DEEP SPECTROSCOPY OF ULTRA-STRONG EMISSION-LINE GALAXIES

ESTHER M. HU1, LENNOX L. COWIE1, YUKO KAKAZU2, and AMY J. BARGER1,3,4

1 Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
2 Institut d’Astrophysique, Paris, 98 bis Boulevard Arago, F-75014 Paris
3 Department of Astronomy, University of Wisconsin-Madison, 473 North Charter Street, Madison, WI 53706, USA
4 Department of Physics and Astronomy, University of Hawaii, 2505 Correa Road, Honolulu, HI 96822, USA

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ABSTRACT

Ultra-strong emission-line galaxies (USELs) with extremely high equivalent widths (EW(Hβ) > 30 Å) can be used to pick out galaxies of extremely low metallicity in the z = 0–1 redshift range. Large numbers of these objects are easily detected in deep narrow band searches. Since most have detectable [O III] λ4363, their metallicities can be determined using the direct method. These large samples hold out the possibility for determining whether there is a metallicity floor for the galaxy population. In this, the second of our papers on the topic, we describe the results of an extensive spectroscopic follow-up of the Kakazu et al. catalog of 542 USELs carried out with the DEIMOS spectrograph on Keck. We have obtained high S/N spectra of 348 galaxies. The two lowest metallicity galaxies in our sample have 12 + log(O/H) = 6.97 ± 0.17 and 7.25 ± 0.03 — values comparable to the lowest metallicity galaxies found to date. We determine an empirical relation between metallicity and the R23 parameter for our sample, and we compare this to the relationship for low-redshift galaxies. The determined metallicity–luminosity relation for this sample is compared with that of magnitude selected samples in the same redshift range. The emission-line-selected galaxies show a metal–luminosity relation where the metallicity decreases with luminosity, and they appear to define the lower bound of the galaxy metallicity distribution at a given continuum luminosity. We also compute the H0 luminosity function of the USELs as a function of redshift and use this to compute an upper bound on the Lyα emitter luminosity function over the z = 0–1 redshift range.

Key words: cosmology; observations – galaxies: abundances – galaxies: distances and redshifts – galaxies: evolution – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

Developing a large sample of low metallicity galaxies is of considerable interest for the clues it can provide to the early stages of galaxy formation and chemical enrichment, such as whether forming galaxies have a baseline metallicity that reflects the early chemical enrichment of the intergalactic medium. The most metal-poor systems currently known are the low-redshift blue compact line-emission galaxies such as I Zw 18 and SBS 0335-052W with measured 12 + log(O/H) of ~7.1–7.2 (Sargent & Searle 1970; Thuan & Izotov 2005; Izotov et al. 2005). However, despite enormous efforts, only a few dozen XMPGs (objects with 12 + log(O/H) < 7.65 or Z < Z⊙/12; Kniazev et al. 2003; Izotov et al. 2006b; Brown et al. 2008) are known (e.g., Oey 2006; Izotov 2006a). There are too few of these for detailed studies of the metallicity distribution function.

In the first paper of the present series we showed that large samples of low-metallicity objects can be found by searching for ultra-strong emission-line galaxies (USELs) using very deep narrowband surveys (Kakazu et al. 2007). The narrowband method has many advantages; it is an efficient way to develop very large samples of objects, and, since it probes to much deeper line-flux limits than objective prism or continuum surveys, we can study populations out to near redshift z ~ 1 where the cosmic star formation history peaks.

In the present work, we report on the detailed spectroscopic follow-up of the catalog of 542 USEL galaxies given in Kakazu et al. (2007). The Kakazu et al. sample was chosen from a set of narrowband images obtained with the SuprimeCam mosaic CCD camera on the Subaru 8.2 m telescope using two ~120 Å (FWHM) filters centered at nominal wavelengths of 8150 Å and 9140 Å in regions of low sky background between the OH bands. The total covered area is 0.5 deg². The catalog consists of all objects with narrowband magnitudes less than 25 and a narrowband excess of 0.8 magnitudes for the 8150 Å filter and of 1.0 magnitudes for the 9140 Å filter compared with their respective reference continuum bands. The sample should contain all galaxies in the fields with observed-frame EWs significantly greater than 120 Å and 180 Å in the two filters, and with line fluxes above ~1.5 × 10⁻¹⁷ erg cm⁻² s⁻¹.

We have obtained spectroscopic redshifts for USEL galaxies using the Deep Extragalactic Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on the 10 m Keck II telescope. We give the general properties of our observations and the sample redshift distribution in Section 2. In Section 3, we discuss the flux calibration and EW measurements. Here, we also describe the resulting measured line ratios. In Section 4, we analyze the metallicities and describe an empirical relation for the metallicity as a function of the R23 parameter, which we compare with low-redshift determinations of the relation. In Section 5, we give the distribution of metallicities as a function of the properties of the galaxies. Here we also compare the results with those in magnitude-selected samples at the same redshift. In Section 6, we show that our results can be used to place upper limits on the Lyman alpha emitter (LAE)
luminosity function in the $z = 0–1$ redshift range. We then compare this with the local *Galaxy Evolution Explorer (GALEX)* measurement of Deharveng et al. (2008) and with higher redshift LAE functions. We present a final summary discussion in Section 7. We use a standard $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ cosmology throughout the paper.

2. SPECTROSCOPIC OBSERVATIONS

Kakazu et al. (2007) reported spectroscopic observations for 161 USELs in their sample. These spectra were obtained using DEIMOS on Keck II in a series of runs between 2003 and 2006. Over the 2007 and 2008 period we have roughly doubled this spectroscopic sample and have also significantly deepened the spectra of many of the objects that had previously been observed.

In order to provide the widest possible wavelength coverage the observations were primarily made with the ZD600 $\ell$/mm grating. We used 1″ wide slitlets, which in this configuration give a resolution of 4.5 Å. This is sufficient to distinguish the $\text{[O} \text{II}]\lambda 3727$ doublet structure, which allows us to easily identify $\text{[O} \text{II}]\lambda 3727$ emitters where often the $\text{[O} \text{II}]\lambda 5007$ emission line is the only emission feature. The spectra cover a wavelength range of approximately 5000 Å with an average central wavelength of 7200 Å, though the exact wavelength range for each spectrum depends on the slit position with respect to the center of the mask along the dispersion direction. The observations were not generally taken at the parallactic angle, since this was determined by the mask orientation, so considerable care must be taken in measuring line fluxes, as we discuss below. Each $\sim$1 hr exposure was broken into three subsets, with the objects stepped along the slit by 1′.5 in each direction. Some USELs were observed multiple times, resulting in total exposure times of up to 10 hours. The two-dimensional spectra were reduced following the procedure described in Cowie et al. (1996), and the final one-dimensional spectra were extracted using a profile weighting based on the strongest emission line in the spectrum.

Our primary goal was to obtain a nearly complete set of spectra for the 200 objects in the catalog with narrowband magnitudes brighter than 24, since, for these brighter objects, we can obtain high-quality spectra suitable for detailed analysis. However, we also observed a large number of the galaxies with magnitudes in the range 24–25. We have now observed 171 of the galaxies brighter than 24. Nearly all of the bright emission-line candidates which were observed were identified (164 of the 171 objects). However, three of the objects in the sample are stars, where the absorption line structure mimics emission in the band. The redshift distribution of the sample and the fraction of objects which have so far been identified is shown as a function of the narrowband magnitude in Figure 1.

The narrowband emission-line selection produces a mixture of objects corresponding to H$\alpha$, $\text{[O} \text{III}]\lambda 5007$, and $\text{[O} \text{II}]\lambda 3727$, and, at the faintest magnitudes (>24), high-redshift ($z > 5$) LAEs. There are almost no high-redshift LAEs at magnitudes brighter than 24. The distribution of the redshifts for objects other than the LAEs is shown in Figure 2. The largest fraction of objects corresponds to cases where the $\text{[O} \text{II}]\lambda 5007$ line lies in the narrowband filters. For the present work only the objects selected in $\text{[O} \text{III}]$ or H$\alpha$ are of interest, since we cannot determine the metallicities or the Balmer line strengths of the $\text{[O} \text{II}]$ selected samples without further near-infrared spectroscopy. Our final sample of galaxies, therefore, consists of 214 galaxies with redshifts between zero and one, of which 189 are chosen with $\text{[O} \text{III}]$ and 25 with H$\alpha$. 125 of these have narrow band magnitudes brighter than AB = 24.

![Figure 1. Redshift vs. narrowband magnitude in the selection filter. The lower histogram (blue line) shows the fraction of objects in the magnitude range that have either not been observed or not been identified.](image1)

![Figure 2. Redshift distribution of the spectroscopically observed sample. The peaks correspond to the positions at which the strong emission lines cross the two filters. Thus, there are galaxies at $z = 0.6$ and $z = 0.8$ corresponding to the $\text{[O} \text{II}]\lambda 5007$ line lying in the 8150 Å and 9140 Å filters, respectively.](image2)

3. FLUX CALIBRATIONS

Generally our spectra were not obtained at the parallactic angle, since this is determined by the DEIMOS mask orientation required to maximize object placement in slits over the entire mask field. Therefore, flux calibration using standard stars is problematic because of atmospheric refraction effects, and special care must be taken for the flux calibration. A much more extensive discussion can be found in Kakazu et al. (2007). Here we focus only on measurements of the relative line fluxes from the spectra, which we require for the metallicity measurements. We also note that in the case of very low metallicity galaxies with 6 hr of spectroscopic integration, the analysis of individual sets of exposures taken at different parallactic angles yield consistent results.

The spectra were initially relatively calibrated using the measured instrument response. Portions of the spectra of the two lowest metallicity galaxies in the sample are shown in Figures 3 and 4. Relative line fluxes can be robustly measured from the spectra without flux calibration as long as we restrict the line measurements to short wavelength ranges where the DEIMOS response is essentially constant. For example, one can assume that the responses of neighboring lines (e.g. $\text{[O} \text{II}]\lambda 4959$ and $\text{[O} \text{III}]\lambda 5007$) are the same and therefore one can measure the flux ratio without calibration. The present problem is considerably simplified by the presence of the H$\beta$ line near $\text{[O} \text{III}]\lambda 4959$ and $\text{[O} \text{III}]\lambda 5007$ (Figure 3(b) and Figure 4(a)) and the H$\gamma$ line near $\text{[O} \text{III}]\lambda 4363$ (Figure 3(c) and Figure 4(b)).
these lines, and also for the [N\textsc{ii}]λ6584 line (Figure 3(a)), we can therefore use the Balmer line ratio to provide extinction-corrected flux ratios for the metal lines. To calibrate these lines, we used neighboring Balmer lines with the assumption of case B recombination conditions. We cannot so easily do this near [O\textsc{ii}]λ3727 where the Balmer lines are weak and in some cases contaminated (Figure 3(d) and Figure 4(c)). Fortunately, [O\textsc{ii}]λ3727 is generally extremely weak in the spectra, and the uncertainty in the calibration has little effect on the metal determination.

For each spectrum we fitted a standard set of lines. For the stronger lines we used a full Gaussian fit together with a linear fit to the continuum baseline. For weaker lines we held the full width constant using the value measured in the stronger lines and set the central wavelength to the nominal redshifted value. The [O\textsc{ii}]λ3727 line was fitted with two Gaussians with the appropriate wavelength separation. We also measured the noise as a function of wavelength by fitting to random positions in the spectrum and computing the dispersion in the results.

The [N\textsc{ii}]λ6584/\textit{Hα}, [O\textsc{iii}]λ5007/\textit{Hβ}, and [O\textsc{ii}]λ3727/\textit{[O\textsc{iii}]λ5007} ratios are shown as a function of the narrowband magnitude in the selection filter in Figure 5. The population is relatively uniform in its line properties. Nearly all of the galaxies have weak [N\textsc{ii}]/\textit{Hα} (a median ratio of 0.02), weak [O\textsc{ii}]λ3727 relative to [O\textsc{iii}]λ5007 (a median ratio of 0.22), and strong [O\textsc{iii}]λ5007/\textit{Hβ} (a median ratio of 5.2). There seems to be little difference between the \textit{Hα} selected population (shown with purple diamonds in Figure 5(b)) and the [O\textsc{iii}] selected population (shown with black squares). The very weak [N\textsc{ii}] lines, in combination with the very strong [O\textsc{iii}] lines, show that these galaxies are not excited by active galactic nuclei and that the galaxies have very high ionization parameters and low metallicity, as we shall quantify in the following section.

4. GALAXY METALLICITIES

The spectra are of variable quality, reflecting the range of magnitudes and exposure times. In order to measure the metallicities, we need very high signal to noise observations. It is also important that the Balmer lines are well detected, since our flux calibrations rely on the neighboring Balmer lines. We therefore restrict to emitters whose \textit{Hγ} line fluxes are detected above the 10σ level. Among the 25 \textit{Hγ} selected emitters in our total spectroscopic sample, there are eight sources with spectra of sufficient quality for the metallicity analysis, and among the 189 sources selected using [O\textsc{iii}]λ5007, there are 23 such sources, giving a total sample of 31 sources for the metallicity analysis.

As we illustrate in Figure 6, nearly all of these sources are detected in the [O\textsc{iii}]λ4363 auroral line. Of the 31 sources, 23 are detected above the 3σ level and nine above the 5σ level. The median value of the ratio of the [O\textsc{iii}]λ4363 auroral line to the [O\textsc{iii}]λ5007 line is 0.018 for the 31 objects, and there is no indication that the values seen in spectra selected with the \textit{Hα} line, which are shown by the purple diamonds in Figure 6, are any different from those selected with [O\textsc{iii}]λ5007, which are shown by the black squares.

The presence of [O\textsc{iii}]λ4363 immediately suggests that these are metal-deficient systems, but, more importantly, it allows us to determine the electron temperature from the ratio of the [O\textsc{iii}]λ4363 line to [O\textsc{iii}]λ5007, λ4959. This procedure is often referred to as the “direct” method or \textit{Te} method (e.g., Seaton 1975; Pagel et al. 1992; Pilyugin & Thuan 2005; Izotov et al. 2006c). To derive \textit{T}_e[O\textsc{iii}] and the oxygen abundances, we used the Izotov et al. (2006c) formulae, which were developed with the latest atomic data and photoionization models. Using the Pagel et al. (1992) calibrations with the \textit{T}_e[O\textsc{ii}]-\textit{T}_e[O\textsc{iii}] calibration.

Figure 3. Portions of the spectrum of the lowest metallicity galaxy in the sample showing detected emission lines. This is object 29 in the Kakazu et al. (2007) catalog of objects selected in the NB912 filter. It lies at a redshift of 0.3931. The emission-line features are labeled and marked with the solid lines. In panels (a) and (b) we have increased the scale of the vertical axis to show the extremely strong \textit{Hβ}, [O\textsc{iii}], and \textit{Hγ} lines. The [O\textsc{ii}] line is only marginally detected in this spectrum and the two [N\textsc{ii}] lines in panel (a) are not seen.

(A color version of this figure is available in the online journal.)
The spectra of the three lowest redshift Hα emission-line selected galaxies do not cover the [O II]λ3727 line, leaving us with a final sample of 28 galaxies for our analysis. Seven of these objects satisfy the definition of XMPGs (12 + log(O/H) < 7.65; Kunth & Östlin 2000). The lowest metallicity galaxies in the sample are KHC912-29 with $12 + \log(O/H) = 6.97 \pm 0.17$ and KHC912-269 with $12 + \log(O/H) = 7.25 \pm 0.03$. The spectra of these two galaxies are shown in Figures 3 and 4. Their metallicities are comparable to the currently known most metal-poor galaxies (I Zw 18 and SBS0335−052W; $12 + \log(O/H) \sim 7.1$–7.2).

Figure 4. Portions of the spectrum of the second lowest metallicity galaxy in the sample showing detected emission lines. This is object 269 in the Kakazu et al. (2007) catalog of objects selected in the NB912 filter. It lies at a redshift of 0.8175. In (a) we have increased the scale of the vertical axis to show the extremely strong [O III] and Hβ lines. The emission-line features are labeled and marked with the solid lines.

Figure 5. Flux ratios of [N II]6584/Hα (panel a), [O III]5007/Hβ (b), and [O II]3727/[O III]5007 (c) computed from the spectra. The line ratios are only plotted for spectra where the signal to noise of the Hβ line is greater than 5. In a small number of cases the line fluxes of the weak [N II]6584 and [O II]3727 lines in the spectra scatter to negative values. The data are plotted against the narrowband magnitude, and the error bars are 1σ. Hα selected spectra are shown with purple diamonds in panel (b). The red solid lines show the median values in the sample.

Figure 6. Ratio of the [O III]λ4363/[O III]λ5007 fluxes. The data are plotted against the narrowband magnitude and the error bars are 1σ. Only spectra where the signal to noise of the Hγ line is above 10 are included. The values for the Hα selected spectra are shown with purple diamonds and for the [O III]λ5007 selected spectra with black squares. The red solid line shows the median value in the combined sample of 31 galaxies. The black solid line shows the zero ratio. Only three of the sources do not have [O III]λ4363 detected above the 1σ level.
Figure 7. [O iii]λ4363+[O ii]λ5007 vs. [O ii]λ3727/[O iii]λ5007 for the 28 galaxies in the metallicity sample. 1σ error bars are shown for both ratios.

Figure 8. (a) The ionization parameter $q$ vs. [O ii]λ3727/[O iii]λ5007 for the metallicity sample. (b) 12 + log(O/H) vs. [O ii]λ3727/[O iii]λ5007 for the metallicity sample. Only the 28 objects with [O ii]λ4363 detected above the 1σ level are shown, and 1σ error bars are given in both cases.

5. DISCUSSION

5.1. Metallicity and the Ionization Parameter

Figure 7 shows the electron temperature sensitive line ratio, [O iii]λ4363/[O ii]λ5007 versus [O ii]λ3727/[O iii]λ5007. If we have an estimate of the metallicity, as in the present case, we can use the [O ii]λ3727/[O iii]λ5007 ratio to estimate the ionization parameter $q$, defined as the number of hydrogen ionizing photons passing through a unit area per second per unit hydrogen number density. We can see from Figure 7 that there is a strong inverse correlation of [O iii]λ4363 and [O ii]λ3727. Systems with weak [O ii]λ3727 generally have strong [O iii]λ4363.

We have computed the ionization parameters ($q$) for the sample using the parameterized forms of the dependence of [O ii]λ3727/[O iii]λ5007 on $q$ and 12 + log(O/H) from Kóbulyinický & Kewley (2004). In Figure 8(a), we show the dependence of the $q$ parameter on [O ii]λ3727/[O iii]λ5007 and in Figure 8(b) we show the dependence of 12 + log(O/H) on [O ii]λ3727/[O iii]λ5007.

There is a clear dependence between the metallicity and [O ii]λ3727/[O iii]λ5007. Objects with low metallicity have low [O ii]λ3727/[O iii]λ5007, and all of the XMPGs have values of this ratio below 0.12. Conversely, seven of the 13 galaxies satisfying this condition are XMPGs. This is potentially a very valuable tool for optimizing the search for the lowest metallicity galaxies at these redshifts, since we can focus our spectroscopic follow-up on galaxies with weak [O ii]λ3727 lines.

The ionization parameter also increases with decreasing [O ii]λ3727/[O iii]λ5007 (Figure 8(a)), though the ionization parameters lie in a relatively narrow range for log $q$ $\sim$ 7.8–8.5. However, there is considerable variation in the theoretical models (e.g., McGaugh et al. 1991; Pilyugin 2000), and the exact shape and normalization are somewhat uncertain. The range of ionization parameters is similar to that found in magnitude-limited samples of galaxies at the same redshift (Cowie & Barger 2008).

In Figure 9, we show the ionization parameter $q$ as a function of the metallicity. It is clear that the lower metallicity galaxies have higher ionization parameters. However, we again note the uncertainties in the theoretical modeling.

5.2. Metallicity and the R23 Parameter

The R23 ratio $\beta(\text{O ii}) = f([\text{O ii}]\lambda4363) + f([\text{O ii}]\lambda5007) + f([\text{O ii}]\lambda3727)/f(\text{H β})$ of Pagel et al. (1979) is one of the most frequently used metallicity diagnostics. As is well known, it is unfortunately multivalued with both a low-metallicity and a high-metallicity branch. Moreover, while for the present galaxies we may be reasonably secure that we are on the low metallicity branch (12 + log(O/H) $\lesssim$ 8.4), R23 is only weakly dependent on metallicity on this branch and has a strong ionization dependence (e.g., McGaugh et al. 1991).

Nevertheless, recent analyses of substantial samples of local galaxies with well determined abundances from the direct method have shown a good empirical correlation of 12 + log(O/H) with R23 in the low-metallicity range (Nagao et al. 2006; Yin et al. 2007). Izotov & Thuan (2007) favor the empirical fits of Yin et al. (2007; red dotted curve) and Nagao et al. (2006; green dashed curve). It is clear that the present data have lower 12 + log(O/H) determinations at the same R23. This would be expected if the ionization parameters are higher in the present sample. A factor of 5 increase in the $q$ parameter could easily produce the offsets seen. Empirically, we find a relation of the form 12 + log(O/H) = 6.486 + 1.401 log(R23) based on comparisons with their local sample. However, in comparing these with the present sample, we must be concerned about differences in the galaxy properties, and, in particular, about whether evolution in the distribution of the ionization parameter between the local and distant samples might change the relation.

In Figure 10, we show the dependence of the present measurements of 12+log(O/H) on the R23 parameter. We also show the local points from Izotov & Thuan (2007) and the empirical fits of Yin et al. (2007; red dotted curve) and Nagao et al. (2006; green dashed curve). It is clear that the present data have lower 12 + log(O/H) determinations at the same R23. This would be expected if the ionization parameters are higher in the present sample. A factor of 5 increase in the $q$ parameter could easily produce the offsets seen. Empirically, we find a relation of the form 12 + log(O/H) = 6.45 + 0.15 R23, which is shown as the black line in Figure 10, provides a reasonable description of the data.

5.3. Metallicity versus Hβ Equivalent Width

As is well known, the Hβ equivalent width can give a rough estimate of the age of the star formation in a galaxy. For a
Salpeter initial mass function and a constant star formation rate, EW(Hβ) would drop smoothly to a value of 30 Å at about $10^9$ yr (Leitherer et al. 1999), while an instantaneous starburst would drop below this value after about $10^7$ yr. It is therefore of considerable interest to determine the relation between $12 + \log(O/H)$ and EW(Hβ) in order to find if the metal buildup is a function of the age of the galaxy.

We can determine EW(Hβ) in two ways. We can measure it directly from the spectra, or we can determine the EW of the line falling in the narrowband filter from the imaging observations and then use the line ratios to determine EW(Hβ). However, both methods are somewhat problematic. Because the continua in the spectra are extremely weak, it can be difficult to precisely measure them. The errors here are complex and systematic effects can be important. Thus, EW(Hβ) can only be confidently measured in the highest S/N spectra. The imaging data make a much deeper and more accurate measurement of the continuum, but translating this to the observed-frame EW of the measured line requires us to know the filter profile extremely accurately. This is a particular problem for objects whose wavelengths lie at the edges of the filter, where the response changes rapidly.

We measured EW(Hβ) with both methods. For the spectral determination we restricted to spectra with S/N $> 25$ in the [O III] $\lambda$5007 line. For the images we restricted to galaxies where the transmission in the filter was above 80% of the peak transmission. We took the continuum from line-free broadband

Figure 9. $q$ parameter vs. oxygen abundance for the metallicity sample. 1σ errors are shown for the oxygen abundances and the $q$ parameters. Only the 25 objects with greater than 1σ detections of the [O iii] $\lambda$4363 line are shown. The red line shows the median value of the $q$ parameter in the sample.

Figure 10. The oxygen abundance vs. the R23 parameter for the [O iii] selected objects (black squares) and the Hα selected objects (blue diamonds). Galaxies with [O iii] $\lambda$4363 lines below the 2σ level are shown with open squares at a nominal O abundance. 1σ errors are shown for the oxygen abundances. A linear fit to the combined data sets is shown by the black line, while fits to the local data by Nagao et al. (2006) are shown with the green dashed line and by Yin et al. (2007) as the red dotted line. Local data from Izotov & Thuan (2007) are shown by the red triangles.

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amount of scatter reflecting the uncertainties in the two methods. However, as is shown in Figure 12, regardless of which method we use, we see a clear relationship between $12 + \log(O/H)$ and EW(H$\beta$). The best-fit relationship of $12 + \log(O/H) = 9.72 - 1.07 \log \text{EW}(H\beta)$ based on the imaging EWs also provides a good description for the spectroscopically based EWs. This relation was less clear in the EWs determined from the poorer spectra used in Kakazu et al. (2007). With the new data there is now clear evidence for the build-up of metals as a function of age in the galaxies.

5.4. Metallicity Luminosity Relation

We next computed the absolute rest-frame $B$ magnitudes using magnitudes from imaging observations in bandpasses which are clear of the emission lines and assuming a flat $f_{\nu}$ spectral energy distribution to compute the $K$-correction. We plot these absolute rest-frame $B$ magnitudes versus the oxygen abundance derived by the direct method in Figure 13. The metallicity–luminosity relation can be written as $12 + \log(O/H) = 8.01 - 0.15 \times (M_B(AB) - 20)$.

We can compare the metallicity–luminosity relation with the local metallicity–luminosity relation from Tremonti et al. (2004) (green line in Figure 13) and with observations of magnitude-limited samples at $z = 0.6–0.9$ from Cowie & Barger (2008) (red points) and the corresponding metal–luminosity relation at this redshift (red line). The present sample lies about 0.6 dex below the $z = 0.6–0.9$ relation and about 0.8 dex below the local relation. The Cowie & Barger metallicities are based on the upper branch of the O versus R23 relation and may miss some low-metallicity objects. We have also searched their magnitude-limited sample for strong emitters (blue diamonds in Figure 13) and checked these galaxies for $[O\text{iii}]\lambda4363$, but none of these shows the auroral line.

6. LUMINOSITY FUNCTIONS AND THE LOCAL LYMAN ALPHA EMITTER POPULATION

We next constructed the H$\alpha$ luminosity functions of the USEL sample following the procedures used in Kakazu et al. (2007) but using the present larger spectroscopic sample. We used the narrowband magnitudes to determine the line strength of the selection line: H$\alpha$ at low redshift and $[O\text{iii}]\lambda5007$ at high redshift. For the higher redshift objects we computed the

\[ 12 + \log(O/H) = 8.01 - 0.15 \times (M_B(AB) - 20) \]
the emission-line wavelength, so we restricted to redshifts where the nominal filter response is greater than 80% of the peak value, following the procedure used in the EW analysis. This also has the advantage of providing a uniform selection, and we assume the window function is flat over the defined redshift range. Now the volume is simply defined by the selected redshift range for all objects above the minimum luminosity, which we take as corresponding to an observed flux of $1.5 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ in the $H\alpha$ line. For the high-redshift sample selected in the [O III]λ5007 line the true limit will generally be lower than this, since the [O III]λ5007 line is normally stronger than $H\alpha$, and we restrict the sample to objects with $H\alpha$ line fluxes lying above this threshold. The luminosity function is now obtained by dividing the number of objects in each luminosity bin by the volume. The incompleteness-corrected luminosity function is obtained from the sum of the weights in each luminosity bin divided by the volume. Here, the weight of an object of a given magnitude corresponds to the total number of objects at that magnitude divided by the number of identified objects at that magnitude. Because of the high spectroscopic completeness, the incompleteness corrections are small, except at the very lowest luminosities. The 1σ errors shown are calculated from the Poissonian errors based on the number of spectroscopically identified objects in the bin. The calculated $H\alpha$ luminosity function is shown for $z = 0.2$--0.45 corresponding to the NB816 and NB912 $H\alpha$ selections in Figure 14(a), and the corresponding $H\alpha$ luminosity function for $z = 0.6$--0.9 from the [O III]λ5007-selected samples is shown in Figure 14(b).

The USEL $H\alpha$ function at $z = 0.3$ corresponds to about 4% of the total $H\alpha$ luminosity function at this redshift (Tresse & Maddox 1998), which is shown as the blue dashed line in Figure 14(a). This is similar to the fraction of the total star formation rate that Kakazu et al. (2007) estimated was in the USELs. The USEL $H\alpha$ luminosity function rises rapidly with redshift and the luminosity density at $z = 0.7$ is about 4.5 times higher than at $z = 0.3$, paralleling the rapid rise in the star formation rates over this redshift interval.

These $H\alpha$ luminosity functions also allow us to construct upper limits on the $z = 0$--1 LAE luminosity functions for comparison with the local LAE luminosity function from GALEX (Deharveng et al. 2008) and with the measurements of the LAE luminosity function at high redshift ($z = 2$--7). As we discuss in more detail below, a galaxy with a high EW in the Ly$\alpha$ line will also have a high EW in the $H\alpha$ line, so the LAEs are a subset of the present sample. This allows us to construct an upper bound on the complete LAE sample to a fixed Ly$\alpha$ EW, which can then be compared with the local and high-redshift population in detail.

As is well known, the short path length to optical scattering on neutral hydrogen ensures that Ly$\alpha$ photons follow a complex escape from a galaxy. While the low metallicity and extinction of the present USEL sample are clearly positive indicators of a higher Ly$\alpha$ escape fraction, they are by no means the only factor. Internal structure, kinematics, and the distribution of star formation sites may also play key roles and may in fact be the more critical determinants. We take the case B ratio of 8--12 for the Ly$\alpha$/H$\alpha$ flux, depending on the electron density, to be an upper bound on the line ratio (Ferland & Osterbrock 1985) (Though we note that it is possible to have geometries in which the scattering can enhance the Ly$\alpha$ line relative to the UV continuum; Finkelstein et al. 2007.) Given the roughly flat $f_{\alpha}$ continua in these galaxies (or $f_{\alpha} \sim \lambda^{-2}$) and the rest-frame selection of $\sim 90$ Å equivalent width in the $H\alpha$ line, this in turn means that we will end up with a Ly$\alpha$ sample that is fully complete to a rest EW of 30 Å compared to the 20 Å EW normally used to select the high-redshift LAE population. The higher redshift $z \sim 0.7$ sample will contain all LAEs above 20 Å for the case B assumption. However, empirical estimates of the Ly$\alpha$ escape fraction in the high-redshift LAE population made by comparing star formation rates estimated from the UV continuum with those from the Ly$\alpha$ line suggest escape fractions of 30%--50% (Gawiser et al. 2007; Gawiser 2008). If this lower ratio is applicable for the ratio of the Ly$\alpha$/H$\alpha$ fluxes, then all LAEs will be included in the present samples, though objects close to the $H\alpha$ limiting EW will fall from the LAE sample. The LAE sample is therefore a subset of the present sample, and we can directly obtain an upper bound on the LAE luminosity function from the USEL $H\alpha$ luminosity function.

The sample is small, but it provides a first-cut estimate of the evolution of the LAE luminosity function. We illustrate this in Figure 15, where we show the $z = 0.3$ and the $z = 0.7$ LAE luminosity functions that would be derived from our $H\alpha$ sample under the assumption Ly$\alpha$/H$\alpha = 5$ for objects with rest-frame Ly$\alpha$ EWs above 20 Å. The $z = 0.3$ LAE luminosity function can be compared with the direct determinations of the LAE luminosity function at this redshift from the GALEX observations of Deharveng et al. (2008), which are shown with the open red diamonds. The GALEX data only contain objects with strong UV continuum detections, and these correspond to the highest luminosity emitters. In this sense they parallel the high-redshift Lyman break galaxies with strong Ly$\alpha$ emission, rather than the line selected LAE samples. Deharveng et al. estimated that there should be a large incompleteness correction to allow for this selection effect, and the solid red diamonds show their incompleteness corrected luminosity function. However, the present data, even under the case B assumption, suggest that the incompleteness corrections at low luminosities are smaller than the Deharveng et al. (2008) estimate. We recall that the present data provide an absolute upper limit for the case B assumption. The present $z = 0.3$ sample has too small a volume to probe the high-luminosity end.

At high redshifts the LAE luminosity function is surprisingly invariant in the range $z = 2.5$--6, but there are signs it begins to drop at both higher and lower redshifts. The present data show that it must have dropped substantially at $z = 0.7$ and even further at $z = 0.3$. In Figure 15, we show the most recent determination of the $z = 3$ LAE luminosity function from Gronwall et al. (2007). In order to match the present data the LAE luminosity function would have to drop by about a factor of 4 between $z = 3$ and $z = 0.7$ (dashed red line) and by a factor of very roughly 20 between $z = 3$ and $z = 0.3$ (dotted red line). Even under the case B assumption these drops would be two and ten, respectively. The drop in the LAE luminosity function parallels the drop in the star formation over this redshift interval, and there is even a suggestion of downsizing in the shape of the LAE luminosity function at the lowest redshift, which is deficient in high-luminosity objects relative to the low-luminosity end.

7. SUMMARY

We have described the results of deep spectroscopic observations of a narrowband-selected sample of extreme emission line objects. Using a sample that follows up roughly twice the number of high equivalent width emission-line objects with spectroscopic identifications from the catalog presented in Kakazu...
et al. (2007), and considerably deeper spectroscopic observations of the lowest metallicity identifications from that paper, we confirm and extend the conclusions that such objects are common in the \( z = 0 \)–1 redshift interval and that a very large fraction of the strong emitters are detected in the \([\text{O} \text{iii}] \lambda 4363\) line where oxygen abundances can be measured using the direct method. For this larger sample based on spectroscopic follow-up of two-thirds of the catalog, the abundances primarily lie in the 12 + \( \log(O/H) \) range of 7–8 characteristic of XMPGs. Using the highest quality subsample of our present spectroscopic sample, we have determined the metal–luminosity relation for this class of object, finding it lies about 0.6 dex below a magnitude selected sample in the same redshift interval. We further give an empirical relation between R23 and 12 + \( \log(O/H) \), which differs from local estimates. We also show that low-metallicity objects can be picked out by the weakness of \([\text{O} \text{iii}] \lambda 5007\) in the spectra. The two lowest metallicity galaxies in the sample can be picked out by the weakness of \([\text{O} \text{iii}] \lambda 5007\) from local estimates. We also show that low-metallicity objects empirically selected sample in the same redshift interval. We further give an empirical relation between R23 and 12 + \( \log(O/H) \), which differs from local estimates. We also show that low-metallicity objects can be picked out by the weakness of \([\text{O} \text{iii}] \lambda 5007\) in the spectra. The two lowest metallicity galaxies in the sample have 12 + \( \log(O/H) \) = 6.97 ± 0.17 and 7.25 ± 0.03, making them among the lowest metallicity galaxies known, but we expect that as the sample size is increased, yet lower metallicity galaxies may be found, and we may hope to be able to determine if there is a floor in the galaxy metallicity at these redshifts. We have computed the USEL H\(\alpha\) luminosity functions at redshifts \( z = 0.3 \) and \( z = 0.7 \) and used this to constrain the LAE luminosity function at these redshifts assuming Case B recombination values. These data, compared with the local LAE luminosity function from \textit{GALEX} and LAE luminosity functions at high redshifts, demonstrate a substantial drop in the LAE luminosity function by redshift \( z = 0.7 \).

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