ using the relation

$$t_2 = 0.264 + 0.835 t_3$$

(1)

where $t = T/10^4$ from Pilyugin et al. (2009). Due to the substantial noise from sky contamination and the relative weakness of the $[\text{O}\text{ II}] \lambda\lambda 7320, 30$ lines, we do not achieve a strong detection of these lines in all of our targets. In the two cases where we are able to make a robust measurement of $T_3$, we find reasonable agreement between the calculated $T_3$ and $T_2$. For simplicity, in the low ionization region (with $J_{004054} = 1.189 \pm 0.05420$), we assume $\lambda\lambda 6717/6731 < 100$ cm$^{-3}$, as lower densities are consistent with 100 cm$^{-3}$. While J005527 shows signs of slightly higher electron density, we are still well inside the low density regime for each of our targets. Table 2 lists the measured temperatures and densities for each LBA in our sample. Given the redshift of these objects, several $[\text{S}\text{ III}]$ lines (e.g., $[\text{S}\text{ III}] \lambda\lambda 9069, 9532$) are unobservable with MODS1, and so we exclude sulfur from our abundance determinations.

Table 2

| Target      | $T_e([\text{O}\text{ II}])$ (K) | $T_e([\text{O}\text{ III}])$ (K) | $N_e([\text{S}\text{ II}])$ (cm$^{-3}$) |
|-------------|---------------------------------|---------------------------------|---------------------------------|
| J092600     | $1.189 \pm 0.11843 \times 10^4$ | $1.324 \pm 0.01609 \times 10^4$ | 100                             |
| J004054     | $\ldots$                      | $1.262 \pm 0.05396 \times 10^4$ | 100                             |
| J020556     | $\ldots$                      | $1.040 \pm 0.04571 \times 10^4$ | 100                             |
| J005527     | $1.390 \pm 0.05420 \times 10^4$ | $1.000 \pm 0.02756 \times 10^4$ | 312                             |

We then take our electron temperatures and densities and use Moustakas’ im_nlevel routine to compute the relative populations and emissivities for the different ions using an n-level atom calculation. For simplicity, in the low ionization zone, we adopt the reasonable canonical assumptions that $T_e([\text{N}\text{ II}]) = T_e([\text{O}\text{ II}]) = T_2$, where $T_2$ is the theoretical value derived from our measured $T_3$. Similarly, for the high ionization region, we assume $T_e([\text{Ne}\text{ III}]) = T_e([\text{O}\text{ III}]) = T_3$. Finally, in the intermediate ionization region, we assume $T_e([\text{Ar}\text{ III}]) = 0.837 t_2 + 0.17$ from Garnett (1992). We obtain a density for each ion using

$$N(X^i)/N(H^+) = \frac{l_{\text{H}}}{l_{\text{H}} \beta} j_{\text{H}} = \frac{\beta \beta}{\beta \beta} j_{\text{H}}.$$  

In order to compute the total abundance of a given element, we sum the observable ionic states. In the case of oxygen, we assume

$$O/\text{H} = \frac{0^0 + 0^+ + O^{++}}{H^+}.$$  

We compute both total and ionic abundances for O, N, Ne, and Ar. We compute ionization correction fractions (ICFs) for N, Ne, and Ar. We adopt the ICFs from Thuan et al. (1995):

$$\text{ICF}(\text{N}) = \frac{O}{O^+},$$

$$\text{ICF}(\text{Ne}) = \frac{O}{O^{++}},$$

$$\text{ICF}(\text{Ar}) = \frac{Ar}{Ar^{++}} = [0.15 + x(2.39 - 2.64x)]^{-1},$$

where $x = O^+/O$. The abundance estimates (and associated uncertainties) for each object are presented in Table 3.

Figure 2. BPT diagram composed of star forming SDSS galaxies (gray contours), H II regions from Pilyugin et al. (2012) (black points), and the LBAs from our sample (cyan/red circles). The uncertainties in the line ratios for the LBAs are smaller than the plotting symbols. The dashed and solid red lines are from Kauffmann et al. (2003a) and Kewley et al. (2006), and denote the boundaries between star forming galaxies and AGN. The red circle represents J005527, which seems to exhibit enhanced nitrogen relative to the other LBAs. (A color version of this figure is available in the online journal.)

4. RESULTS

4.1. Excitation

In Figure 2, we show the standard diagnostic Baldwin–Phillips–Terlevich (BPT) diagram (Baldwin et al. 1981) used to distinguish between ionization regions heated primarily by star-formation and regions heated primarily by active galactic nuclei (AGNs). Star forming SDSS galaxies$^7$ from the MPA-JHU catalog are shown as gray contours, H II regions$^8$ from Pilyugin et al. (2012) are shown as black points, and our LBAs are shown as the large cyan dots. The dashed and solid red lines are from Kauffmann et al. (2003a) and Kewley et al. (2006) and denote the boundaries between star forming galaxies and AGNs. Our results are consistent with those presented in previous studies; the LBAs fall squarely in the star-formation-dominated region of the BPT diagram. We find that J005527 (red circle) is offset to the right in Figure 2 relative to other LBAs and the H II regions from Pilyugin et al. (2012), indicative of enhanced [N II] emission.

Figure 3 shows the excitation conditions of our LBAs based on the relative oxygen line ratios. We plot the star forming SDSS galaxies (gray contours), the H II regions from Pilyugin et al. (2012) (black dots), and our 4 LBAs (cyan dots). The left panel compares the relative [O II] and [O III] line ratios. The dotted lines show constant $R_{23}$; from bottom left to top right $log(R_{23}) = 0, 0.5, 1.0$. As seen in Figure 2, the LBAs and H II regions from Pilyugin et al. (2012) have higher [O III] emission compared to the SDSS galaxies. The right panel shows $P = R_3/R_{23}$ as a function of $log(R_{23})$. Again, the LBAs display excitation conditions which are typical of H II regions but quite unusual for star forming SDSS galaxies.

$^7$ Available at http://www.mpa-garching.mpg.de/SDSS/DR7/

$^8$ Available at http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/MNRAS/424/2316.
Figure 3. Excitation diagnostic plots for SDSS galaxies (gray contours), H\textsc{ii} regions from Pilyugin et al. (2012) (black points), and the LBAs from our sample (cyan points). The uncertainties in the line ratios for the LBAs are smaller than the plotting symbols. The left panel shows [O\textsc{ii}]\,$\lambda\lambda$3727, 29 as a function of [O\textsc{iii}]\,$\lambda$5007. Dotted lines show constant R$_{23}$; from bottom left to top right log($R_{23}$) = 0, 0.5, 1.0. In general, the LBAs display higher excitation conditions more similar to H\textsc{ii} regions than the SDSS star forming galaxies. The right panel shows $P = R_3 / R_{23}$ as a function of log($R_{23}$). Again, the LBAs occupy an excitation regime closer to that of H\textsc{ii} regions than star forming SDSS galaxies.

(A color version of this figure is available in the online journal.)

Figure 4. Diagnostic emission-line ratios as a function of oxygen abundance for our LBAs and a comparison set of local H\textsc{ii} regions from Pilyugin et al. (2012). The LBAs from our sample are shown as cyan points, with the location of J005527 marked with a red circle; the H\textsc{ii} regions with well measured metallicities from Pilyugin et al. (2012) are shown as black points. The error bars in the lower right of each plot represent an uncertainty in the oxygen abundance of 0.07 dex. J005527 displays relatively stronger [N\textsc{ii}] emission compared to the other LBAs, but remains well within the parameter space occupied by the H\textsc{ii} regions. The LBA line ratios are remarkably similar to those of the “warm” H\textsc{ii} regions from Pilyugin et al. (2010), suggesting that the excitation conditions in LBAs are actually quite similar to that of typical H\textsc{ii} regions.

(A color version of this figure is available in the online journal.)
In Figure 4, we show line diagnostic diagrams from Pilyugin et al. (2010). The LBAs display line ratios that are remarkably similar to “warm” H\(\text{ii}\) regions. Again, the red circle marks the location of J005527, which shows signs of enhanced nitrogen relative to the other LBAs, even though it still remains well within the parameter space occupied by H\(\text{ii}\) regions.

Figure 5 shows the region around 4660 Å where we detect characteristic Wolf–Rayet features (e.g., Bresolin et al. 2004; Brinchmann et al. 2008) in each of our four targets. The most common features are \(\lambda\text{C IV} = 4658\) Å and \(\lambda\text{He II} = 4686\) Å. J005527 displays the strongest Wolf–Rayet signatures, specifically \(\lambda\text{N III} = 4640\) and a broad bump from 4600–4700 Å, in addition to the \(\lambda\text{C IV}\) and \(\lambda\text{He II}\) emission lines. These high ionization features are associated with very young stellar populations, as they are typically visible for only a few million years following an episode of significant star formation.

### 4.2. Oxygen Abundances

Our oxygen abundances are presented in Table 4. We are able to reproduce the oxygen abundances from Overzier et al. (2009) to within a few percent using the PP04 O3N2 method on the SDSS spectra. We have included the original N2 and O3N2 calibrations from PP04 as well as newer CALIFA-T\(\gamma\) calibrations from Marino et al. (2013) that use a larger sample of H\(\text{ii}\) regions with direct oxygen abundances. The calibrations from Marino et al. (2013) are generally shallower than those presented in PP04 but in the abundance range we are concerned with, the CALIFA and PP04 calibrations produce nearly identical results.

Due to the location of the LBAs in the transition zone of the \(R_{23}\) index, the popular theoretical strong-line calibrations are generally shallower than those presented in PP04 but in the abundance range we are concerned with, the CALIFA and PP04 calibrations produce nearly identical results.

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Figure 5 shows the region around 4660 Å where we detect characteristic Wolf–Rayet features (e.g., Bresolin et al. 2004; Brinchmann et al. 2008) in each of our four targets. The most common features are \(\lambda\text{C IV} = 4658\) Å and \(\lambda\text{He II} = 4686\) Å. J005527 displays a broad bump from 4600–4700 Å as well as \(\lambda\text{N III}\) emission, both of which are characteristic of a Wolf–Rayet galaxy. The noise spike and drop in flux seen in the J020356 panel are due to the coincidental location of the dichroic cutoff for this particular target.

### Table 3

| Parameter                | J092600  | J004054  | J020356  | J005527  |
|--------------------------|----------|----------|----------|----------|
| \(\text{O}/\text{H}\) \((\times 10^{3})\) | 0.302 ± 0.025 | 0.357 ± 0.067 | ... | 1.162 ± 0.111 |
| \(\text{O}/\text{H}\) \((\times 10^{3})\) | 1.787 ± 0.035 | 2.155 ± 0.040 | 6.042 ± 0.100 | 5.388 ± 0.187 |
| \(\text{O}^+ / \text{H}^+ (\times 10^{3})\) | 8.263 ± 0.176 | 10.234 ± 0.277 | 11.309 ± 0.245 | 12.829 ± 0.380 |
| \(12+\log(O/H)\) | 8.02 ± 0.06 | 8.11 ± 0.08 | 8.24 ± 0.05 | 8.29 ± 0.08 |
| \(\text{N}/\text{H} (\times 10^{3})\) | ... | ... | ... | ... |
| \(\text{Ne}^+ / \text{H}^+ (\times 10^{3})\) | 1.019 ± 0.012 | 1.010 ± 0.027 | 0.342 ± 0.023 | 0.645 ± 0.041 |
| \(12+\log(N/H)\) | 5.805 ± 0.152 | 5.839 ± 0.170 | 2.872 ± 0.065 | 3.504 ± 0.141 |
| \(\log(O/H)\) | 6.80 ± 0.05 | 6.77 ± 0.09 | 6.99 ± 0.03 | 7.35 ± 0.03 |
| \(\text{Ne}^+ / \text{H}^+ (\times 10^{3})\) | -1.22 ± 0.26 | -1.33 ± 0.47 | -1.25 ± 0.16 | -0.94 ± 0.17 |
| \(12+\log(N/H)\) | 1.719 ± 0.058 | 2.063 ± 0.068 | 2.748 ± 0.107 | 3.158 ± 0.154 |
| \(\log(N/O)\) | 1.252 ± 0.035 | 1.245 ± 0.044 | 1.534 ± 0.041 | 1.526 ± 0.057 |
| \(\text{Ar}^+ / \text{H}^+ (\times 10^{3})\) | 7.33 ± 0.14 | 7.41 ± 0.15 | 7.62 ± 0.16 | 7.68 ± 0.20 |
| \(12+\log(O/H)\) | -0.68 ± 0.09 | -0.70 ± 0.10 | -0.61 ± 0.10 | -0.61 ± 0.13 |
| \(\log(N/O)\) | 0.032 ± 0.004 | 0.039 ± 0.010 | ... | 0.061 ± 0.004 |
| \(\text{ICF Ne}\) | 2.069 ± 0.207 | 2.089 ± 0.209 | ... | 1.621 ± 0.162 |
| \(\log(N/O)\) | 5.82 ± 0.42 | 5.91 ± 0.73 | ... | 5.99 ± 0.32 |
| \(\log(Ar/O)\) | -2.19 ± 0.38 | -2.20 ± 0.66 | ... | -2.30 ± 0.28 |

### Table 4

| Method            | J092600  | J004054  | J020356  | J005527  |
|-------------------|----------|----------|----------|----------|
| Direct (this work) | 8.02 ± 0.06 | 8.11 ± 0.08 | 8.24 ± 0.05 | 8.29 ± 0.08 |

| Strong-line estimates—this work |
|----------------------------------|
| PP04 N2                          | 8.127    | 8.107    | 8.251    | 8.375    |
| PP04 O3N2                        | 8.056    | 8.026    | 8.215    | 8.293    |
| CALIFA N2                        | 8.105    | 8.081    | 8.251    | 8.365    |
| CALIFA O3N2                      | 8.082    | 8.062    | 8.189    | 8.240    |

| Overzier estimates               |
|----------------------------------|
| PP04 O3N2                        | 8.09     | 8.03     | 8.21     | 8.28     |

Notes. The scatter in these empirical calibrations is \(\sim 0.3\) in \(12+\log(O/H)\); see Pettini & Pagel (2004) and Marino et al. (2013) for details.
of SDSS galaxies versus direct method abundance of LBAs). Our direct method measurements of the LBAs are shown as cyan dots. Due to the difficulty of measuring the auroral lines, we do not have direct method abundances for a statistically significant number of individual SDSS galaxies. We do, however, have the best-fit relation to the direct method oxygen abundance of stacked SDSS spectra from Andrews & Martini (2013), which we have included in Figure 6 as the thick black line.

The SDSS galaxies (gray contours) have masses from the MPA-JHU catalog (see Kauffmann et al. 2003b; Salim et al. 2007) and have had the oxygen abundances estimated using the N2 calibration from PP04. The LBA N2 estimates of oxygen abundance are shown as orange and green dots for the SDSS and MODS1 data, respectively; the offset from the locus of individual SDSS contours is clear and consistent with Overzier et al. (2010). While the relation from Andrews & Martini (2013) systematically deviates from the N2 oxygen abundance estimates (as expected), our direct method oxygen abundances of the LBAs still fall well below those of the stacked SDSS spectra. Thus, it appears that systematic effects in the strong-line calibrations cannot explain the offset of the LBAs from the MZ relation; these LBAs have low oxygen abundance given their mass.

5. DISCUSSION

5.1. Excitation Conditions of LBAs

Empirical abundance calibrations are typically based on samples of H ii regions with well-determined electron temperatures and thus directly measured abundances. However, the direct method is subject to a number of observational biases. For instance, metal-poor objects generally have higher electron temperatures, brighter auroral lines, and more easily determined abundances. This results in a preferential selection of low metallicity objects in empirical calibrations. Furthermore, most large-scale surveys of emission line galaxies, like the SDSS, are composed of predominantly low-excitation galaxies relative to the H ii regions on which the empirical calibrations are based (see Figure 3). Moustakas et al. (2010) cautions against haphazardly extrapolating empirical relations to lower excitation regimes occupied by the majority of galaxies in large surveys, as doing so could result in erroneous abundance determinations.

Looking at Figure 4, the emission line flux ratios of all four of our LBAs are remarkably similar to those of the “warm” H ii ratios from Pilyugin et al. (2010). Additionally, even though J005527 displays fairly strong [N ii] emission compared to the other LBAs in our sample, it remains in an excitation regime fairly typical of local H ii regions. This supports the idea that locally determined empirical calibrations ought to return reasonable abundance estimates for LBAs. This is a crucial step in justifying the application of locally calibrated empirical relations to LBAs and LBGs. However, caution must still be exercised when extrapolating these relations to high redshifts, as recent work has suggested that the LBG population as a whole evolves rapidly with redshift (Stanway & Davies 2014).

It is readily apparent that LBAs are undergoing an episode of significant star formation. Within a few million years of the initial burst, large numbers of Wolf–Rayet stars, supernova remnants, and other extremely hot objects could conspire to produce an abnormally hard ionization spectrum. If we suppose that the gas surrounding these hot objects was subject to a harder ionization spectrum than what is observed in local H ii regions, then we would expect to see relatively enhanced ionic
emission features. High energy photons have a smaller cross section for interaction. As a result, these high energy photons have a longer mean free path, resulting in larger partially ionized regions. In general, this results in enhanced ionic emission. In the case of ionized nitrogen, an anomalously hard ionization spectrum would produce enhanced $[\text{N~ii}]$ emission and result in systematically high abundance estimates when using a locally calibrated empirical relation.

Berg et al. (2011) showed that enhanced nitrogen abundance (relative to oxygen) could also bias strong-line estimates toward high oxygen abundance. However, the excitation conditions of our LBAs are quite different from what is expected in the evolved Wolf–Rayet galaxies from Berg et al. (2011). Furthermore, our LBAs do not show abnormally high $[\text{N~ii}]/[\text{O~ii}]$ ratios. If the high N2 method estimates observed in some of our targets were the result of an abnormally hard ionization spectrum, we would not expect the O3N2 method to yield a high abundance estimate, as such a radiation field would have a similar effect on both $\text{N}^+$ and $\text{O}^{++}$ emission.

5.2. LBAs and the Fundamental Metallicity Relation

LBAs have masses typical of entire galaxies and thus it is interesting to note that their excitation conditions fall in a region that is sparsely populated by the SDSS star forming galaxies, but well occupied by the $\text{H~i}$ regions from Pilyugin et al. (2012). It seems that the LBAs more closely resemble giant $\text{H~i}$ regions in terms of photoionization conditions than typical SDSS galaxies. What is the primary physical process causing the LBAs to be so significantly offset from SDSS galaxies?

The defining characteristic of LBAs is their compact UV emission arising from recent star formation, and indeed, the typical SFR for an LBA is an order of magnitude higher than a typical SDSS galaxy (Overzier et al. 2009). Such high rates of star formation imply a recent replenishment of star forming material in the LBA systems. This influx of gas could be due to a tidal interaction (e.g., Peeples et al. 2009), or perhaps a recent merger. Generally, these events will result in dilution of the interstellar gas and a corresponding reduction in the observed metallicity.

Peeples et al. (2009) compute the expected dilution which might result from the funneling of gas from large galactocentric radius into the center of a galaxy. They find that for a galaxy with a reasonable metallicity gradient and gas surface density profile, gas flowing inward from within 20 kpc would result in a metallicity dilution of $\Delta(\text{O/H}) = -0.5$ dex, which is remarkably close to the MZ relation offsets observed for their morphologically disturbed galaxies. The LBAs in our sample also tend to be offset from the SDSS MZ relation of Andrews & Martini (2013) by a comparable amount, suggesting that LBAs may have recently experienced an inflow of unenriched gas. This is consistent with the disturbed morphology of LBAs seen in the $HST$ images from Overzier et al. (2009, 2010) and the dispersion-dominated kinematics (e.g., $\sigma/v > 1$) presented in Gonçalves et al. (2010).

A global inflow of star forming material could also result in an intense burst of star formation (Rupke et al. 2008; Kewley et al. 2010). It is often assumed that the timescale for the enrichment of the interstellar medium (ISM) is short compared to the overall galaxy evolution timescale. However, the photoionization conditions of LBAs indicate that we are observing the actual burst of star formation take place. The LBAs have not had time to convert the infalling gas into stars and then have those stars chemically enrich their ISM. If the burst of star formation in LBAs is indeed being powered by relatively low metallicity gas, then we would expect that their residuals from the MZ relation would correlate with the SFR.

The fundamental metallicity relation (FMR; Mannucci et al. 2010; Andrews & Martini 2013) parameterizes the correlation of residuals from the MZ relation and SFR by introducing the parameter $\mu_\alpha$ such that $\mu_\alpha = \log M_* - \alpha \log(\text{SFR})$. The sample of galaxies compiled by Mannucci et al. (2010) consists of >140,000 SDSS galaxies at $z \sim 0$. 182 objects from 0.5 $< z < 2.5$, the 91 galaxies from Erb et al. (2006), and an additional 16 galaxies from 3 $< z < 4$. Typically, $\alpha$ is chosen such that it minimizes the scatter in the resulting FMR. Mannucci et al. (2010) find $\alpha = 0.32$ for their sample of galaxies, and no evolution of the FMR up to $z = 2.5$.

The exact value of $\alpha$ is quite sensitive to the abundance diagnostic used. Yates et al. (2012) found $\alpha = 0.19$ when using the oxygen abundances from Tremonti et al. (2004) and Andrews & Martini (2013) found $\alpha = 0.66$ when using direct method abundances, both of which are significantly different from the $\alpha = 0.32$ presented in Mannucci et al. (2010). Additionally, the determination of $\alpha$ merely minimizes the scatter for a given abundance diagnostic; two strong-line calibrations will generally not share the same FMR.

Determining where an object sits on the FMR requires knowledge of the SFR in addition to the mass and metallicity of the object. Overzier et al. (2009) adopts SFR calibrations from Calzetti et al. (2009) and computes various SFRs using $H\alpha$, $H\alpha + 24\mu m$, and FUV luminosities. The $H\alpha$ flux is associated with only the most recent star formation activity, whereas the FUV calibration is sensitive to the integrated star formation activity over the previous 1 Gyr. The appearance of the LBAs is dominated by the current burst of star formation activity, so we adopt the $H\alpha + 24\mu m$ SFRs (Kennicutt et al. 2007; Calzetti et al. 2007).

The $H\alpha + 24\mu m$ calibration is not without its own systematic effects. For example, an AGN could preferentially heat dust and result in $24\mu m$ flux above that which would arise from star formation alone. However, none of the Overzier et al. (2009) LBAs appear to host a Type 1 (unobscured) AGN. While the presence of a Type 2 (obscured) AGN is not ruled out, it seems unlikely given where these LBAs lie on the diagnostic diagrams (Overzier et al. 2009). If an AGN were present, it is likely to only have a very small effect.

Figure 7 shows the oxygen abundances of the SDSS star forming galaxies and the LBAs as a function of $\mu_\alpha$, where we have adopted the values of $\alpha = 0.30$ and $\alpha = 0.66$ corresponding to the N2 index and direct method, respectively, from Andrews & Martini (2013). The cyan dots show our LBAs with direct method oxygen abundances: the thick black line shows the linear fit to the FMR for stacked SDSS spectra from Andrews & Martini (2013). The N2 estimates of oxygen abundance for our LBAs are shown as orange and green dots for the SDSS and MODIS1 data, respectively. The gray contours are the star forming SDSS galaxies from the MPA-JHU catalog (see Kauffmann et al. 2003b and Salim et al. 2007 for mass determinations and Brinchmann et al. 2004 for SFR determinations). The oxygen abundances of the SDSS galaxies are estimated from the PP04 N2 calibration. We see that plotting oxygen abundance as a function of both mass and SFR does indeed reduce the scatter between the LBAs and SDSS data for a given abundance estimation method (direct or empirical).

It is important to keep in mind that a comparison of where the direct abundance measurements fall on the FMR relative to the
contoured SDSS data is meaningless, since we do not expect the
different abundance diagnostics to produce consistent results.
However, the fact that incorporating SFR drastically reduces
the scatter for a given abundance diagnostic suggests that the
high SFR, low oxygen abundance, and disturbed morphology of
these LBAs could be explained by a recent inflow of relatively unenriched gas and is consistent with the existence of an FMR
that the LBAs appear to follow.

6. SUMMARY

It is believed that LBAs ($z \sim 0.2$) are true analogs of
LBGs ($z \gtrsim 3$), and thus are laboratories for studying one of
the dominant modes of star formation in the early universe in
exquisite detail. Before applying locally calibrated empirical
relations to these LBAs, it is important to investigate whether
or not the locally calibrated empirical relations based on single,
bright H\textsc{ii} regions in normal galaxies still hold for the physical
conditions present in LBAs.

The empirically derived oxygen abundances of LBAs show
them to be metal deficient for their mass, falling $\gtrsim 0.2$ dex
below the MZ relation defined by local star forming galaxies.
We have presented direct abundance measurements of four
LBAs using MODS1 on the LBT to detect [O\textsc{iii}] $\lambda 4363$
in each target, allowing for a direct measurement of the electron
temperature and thus a robust determination of the gas-phase
oxygen abundance. We have demonstrated the following.

1. LBAs display excitation conditions that are unusual for
SDSS galaxies, but are quite typical of H\textsc{ii} regions from
Pilyugin et al. (2012).

2. The N2 empirical calibration is generally valid for the LBAs
presented here. Objects with particularly hard ionizing
spectra may have biased strong-line abundance estimates,
but the effect is likely to be smaller than the scatter in the
empirical calibrations.

3. LBAs are offset from the MZ relation of local star forming
galaxies in the sense that they have lower oxygen abund-
dances for a given mass. However, when their abnormally
high SFRs are taken into account, we find that they do not
appear to deviate significantly from the FMR. This, cou-
pled with their disturbed morphologies, is consistent with
an interaction-driven gas inflow paradigm.

We can improve our understanding of LBAs in a statistical
sense by increasing the size of the sample studied. Here, we
have presented observations of only 4 of the 31 LBAs in the
Overzier et al. (2009) sample. With instruments like MODS1,
precise spectroscopic observations of LBAs are quite feasible
and can be performed with a modest amount of telescope time.

An increased number of LBAs with robustly determined
abundances would allow us to place tighter constraints on the
systematic effects between locally calibrated strong-line
abundance estimates and direct method abundances. This will
aid greatly in our understanding of how LBAs differ from
local galaxies, and improve our understanding of the processes
governing the observed trends in mass, metallicity, and SFR.

Finally, it has been suggested that both the MZ relation
and FMR are a consequence of the relation between gas-phase
oxygen abundance and stellar-to-gas mass ratio (the Universal
Metallicity Relation; Zahid et al. 2014). They argue that once
the ISM of a galaxy has been enriched to a point such that
the amount of oxygen being locked up in low mass stars is
comparable to the oxygen produced by massive stars, the
oxygen abundance asymptotically approaches a value which is
independent of redshift. If the LBAs have indeed experienced a
significant inflow of gas mass relative to their stellar mass, they
could potentially serve as key testing grounds for the Universal
Metallicity Relation.

We thank the referee for a constructive report. This paper uses
data taken with the MODS spectrographs built with funding
from NSF grant AST-9987045 and the NSF Telescope System
Instrumentation Program (TSIP), with additional funds from the
Ohio Board of Regents and the Ohio State University Office of
Research. KVC and MODS pipeline software development was
supported by NSF grant AST-1108693.

We appreciate the MPA-JHU group for making their cata-
alog publicly available, and Leonid Pilyugin, Eva Grebel, and
Lars Mattsson for making their catalog of H\textsc{ii} regions avail-
able. We also thank John Moustakas for making his routines
publicly available. The STARLIGHT project is supported by
the Brazilian agencies CNPq, CAPES, and FAPESP and by the
France-Brazil CAPES/Cofecub program.

Funding for the SDSS and SDSS-II has been provided by
the Alfred P. Sloan Foundation, the Participating Institutions,
the National Science Foundation, the U.S. Department of
Energy, the National Aeronautics and Space Administration,
the Japanese Monbukagakusho, the Max Planck Society, and
the Higher Education Funding Council for England. The SDSS
Web site is http://www.sdss.org/.
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