MMT OBSERVATIONS OF NEW EXTREMELY METAL-POOR EMISSION-LINE GALAXIES IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We present 6.5 m MMT spectrophotometry of 20 H ii regions in 13 extremely metal-poor emission-line galaxies selected from Data Release 5 of the Sloan Digital Sky Survey to have [O iii] λ4959/Hβ ≲ 1 and [N ii] λ6583/Hβ ≲ 0.05. The electron-temperature–sensitive emission line [O iii] λ4363 is detected in 13 H ii regions, allowing a direct abundance determination. The oxygen abundance in the remaining H ii regions is derived using a semiempirical method. The oxygen abundance of the galaxies in our sample ranges from 12 + log (O/H) ≈ 7.1 to ~7.8, with 10 H ii regions having an oxygen abundance lower than 7.5. The lowest oxygen abundances, 7.14 ± 0.03 and 7.13 ± 0.07, are found in two H ii regions of the blue compact dwarf galaxy SDSS J0956+2849 (≡DDO 68), making it the second most metal-deficient emission-line galaxy known, after SBS 0335–052W.

Subject headings: galaxies: abundances — galaxies: evolution — galaxies: formation — galaxies: irregular — galaxies: ISM — H ii regions — ISM: abundances

1. INTRODUCTION

Extremely metal-deficient emission-line galaxies at low redshift are the most promising young-galaxy candidates in the local universe (Guseva et al. 2003; Izotov & Thuan 2004b). They are important to identify for several reasons. First, studies of their nearly pristine interstellar medium (ISM) can shed light on the properties of the primordial ISM at the time of galaxy formation. It appears now that even the most metal-deficient galaxies in the local universe formed from matter that was already preenriched by a previous star formation episode, for example, by Population III stars (Thuan et al. 2005). It is thus quite important to establish firmly the level of this preenrichment by searching for the most metal-deficient emission-line galaxies. Second, because they have not undergone much chemical evolution, these galaxies are also the best objects for the determination of the primordial He abundance and for constraining cosmological models (e.g., Izotov & Thuan 2004a; Izotov et al. 2007). Third, in the hierarchical picture of galaxy formation, large galaxies form through the assembly of small dwarf galaxies. While much progress has been made in finding large populations of galaxies at high redshift (z ≥ 3; Steidel et al. 2003), truly young galaxies in the process of forming remain elusive in the distant universe. The spectra of those faraway galaxies generally indicate the presence of a substantial amount of heavy elements, indicating previous star formation and metal enrichment. Therefore, extremely metal-deficient dwarf galaxies are possibly the closest examples we can find of the elementary primordial units from which galaxies formed. Their relative proximity allows studies of their stellar, gas, and dust content with a sensitivity and spectral and spatial resolution that faint, distant high-redshift galaxies do not permit.

Extremely metal-deficient emission-line galaxies are however very rare. Many surveys have been carried out to search for such galaxies without significant success. For more than three decades, one of the first blue compact dwarf galaxies (BCDs) discovered, I Zw 18 (Sargent & Searle 1970) continued to hold the record as the most metal-deficient emission-line galaxy known, with an oxygen abundance 12 + log (O/H) = 7.17 ± 0.01 in its northwestern component and 7.22 ± 0.02 in its southeastern component (Thuan & Izotov 2005). Only very recently has I Zw 18 been displaced by the BCD SBS 0335–052W. This galaxy, with an oxygen abundance 12 + log (O/H) = 7.12 ± 0.03, is now the emission-line galaxy with the lowest metallicity known (Izotov et al. 2005).

Because of the scarcity of extremely low-metallicity galaxies such as I Zw 18 and SBS 0335–052W, we stand a better chance of finding them in very large spectroscopic surveys. One of the best surveys suitable for such a search is the Sloan Digital Sky Survey (SDSS; York et al. 2000). However, despite intensive studies of galaxies with a detected temperature-sensitive [O iii] λ4363 Å emission line in their spectra, no emission-line galaxy with an oxygen abundance as low as that of I Zw 18 has been discovered in the SDSS Data Release 3 and earlier releases. The lowest-metallicity emission-line galaxies found so far in these releases have oxygen abundances 12 + log (O/H) > 7.4 (Kniazev et al. 2003, 2004; Izotov et al. 2004, 2006b). Only recently, Izotov et al. (2006a) showed that two galaxies, J2104–0035 and J0113+0052, selected from the SDSS Data Release 4, are very metal-poor, with values of 12 + log (O/H) of 7.26 ± 0.03 and 7.17 ± 0.09, respectively.

In order to find new candidate extremely metal-deficient emission-line galaxies, we have carried out a systematic search for such objects in the SDSS Data Release 5 (DR5; Adelman-McCarthy et al. 2007). We have chosen them on the basis of the relative fluxes of selected emission lines, as in Izotov et al. (2006a). All known extremely metal-deficient emission-line galaxies are characterized by relatively weak (compared with Hβ) emission lines of [O ii] λ3727, [O iii] λλ4959, 5007, and [N ii] λλ6583 (e.g., Izotov & Thuan 1998a, 1998b; Izotov et al. 2005; Pustil’nik et al. 2005; Izotov et al. 2006a). These spectral properties uniquely select out low-metallicity dwarfs, since no other type of galaxy possesses them. In contrast to previous studies (Kniazev et al. 2003, 2004; Izotov et al. 2004, 2006b) that focused exclusively on objects with a detected [O iii] λ4363 Å emission line, we have also considered objects that satisfy the criteria described above, but with
spectrum where \([\text{O} \, ii] \lambda 4363\) is weak or not detected. Since \([\text{O} \, ii] \lambda 3727\) is out of the observed wavelength range in SDSS spectra of galaxies with a redshift \(z\) lower than 0.02, we use two criteria, \([\text{O} \, iii] \lambda 4959/\lambda 3727 \leq 1\) and \([\text{N} \, ii] \lambda 6583/\lambda 3727 \leq 0.05\), to pick out \(~\sim 100\) galaxies from the DR5. The efficiency of this technique to pick out extremely low metallicity galaxy candidates has been demonstrated in Izotov et al. (2006a).

While the SDSS spectra allow us to select very low metallicity galaxies, we need additional spectral observations for the following reasons: (1) a spectrum that goes further into the blue wavelength range is required in order to detect the \([\text{O} \, ii] \lambda 3727\) \(\lambda\) line. For a precise oxygen abundance determination, this line is needed. For a spectrum that goes further into the blue wavelength range, we need additional spectral observations for the follow-

### Table 1: General Characteristics of the Galaxies

| SDSS Name           | R.A. (J2000.0) | Decl. (J2000.0) | Redshift | SDSS Spectrum ID | Other Names       |
|---------------------|---------------|----------------|----------|------------------|------------------|
| SDSS J0113+0052     | 01 13 40.44   | +00 52 39.2    | 0.0037630| 53001-1499-525   | UGC 772          |
| SDSS J0204−1009     | 02 04 25.61   | −10 09 35.0    | 0.0063795| 52149-0666-088   | KUG 0201−103     |
| SDSS J0254+0035     | 02 54 28.94   | +00 35 50.5    | 0.0148437| 53035-1521-400   |                  |
| SDSS J0301−0052     | 03 01 49.01   | −00 52 57.4    | 0.0072615| 52616-1067-204   |                  |
| SDSS J0313+0010     | 03 13 01.60   | +00 10 40.2    | 0.0077796| 52203-0710-597   |                  |
| SDSS J0747+1111     | 07 47 33.18   | +51 11 24.8    | 0.0014436| 53327-1869-282   | KUG 0743+513     |
| SDSS J0812+4836     | 08 12 39.53   | +48 36 45.5    | 0.0017567| 51885-0440-170   |                  |
| SDSS J0859+3923     | 08 59 46.93   | +39 23 05.6    | 0.0019601| 52699-1989-590   |                  |
| SDSS J0911+3135     | 09 11 59.42   | +31 35 35.9    | 0.0025028| 52976-1591-097   |                  |
| SDSS J0940+2935     | 09 40 12.84   | +29 35 30.3    | 0.0018161| 53415-1942-055   | KUG 0937+298     |
| SDSS J0946+5452     | 09 46 22.87   | +54 52 08.4    | 0.0054097| 52282-0769-376   | KUG 0942+551     |
| SDSS J0956+2849     | 09 56 46.05   | +28 49 43.8    | 0.0016006| 53431-1947-040   | DDO 68           |
| SDSS J2238+1400     | 22 38 31.12   | +14 00 29.8    | 0.0206160| 53239-1893-476   | HS 2236+1344     |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

1 The MMT is operated by the MMT Observatory (MMTO), a joint venture of the Smithsonian Institution and the University of Arizona.

cension, along with some of their general properties such as coordinates, redshifts, identifications of their SDSS spectra, and other designations. The SDSS images of the observed galaxies are shown in Figure 1. Labels of individual H \(\pi\) regions are shown when several of them have been observed within the same galaxy. We show in Figure 2 the SDSS spectra used to select the galaxies from the DR5. It can be seen from the figure that the \([\text{O} \, ii] \lambda 3727\) \(\lambda\) emission line is out of the observed spectral range and that the \([\text{N} \, ii] \lambda 6584\) \(\lambda\) emission line is weak in all spectra.

Ten out of the 13 galaxies listed in Table 1 were chosen from the DR5 with the selection criteria described above. Their oxygen abundances were not known before this work. The three remaining galaxies also satisfy the selection criteria, except for J2238+1400, for which \([\text{O} \, iii] \lambda 4959/\lambda 3727 \sim 1.6\). However, their oxygen abundances have been determined before. Two galaxies have been included in our observing program because they are among the five most metal-deficient emission-line galaxies known, and we believe that more information can be obtained about them with supplementary observations. Izotov et al. (2006a) obtained 12 + log \((\text{O/H}) = 7.17 \pm 0.09\) for J0113+0052 (UGC 772), and Pustil’nik et al. (2005) measured 12 + log \((\text{O/H}) = 7.21 \pm 0.07\) for J0946+5452 (DDO 68). We wish to improve the abundance determination in these two galaxies with higher signal-to-noise ratio observations. The third galaxy is J2238+1400 (HS 2236+1344), which has been studied spectroscopically by Ugryumov et al. (2003), Izotov & Thuan (2004a), and Guseva et al. (2007). Izotov & Thuan (2004a) found in its spectrum a strong high-ionization \([\text{Fe} \, v] \lambda 4227\) \(\lambda\) emission line, with an ionization potential of 4 ryd. We have included this galaxy in our observing program because they are among the five most metal-deficient emission-line galaxies known, and we believe that more information can be obtained about them with supplementary observations. Izotov et al. (2006a) obtained 12 + log \((\text{O/H}) = 7.17 \pm 0.09\) for J0113+0052 (UGC 772), and Pustil’nik et al. (2005) measured 12 + log \((\text{O/H}) = 7.21 \pm 0.07\) for J0946+5452 (DDO 68). We wish to improve the abundance determination in these two galaxies with higher signal-to-noise ratio observations. The third galaxy is J2238+1400 (HS 2236+1344), which has been studied spectroscopically by Ugryumov et al. (2003), Izotov & Thuan (2004a), and Guseva et al. (2007). Izotov & Thuan (2004a) found in its spectrum a strong high-ionization \([\text{Fe} \, v] \lambda 4227\) \(\lambda\) emission line, with an ionization potential of 4 ryd. We have included this galaxy in our observing program because they are among the five most metal-deficient emission-line galaxies known, and we believe that more information can be obtained about them with supplementary observations. Izotov et al. (2006a) obtained 12 + log \((\text{O/H}) = 7.17 \pm 0.09\) for J0113+0052 (UGC 772), and Pustil’nik et al. (2005) measured 12 + log \((\text{O/H}) = 7.21 \pm 0.07\) for J0946+5452 (DDO 68). We wish to improve the abundance determination in these two galaxies with higher signal-to-noise ratio observations. The third galaxy is J2238+1400 (HS 2236+1344), which has been studied spectroscopically by Ugryumov et al. (2003), Izotov & Thuan (2004a), and Guseva et al. (2007). Izotov & Thuan (2004a) found in its spectrum a strong high-ionization \([\text{Fe} \, v] \lambda 4227\) \(\lambda\) emission line, with an ionization potential of 4 ryd. We have included this galaxy in our observing program because they are among the five most metal-deficient emission-line galaxies known, and we believe that more information can be obtained about them with supplementary observations. Izotov et al. (2006a) obtained 12 + log \((\text{O/H}) = 7.17 \pm 0.09\) for J0113+0052 (UGC 772), and Pustil’nik et al. (2005) measured 12 + log \((\text{O/H}) = 7.21 \pm 0.07\) for J0946+5452 (DDO 68).
Total exposure times varied between 30 and 45 minutes. Each exposure was broken up into two or three subexposures, not exceeding 15 minutes, to allow for removal of cosmic rays. Several objects were observed at low air masses (<1.3) or with the slit oriented along the parallactic angle. The latter observations are noted in Table 2. The effect of atmospheric refraction for these observations is small. However, it can be important in the spectra of galaxies observed at high air mass (>1.3). Fortunately, strong hydrogen lines are observed in some spectra (i.e., those of J0204−1009 and J0747+5111), and correction for interstellar extinction with the use of those lines will automatically take into account the effect of atmospheric refraction. This is because the interstellar extinction correction is performed in such a way that the intensities of all observed hydrogen lines after correction are as close as possible to their theoretical recombination values, for a given electron temperature. However, in some other spectra obtained at high air masses (those of J0301−0052, J0812+4836, J0911+3135, J0940+2935, and J0946+5452), the hydrogen lines are weaker,

Fig. 1.—SDSS images of galaxies in the MMT subsample.
making such correction less certain. Three Kitt Peak IRS (Intensified Reticon Scanner) spectroscopic standard stars, G191-B2B, Feige 110, and BD +28 4211, have been observed for flux calibration. Spectra of He-Ne-Ar comparison arcs were obtained before and after each observation to calibrate the wavelength scale.

The two-dimensional spectra were bias-subtracted and flatfield–corrected using IRAF. We then used the IRAF software routines IDENTIFY, REIDENTIFY, FITCOORD, and TRANSFORM to perform wavelength calibration and correct for distortion and tilt for each frame. One-dimensional spectra were then extracted from each frame using the APALL routine. Before extraction, distinct two-dimensional spectra of the same H II region were carefully aligned using the spatial locations of the brightest part in each spectrum, so that spectra were extracted at the same positions in all subexposures. For all objects, we extracted the brightest part of the BCD, corresponding to a different spatial size for each object. In all cases, 6'' × 1.5'' extraction apertures were used. All extracted spectra from the same object were then co-added. We have summed the individual spectra from each subexposure after removal of the cosmic-ray hits with the IRAF routine CRMEDIAN. The spectra obtained from each subexposure were also checked for cosmic-ray hits at the location of strong emission lines, but none were found.

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2 IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The extinction coefficient is de- 

Table 2

| SDSS Name         | Date (2006) | Exposure (s) | Air Mass | P.A. |
|-------------------|-------------|--------------|----------|------|
| SDSS J0113+0052   | Dec 15      | 2460         | 1.17     | +63.0|
| SDSS J0204−1009   | Dec 15      | 1800         | 1.40     | −11.3|
| SDSS J0254+0035   | Dec 15      | 2700         | 1.18     | −22.5b|
| SDSS J0301−0052   | Dec 16      | 2700         | 1.18     | +4.8b|
| SDSS J0313+0010   | Dec 16      | 1800         | 1.44     | −76.0^b|
| SDSS J0747+5111   | Dec 16      | 1800         | 1.42     | 0.0  |
| SDSS J0812+4836   | Dec 15      | 1800         | 1.38     | +67.3|
| SDSS J0859+3923   | Dec 15      | 1800         | 1.44     | −76.0^b|
| SDSS J0911+3135   | Dec 16      | 1800         | 1.42     | 0.0  |
| SDSS J0940+2935   | Dec 16      | 1800         | 1.39     | +24.2|
| SDSS J0946+5452   | Dec 16      | 1800         | 1.71     | +58.2|
| SDSS J0956+2849   | Dec 16      | 1800         | 1.29     | −0.8 |
| SDSS J2238+1400   | Dec 15      | 1800         | 1.17     | 0.0  |

^a In degrees east of north.
^b Slit oriented along the parallactic angle.

The sensitivity curve was obtained by fitting with a high-degree polynomial the observed spectral energy distribution of the bright hot white dwarf standard stars G191-B2B, Feige 110, and BD +28 4211. Because the spectra of these stars have only a small number of relatively weak absorption features, their spectral energy distributions are known to very good accuracy (Oke 1990). Moreover, the response function of the CCD detector is smooth, so we could derive a sensitivity curve with a precision better than 1% over the whole optical range.

The spectra for the 20 H ii regions observed with the MMT are shown in Figure 3. These spectra have been reduced to zero red-

The observed line fluxes \( F(\lambda) \), normalized to \( F(H\beta) \) and multiplied by a factor of 100, and their errors for the 20 H ii regions shown in Figure 3 are given in Table 3. They were measured using the IRAF SPLIT routine. The line flux errors listed include statistical errors derived with SPLIT from non-flux-calibrated spec-

The derived oxygen abundances for these H ii regions are shown in the second column of Table 5. The galaxy J2238+1400, with two high-excitation H ii regions, was observed in order to check for the presence of the high-ionization emission lines \([\text{Ne v}]\lambda 5346, 3425\) in its spectra. The galaxy J2238+1400 is in good agreement with the values 7.49 and 7.58 derived in regions J2238+1400 No. 1 and No. 2 are in agreement with the values 7.49 and 7.58 derived by Guseva et al. (2007) for the same H ii regions. A very similar oxygen abundance of 7.47 was obtained for region No. 1 by Uryumov et al. (2003) and Izotov & Thuan (2004a). This shows that the abundances obtained for this galaxy by different authors, using different telescopes, are very consistent. Two other galaxies, J0113+0052 and J0956+2849, have been observed before. Izotov et al. (2006a) obtained 12 + log (O/H) = 7.12 ± 0.09 for J0113+0052 No. 1. With our higher signal-to-noise ratio spectrum, we derive 12 + log (O/H) = 7.24 ± 0.05. Pustil’nik et al. (2005) obtained 12 + log (O/H) = 7.23 ± 0.06 and 7.21 ± 0.07 for H ii

\[
t_{\lambda}(O\ ii) = -1.36854 \log \left( \frac{I(\lambda 3727) + I(\lambda 4959) + I(\lambda 5007)}{I(H\beta)} \right) + 2.62577, \tag{1}
\]

where \( t_{\lambda}(O\ ii) = 10^{-4}T_{\lambda}(O\ ii) \).

For \( T_{\lambda}(O\ ii) \), we use the relation between the electron tempera-

ducers do not depend on \( N_e \) as long as its value is lower than

\[
\frac{10^{-10}}{10^3} \text{ cm}^{-3}, \text{ which is the case for the vast majority of the H ii regions in the emission-line galaxies considered here (see, e.g., Izotov et al. 2006b). Ionic and total heavy-element abundances are derived using expressions for ionic abundances and ioniza-

tion correction factors (ICFs) obtained in Izotov et al. (2006b). The element abundances are given in Table 4 along with the adopted electron temperatures for different ions. Consider first the results obtained with the direct method for the 13 H ii regions with a detected \([\text{O iii}]\lambda 4363 \text{ Å} \) emission line.

The derived oxygen abundances for these H ii regions are shown in the second column of Table 5. The galaxy J2238+1400, with two high-excitation H ii regions, was observed in order to check for the presence of the high-ionization emission lines \([\text{Ne v}]\lambda 5346, 3425\) in its spectra. No such lines were detected (Figs. 3, 3u). Thus, despite the presence of the \([\text{Fe v}]\lambda 4227 \text{ Å} \) emission line in the spectrum of its H ii region No. 1 (Table 3), implying ionizing radiation with photon energies in excess of 4 ryd, no ionizing radiation with photon energies above 7 ryd is present in this galaxy. This is in contrast to the situation in the three low-metallicity BCDs, SBS 0335−052E, Tol 1214−277, and HS 0837+4717, known thus far to exhibit both \([\text{Fe v}]\) and \([\text{Ne v}] \) emission (Thuan & Izotov 2005). The oxygen abundances 12 + log (O/H) = 7.45 and 7.56 derived respectively in regions J2238+1400 No. 1 and No. 2 are in good agreement with the values 7.49 and 7.58 derived by Guseva et al. (2007) for the same H ii regions. A very similar oxygen abundance of 7.47 was obtained for region No. 1 by Uryumov et al. (2003) and Izotov & Thuan (2004a). This shows that the abundances obtained for this galaxy by different authors, using different telescopes, are very consistent. Two other galaxies, J0113+0052 and J0956+2849, have been observed before. Izotov et al. (2006a) obtained 12 + log (O/H) = 7.12 ± 0.09 for J0113+0052 No. 1. With our higher signal-to-noise ratio spectrum, we derive 12 + log (O/H) = 7.24 ± 0.05. Pustil’nik et al. (2005) obtained 12 + log (O/H) = 7.23 ± 0.06 and 7.21 ± 0.07 for H ii
regions No. 1 and No. 2 in J0956+2849 (we follow Pustil'nik et al. for the nomenclature of the H II regions). We derive $12 + \log (O/H) = 7.14 \pm 0.03$ and $7.13 \pm 0.07$ from our higher resolution and higher signal-to-noise ratio spectra of the same H II regions. The new measured abundances make J0956+2849 the second most metal-deficient emission-line galaxy known after SBS 0335+052W (Izotov et al. 2005). It is more metal-deficient than I Zw 18 NW [$12 + \log (O/H) = 7.17 \pm 0.01$], I Zw 18 SE [$12 + \log (O/H) = 7.22 \pm 0.01$], and SBS 0335–052E [$12 + \log (O/H) = 7.31 \pm 0.01$] (Thuan & Izotov 2005). The other galaxies with detected [O III] $\lambda$4363 have not been observed previously. They have higher oxygen abundances, in the range $12 + \log (O/H) = 7.51–7.75$.

While the determination of oxygen abundance in H II regions with detected [O III] $\lambda$4363 by means of the direct method is straightforward, the determination of oxygen abundances in
those H\textsc{ii} regions with no detected [O\textsc{iii}] $\lambda 4363$ emission has to rely on semiempirical or empirical methods based on the intensities of the strong [O\textsc{iii}] $\lambda 3727$ and [O\textsc{iii}] $\lambda 4959$, 5007 nebular emission lines. In order to evaluate the accuracy of the abundances based on these semiempirical or empirical methods, we have compared oxygen abundances derived with these alternative methods with those obtained by the direct method for the H\textsc{ii} regions with detected [O\textsc{iii}] $\lambda 4363$ emission in our sample.

First, we compare the oxygen abundances derived with the direct method (col. [2] in Table 5) with those obtained by the semiempirical method described above (col. [6] in Table 5). We find a generally good agreement between the two methods. Exceptions are the two high-excitation H\textsc{ii} regions in J2238$+$1400. In these cases, the electron temperatures derived by the semiempirical method (eq. [1]) are $\sim$4000–5000 K lower than those derived from the [O\textsc{iii}] $\lambda 4363/\lambda 3727 (4959 + 5007)$ ratio, yielding significantly higher oxygen abundances. These discrepancies may indicate that these two H\textsc{ii} regions have anomalous properties. This may be the case if [O\textsc{iii}] $\lambda 4363$ emission is enhanced by some mechanism that is different from stellar radiation heating, such as shock heating, or if the [O\textsc{iii}] $\lambda 4363/\lambda 3727 (4959 + 5007)$ ratio is artificially enhanced by a reduction of the fluxes of the [O\textsc{iii}] 4959 Å and 5007 Å emission lines by collisional de-excitation in a dense interstellar medium ($N_e \gtrsim 10^5$ cm$^{-3}$), as discussed in Thuan et al. (1996) for the case of the BCD Mrk 996. In these conditions, the oxygen abundance derived by the direct method will be lower than the true value. Another possible mechanism for the enhancement of [O\textsc{iii}] $\lambda 4363$ emission is nonthermal radiation from a hidden active galactic nucleus (AGN). However, we do not favor this mechanism, because the optical spectra of both H\textsc{ii} regions in J2238$+$1400 do not show the usual features that are characteristic of an AGN Seyfert 2 optical spectrum: the emission lines [Ne\textsc{v}] $\lambda \lambda 3346, 3425$ are not detected (see Fig. 3, inset), the He\textsc{ii} $\lambda 4686$ emission is weak (its intensity is only $\sim$1% of that of H$\beta$; Table 3), and other lines, such as [O\textsc{i}] $\lambda \lambda 6300, [N\textsc{ii}] \lambda 6584$, and [S\textsc{ii}] $\lambda \lambda 6717, 6731$ are many times weaker than those in a typical Seyfert 2 galaxy (see Fig. 2m). We note however that Spitzer observations of several BCDs (Hunt et al. 2006; T. X. Thuan et al. 2007, in preparation) have shown that the [O\textsc{iv}] 25.9 $\mu$m emission line, with an ionization potential of $\sim$4 ryd, is present in the mid-infrared (MIR) spectrum, while the [Fe\textsc{iv}] 4227 Å and He\textsc{ii} 4686 Å emission lines, with about the same ionization potential, are conspicuously absent from the optical spectrum. This suggests that in those BCDs, there may be a dust-enshrouded AGN that is optically invisible and which may be responsible for the hard radiation giving rise to the MIR line. If we exclude the two H\textsc{ii} regions in J2238$+$1400, the average difference between the semiempirical abundances and those derived by the direct method is 0.06 dex. The semiempirical method also gives consistent oxygen abundances for multiple H\textsc{ii} regions within the same galaxy, including those in which the [O\textsc{iii}] $\lambda 4363$ Å emission line is not detected (see the galaxies J0113$+0052$ and J0956$+2849$).

Next, we compare the abundances determined by the direct method with those derived using empirical methods. Recently, several groups have proposed empirical relations for the determination of $12 + \log (O/H)$ using the nebular [O\textsc{ii}] $\lambda 3727$ and [O\textsc{iii}] $\lambda \lambda 4959, 5007$ emission-line intensities:

$$12 + \log (O/H) = \frac{R_3 + 106.4P + 106.8P^2 - 3.40P^3}{17.72P + 6.60P^2 + 6.95P^3 - 0.302R_3}$$

(Pilyugin & Thuan 2005),

$$\log R_{23} = 1.2299 - 4.1926y + 1.0246y^2 - 0.063169y^3$$

(Nagao et al. 2006), and

$$12 + \log (O/H) = 6.486 + 1.401 \log R_{23}$$

(Yin et al. 2007). In equations (2)–(4), $R_3 = [I(\lambda 4959) + I(\lambda 5007)]/I(H\beta)$, $R_{32} = R_3 + I(\lambda 3727)/I(H\beta)$, $P = R_3/R_{32}$, and $y = 12 + \log (O/H)$. We have derived oxygen abundances for all H\textsc{ii} regions in our sample using the above equations. The results are shown in columns (3)–(5) of Table 5. Comparison with the abundances derived by the direct method shows that the empirical
## TABLE 3
EMISSION-LINE INTENSITIES AND EQUIVALENT WIDTHS

### A.

| LINE | J0113+0052 No. 1 | J0113+0052 No. 2 |
|------|------------------|------------------|
| [O ii] λ3727 | 50.41 ± 1.88 | 203.01 ± 6.89 |
| Hα (3835 Å) | 6.83 ± 1.10 | 187.30 ± 7.26 |
| [Ne ii] λ3868 | 12.60 ± 1.06 | 81.68 ± 1.06 |
| He i λ3889 + H8 | 13.18 ± 0.91 | 41.30 ± 2.16 |
| [Ne ii] λ3968 + H7 | 13.89 ± 0.87 | 46.74 ± 3.04 |
| Hγ (4101 Å) | 20.73 ± 1.03 | 19.57 ± 1.74 |
| Hγ (4340 Å) | 38.70 ± 1.21 | 46.82 ± 1.88 |
| [O iii] λ4363 | 5.75 ± 0.60 | 9.60 ± 0.73 |
| He i λ4471 | 3.36 ± 0.55 | 3.86 ± 0.64 |
| Hβ (4861 Å) | 100.00 ± 2.34 | 100.00 ± 3.38 |
| [O ii] λ4959 | 73.86 ± 1.85 | 46.75 ± 2.06 |
| [O ii] λ5007 | 212.88 ± 4.54 | 132.55 ± 4.25 |
| C(Hγ) | 0.630 | 0.000 |
| F(Hβ) | 0.07 | 0.03 |
| EW(abs) (Å) | 0.00 | 3.95 |

### B.

| LINE | J0113+0052 No. 4 | J0204—1009 No. 1 |
|------|------------------|------------------|
| [O ii] λ3727 | 112.24 ± 4.56 | 213.20 ± 11.39 |
| [Ne ii] λ3868 | 14.09 ± 1.92 | 27.71 ± 5.19 |
| Hγ (4340 Å) | 41.84 ± 2.00 | 36.23 ± 3.63 |
| Hβ (4861 Å) | 100.00 ± 3.59 | 100.00 ± 5.49 |
| [O ii] λ4959 | 73.08 ± 2.94 | 64.56 ± 4.45 |
| [O ii] λ5007 | 210.48 ± 6.37 | 205.73 ± 9.53 |
| C(Hγ) | 0.000 | 0.000 |
| F(Hβ) | 0.03 | 0.03 |
| EW(abs) (Å) | 5.95 | 2.00 |

### C.

| LINE | J0204—1009 No. 2 | J0254+0035 |
|------|------------------|------------|
| [O ii] λ3727 | 139.72 ± 2.95 | 166.40 ± 6.42 |
| Hβ (3750 Å) | 2.01 ± 0.53 | 63.33 |
| Hλ (3771 Å) | 3.15 ± 0.67 | 1.00 |
| Hλ (3798 Å) | 4.72 ± 0.61 | 3.10 |
| Hβ (4335 Å) | 6.32 ± 0.68 | 11.40 |
| He i λ3889 + H8 | 19.66 ± 0.85 | 10.44 ± 2.09 |
| [Ne ii] λ3968 + H7 | 22.84 ± 0.99 | 5.32 ± 1.24 |
| Hγ (4101 Å) | 28.84 ± 0.95 | 15.05 ± 2.19 |
| Hγ (4340 Å) | 46.82 ± 1.11 | 38.05 ± 2.36 |
| [O iii] λ4363 | 6.53 ± 0.51 | 3.50 |
| He i λ4471 | 3.70 ± 0.58 | 2.00 |
| Hγ (4861 Å) | 100.00 ± 1.94 | 100.00 ± 3.71 |
| [O ii] λ4959 | 94.11 ± 1.86 | 143.69 ± 5.08 |
| [O ii] λ5007 | 272.63 ± 4.86 | 143.69 ± 5.08 |
| He i λ5015 | 1.97 ± 0.31 | 6.30 |
| C(Hβ) | 0.000 | 0.035 |
| F(Hβ) | 0.20 | 0.00 |
| EW(abs) (Å) | 0.00 | 2.00 |
| TABLE 3 — Continued |
|---------------------|

### D. 

| LINE | $F(\lambda)/F(H\beta)$ | $\lambda(\lambda)/(H\beta)$ | EW* |
|------|-------------------|-----------------|-----|
| [O ii] 3727 | 45.17 ± 2.48 | 59.92 ± 3.55 | 37.3 |
| [O ii] 3731 | 23.35 ± 1.73 | 29.55 ± 2.34 | 17.8 |
| He i 3889 + H8 | 12.20 ± 1.62 | 21.42 ± 3.36 | 9.2 |
| [Ne ii] 3968 + H7 | 15.39 ± 1.78 | 25.59 ± 3.52 | 10.2 |
| Hβ (4101 Å) | 20.49 ± 1.74 | 27.12 ± 2.54 | 28.9 |
| Hγ (4340 Å) | 37.00 ± 1.11 | 47.13 ± 2.07 | 22.1 |
| [O ii] 4363 | 8.63 ± 1.00 | 9.38 ± 1.15 | 5.1 |
| Hβ (4861 Å) | 100.00 ± 2.84 | 100.00 ± 3.22 | 65.7 |
| [O ii] 4959 | 132.88 ± 3.53 | 122.78 ± 3.47 | 82.1 |
| [O ii] 5007 | 395.54 ± 9.32 | 361.08 ± 9.06 | 230.6 |
| C(II) | 0.475 | 0.000 |
| $F(\lambda)/F(H\beta)$ | 0.06 | 0.02 |
| EW(abs) (Å) | 3.65 | 2.00 |

### E. 

| LINE | $F(\lambda)/F(H\beta)$ | $\lambda(\lambda)/(H\beta)$ | EW* |
|------|-------------------|-----------------|-----|
| [O ii] 3727 | 195.99 ± 3.92 | 240.79 ± 5.27 | 37.2 |
| H11 (3771 Å) | ... | ... | ... |
| H10 (3798 Å) | ... | ... | ... |
| H9 (3835 Å) | ... | ... | ... |
| He i 3889 + H8 | 29.31 ± 1.38 | 34.79 ± 1.73 | 4.6 |
| [Ne ii] 3968 + H7 | 14.77 ± 1.07 | 23.37 ± 2.12 | 3.1 |
| Hβ (4101 Å) | 15.41 ± 1.17 | 24.06 ± 2.27 | 3.0 |
| Hγ (4340 Å) | 21.60 ± 1.07 | 29.86 ± 1.87 | 4.6 |
| Hδ (4363 Å) | 39.29 ± 1.11 | 47.11 ± 1.69 | 8.6 |
| [O ii] 4363 | 7.29 ± 0.76 | 7.74 ± 0.84 | 1.3 |
| He i 4471 | 2.07 ± 0.50 | 2.15 ± 0.55 | 0.4 |
| He ii 4686 | ... | ... | ... |
| Hβ (4861 Å) | 100.00 ± 1.93 | 100.00 ± 2.14 | 26.6 |
| [O ii] 4959 | 125.97 ± 2.35 | 119.01 ± 2.32 | 27.4 |
| [O ii] 5007 | 381.73 ± 6.63 | 357.49 ± 6.49 | 83.1 |
| He i 5015 | ... | ... | ... |
| C(II) | 0.345 | 0.045 |
| $F(\lambda)/F(H\beta)$ | 0.28 | 0.29 |
| EW(abs) (Å) | 1.05 | 1.25 |

### F. 

| LINE | $F(\lambda)/F(H\beta)$ | $\lambda(\lambda)/(H\beta)$ | EW* |
|------|-------------------|-----------------|-----|
| [O ii] 3727 | 161.92 ± 5.47 | 194.96 ± 7.50 | 31.6 |
| [Ne ii] 3968 | 5.64 ± 1.38 | 6.54 ± 1.75 | 0.8 |
| He i 3889 + H8 | 6.22 ± 2.35 | 20.45 ± 9.64 | 1.2 |
| [Ne ii] 3968 + H7 | 8.79 ± 1.85 | 20.59 ± 5.50 | 2.0 |
| Hδ (4101 Å) | 14.15 ± 1.91 | 27.21 ± 4.82 | 2.8 |
| Hγ (4340 Å) | 34.67 ± 2.04 | 46.60 ± 3.59 | 7.2 |
| Hβ (4861 Å) | 100.00 ± 3.25 | 100.00 ± 3.79 | 25.8 |
| [O ii] 4959 | 28.99 ± 1.71 | 26.23 ± 1.69 | 6.2 |
| [O ii] 5007 | 93.25 ± 3.09 | 83.59 ± 3.02 | 19.8 |
| C(II) | 0.375 | 0.000 |
| $F(\lambda)/F(H\beta)$ | 0.07 | 0.03 |
| EW(abs) (Å) | 2.15 | 1.65 |
### TABLE 3—Continued

#### G.

| LINE | \( F(\lambda)/F(H\beta) \) | \( R(\lambda)/R(H\beta) \) | \( \text{EW}^a \) |
|------|-----------------|-----------------|---------|
| \([\text{O} \text{ ii}] \lambda 3727\) | 219.22 ± 7.75 | 279.68 ± 10.95 | 21.9 |
| H9 (3835 Å) | ... | ... | ... |
| \([\text{Ne} \text{ ii}] \lambda 3868\) | 10.11 ± 3.28 | 12.39 ± 4.23 | 0.8 |
| He i \lambda 3889 + H8 | 10.00 ± 1.81 | 19.05 ± 5.07 | 1.1 |
| \([\text{Ne} \text{ ii}] \lambda 3968 + H7\) | 6.38 ± 1.16 | 13.99 ± 4.52 | 0.7 |
| H6 (4101 Å) | 22.77 ± 1.68 | 32.22 ± 3.63 | 2.6 |
| Hγ (4340 Å) | 38.21 ± 2.28 | 47.13 ± 3.86 | 4.3 |
| \([\text{O} \text{ ii}] \lambda 4363\) | 2.13 ± 0.67 | 2.29 ± 0.76 | 0.2 |
| He i \lambda 4471 | ... | ... | ... |
| H3 (4861 Å) | 100.00 ± 3.68 | 100.00 ± 4.27 | 13.5 |
| \([\text{O} \text{ ii}] \lambda 4959\) | 35.14 ± 2.36 | 32.92 ± 2.32 | 4.2 |
| \([\text{O} \text{ iii}] \lambda 5007\) | 101.15 ± 3.77 | 93.83 ± 3.67 | 12.0 |
| He i \lambda 5015 | ... | ... | ... |
| C(\(\beta\)) | ... | ... | ... |
| F(\(\text{H}β\))^a | ... | ... | ... |
| \(\text{EW(abs)}\) (Å) | ... | ... | ... |

#### H.

| LINE | \( F(\lambda)/F(H\beta) \) | \( R(\lambda)/R(H\beta) \) | \( \text{EW}^a \) |
|------|-----------------|-----------------|---------|
| \([\text{O} \text{ ii}] \lambda 3727\) | 178.39 ± 5.59 | 208.41 ± 6.99 | 29.9 |
| H12 (3750 Å) | ... | ... | ... |
| H11 (3771 Å) | ... | ... | ... |
| H10 (3798 Å) | ... | ... | ... |
| H9 (3835 Å) | ... | ... | ... |
| \([\text{Ne} \text{ ii}] \lambda 3868\) | 27.44 ± 2.24 | 31.29 ± 2.62 | 3.3 |
| He i \lambda 3889 + H8 | 10.65 ± 1.88 | 14.74 ± 3.21 | 1.8 |
| \([\text{Ne} \text{ ii}] \lambda 3968 + H7\) | 11.55 ± 1.44 | 15.63 ± 2.70 | 1.9 |
| H6 (4101 Å) | 19.65 ± 1.75 | 24.11 ± 2.76 | 3.4 |
| Hγ (4340 Å) | 42.38 ± 1.98 | 47.19 ± 2.75 | 7.5 |
| \([\text{O} \text{ ii}] \lambda 4363\) | 7.72 ± 1.63 | 8.14 ± 1.75 | 1.0 |
| He i \lambda 4471 | ... | ... | ... |
| He n 4686 | ... | ... | ... |
| H3 (4861 Å) | 100.00 ± 3.03 | 100.00 ± 3.32 | 21.9 |
| \([\text{O} \text{ ii}] \lambda 4959\) | 122.28 ± 3.56 | 118.55 ± 3.53 | 20.2 |
| \([\text{O} \text{ ii}] \lambda 5007\) | 371.77 ± 9.26 | 358.18 ± 9.13 | 63.1 |
| C(\(\beta\)) | ... | ... | ... |
| F(\(\text{H}β\))^a | ... | ... | ... |
| \(\text{EW(abs)}\) (Å) | ... | ... | ... |

#### I.

| LINE | \( F(\lambda)/F(H\beta) \) | \( R(\lambda)/R(H\beta) \) | \( \text{EW}^a \) |
|------|-----------------|-----------------|---------|
| \([\text{O} \text{ ii}] \lambda 3727\) | 54.36 ± 2.11 | 68.83 ± 2.76 | 71.9 |
| H11 (3771 Å) | 3.49 ± 0.99 | 6.51 ± 2.17 | 7.2 |
| H10 (3798 Å) | 4.97 ± 0.89 | 8.74 ± 2.03 | 8.6 |
| H9 (3835 Å) | 6.75 ± 1.21 | 10.67 ± 2.23 | 12.6 |
| \([\text{Ne} \text{ ii}] \lambda 3868\) | 8.45 ± 1.15 | 10.34 ± 1.43 | 14.3 |
| He i \lambda 3889 + H8 | 14.92 ± 1.90 | 20.15 ± 2.77 | 32.4 |
| \([\text{Ne} \text{ ii}] \lambda 3968 + H7\) | 15.61 ± 1.01 | 21.38 ± 1.89 | 24.2 |
| H6 (4101 Å) | 20.06 ± 1.03 | 25.75 ± 1.77 | 32.7 |
| Hγ (4340 Å) | 41.50 ± 1.25 | 47.48 ± 1.69 | 85.1 |
| \([\text{O} \text{ ii}] \lambda 4363\) | 4.04 ± 0.72 | 4.41 ± 0.80 | 9.0 |
| He i \lambda 4471 | 3.30 ± 0.59 | 3.52 ± 0.65 | 7.6 |
| He n 4686 | 6.19 ± 0.76 | 6.32 ± 0.79 | 16.4 |
| H3 (4861 Å) | 100.00 ± 2.28 | 100.00 ± 2.38 | 294.2 |
| \([\text{O} \text{ ii}] \lambda 4959\) | 44.81 ± 1.26 | 43.47 ± 1.24 | 145.0 |
| \([\text{O} \text{ iii}] \lambda 5007\) | 138.05 ± 2.96 | 132.73 ± 2.90 | 540.1 |
| C(\(\beta\)) | ... | ... | ... |
| F(\(\text{H}β\))^a | 0.350 | 0.205 |
| \(\text{EW(abs)}\) (Å) | 3.55 | 2.00 |
method of Pilyugin & Thuan (2005) does not work well in some cases. In particular, while the direct method gives abundances that are consistent and in a narrow range for the multiple H ii regions in J0747+5111 and J0956+2849, the spread of the abundances for the same H ii regions derived with the Pilyugin-Thuan relation is much larger (col. [3] of Table 5). The latter relation also gives a larger spread of oxygen abundances for the multiple H ii regions in J0113+0052, as compared with those obtained with the semiempirical method. The average difference between the empirical abundances derived with the Pilyugin-Thuan relation and those derived by the direct method is 0.13 dex, excluding the two H ii regions in J2238+1400. The empirical relation derived by Yin et al. (2007) appears to give abundances that are most consistent with those derived by the direct method (col. [5] of Table 5). The average difference between the empirical abundances derived with the relation by Yin et al. and those derived by the direct method is 0.07 dex, only slightly higher than that between the direct and semiempirical methods.

Thus, we conclude that for our low-metallicity objects the semiempirical method is more appropriate for oxygen abundance determination, because it gives more consistent abundances as compared with empirical methods. Therefore, for the H ii regions without detected [O iii] λ3700 emission, we adopt the oxygen abundances derived with the semiempirical method, and for the remaining H ii regions, those derived with the direct method.
### Ionic and Total Heavy-Element Abundances

#### A.

| Property                | J0113-0052 No. 1 | J0113-0052 No. 2 | J0113-0052 No. 4 | J0204–1009 No. 1 |
|-------------------------|-------------------|-------------------|-------------------|-------------------|
| $T_e$(O ii) (K)         | 19963 ± 1290      | 18766 ± 1011      | 18330 ± 1009      | 18417 ± 1032      |
| $T_e$(O ii) (K)         | 16278 ± 932       | 16014 ± 1255      | 15883 ± 1244      | 15911 ± 1274      |
| O$^+/H^+$ ($\times 10^5$) | 0.056 ± 0.008     | 0.139 ± 0.027     | 0.082 ± 0.016     | 0.125 ± 0.026     |
| O$^{++}/H^+$ ($\times 10^5$) | 0.118 ± 0.017     | 0.081 ± 0.010     | 0.140 ± 0.018     | 0.107 ± 0.015     |
| O/H ($\times 10^4$)      | 0.174 ± 0.019     | 0.220 ± 0.029     | 0.222 ± 0.025     | 0.232 ± 0.030     |
| 12 + log (O/H)           | 7.240 ± 0.048     | 7.343 ± 0.057     | 7.347 ± 0.048     | 7.365 ± 0.057     |
| Ne$^{++}/H^+$ ($\times 10^5$) | 0.235 ± 0.038     | ...               | 0.211 ± 0.030     | 0.331 ± 0.081     |
| ICF                     | 1.116             | ...               | 1.139             | 1.239             |
| log (Ne/O)               | −0.821 ± 0.104    | ...               | −0.966 ± 0.088    | −0.753 ± 0.188    |

#### B.

| Property                | J0204–1009 No. 2 | J0254+0035 | J0301–0052 | J0313+0010 |
|-------------------------|-------------------|------------|------------|------------|
| $T_e$(O ii) (K)         | 16534 ± 665      | 19285 ± 1013 | 17257 ± 1125 | 17839 ± 1028 |
| $T_e$(O ii) (K)         | 15148 ± 553      | 16146 ± 1269 | 15482 ± 913  | 15714 ± 1257  |
| O$^+/H^+$ ($\times 10^5$) | 0.123 ± 0.012     | 0.111 ± 0.022 | 0.049 ± 0.008 | 0.160 ± 0.034 |
| O$^{++}/H^+$ ($\times 10^5$) | 0.239 ± 0.024     | 0.079 ± 0.010 | 0.285 ± 0.045 | 0.114 ± 0.017 |
| O/H ($\times 10^4$)      | 0.361 ± 0.027     | 0.190 ± 0.024 | 0.333 ± 0.046 | 0.274 ± 0.037  |
| 12 + log (O/H)           | 7.558 ± 0.032     | 7.279 ± 0.055 | 7.524 ± 0.060 | 7.438 ± 0.059  |
| Ne$^{++}/H^+$ ($\times 10^5$) | 0.476 ± 0.050     | 0.132 ± 0.033 | 0.537 ± 0.093 | ...           |
| ICF                     | 1.125             | 1.271       | 1.048       | ...           |
| log (Ne/O)               | −0.829 ± 0.070    | −1.053 ± 0.214 | −0.774 ± 0.103 | ...           |

#### C.

| Property                | J0747+5111 No. 1 | J0747+5111 No. 2 | J0812+4836 | J0859+3923 |
|-------------------------|-------------------|-------------------|------------|------------|
| $T_e$(O ii) (K)         | 15816 ± 832      | 15694 ± 412       | 19634 ± 1013 | 16799 ± 1015 |
| $T_e$(O ii) (K)         | 14765 ± 708      | 14695 ± 352       | 16220 ± 1276 | 15276 ± 1221 |
| O$^+/H^+$ ($\times 10^5$) | 0.229 ± 0.030     | 0.155 ± 0.010     | 0.140 ± 0.027 | 0.237 ± 0.049 |
| O$^{++}/H^+$ ($\times 10^5$) | 0.345 ± 0.046     | 0.375 ± 0.025     | 0.049 ± 0.006 | 0.134 ± 0.020 |
| O$^{+++}/H^+$ ($\times 10^5$) | ...               | 0.562 ± 0.146     | ...         | ...         |
| O/H ($\times 10^4$)      | 0.574 ± 0.055     | 0.536 ± 0.027     | 0.189 ± 0.028 | 0.372 ± 0.054 |
| 12 + log (O/H)           | 7.759 ± 0.041     | 7.729 ± 0.022     | 7.276 ± 0.064 | 7.570 ± 0.063 |
| Ne$^{++}/H^+$ ($\times 10^5$) | 0.800 ± 0.114     | 0.778 ± 0.057     | 0.086 ± 0.025 | 0.324 ± 0.081 |
| ICF                     | 1.155             | 1.106            | 1.390       | 1.309       |
| log (Ne/O)               | −0.793 ± 0.098    | −0.795 ± 0.047    | −1.196 ± 0.354 | −0.943 ± 0.238 |

#### D.

| Property                | J0911+3135 | J0940+2935 | J0946+5452 | J0956+2849 No. 1 |
|-------------------------|------------|------------|------------|-------------------|
| $T_e$(O ii) (K)         | 16641 ± 2792 | 14889 ± 923 | 16192 ± 1722 | 19676 ± 685      |
| $T_e$(O ii) (K)         | 15200 ± 2315 | 14196 ± 806 | 14971 ± 1449 | 16228 ± 502      |
| O$^+/H^+$ ($\times 10^5$) | 0.243 ± 0.096 | 0.200 ± 0.032 | 0.190 ± 0.048 | 0.028 ± 0.002     |
| O$^{++}/H^+$ ($\times 10^5$) | 0.081 ± 0.034 | 0.250 ± 0.041 | 0.326 ± 0.087 | 0.108 ± 0.009     |
| O$^{+++}/H^+$ ($\times 10^5$) | ...           | ...         | ...         | 0.352 ± 0.047     |
| O/H ($\times 10^4$)      | 0.325 ± 0.101 | 0.451 ± 0.051 | 0.516 ± 0.099 | 0.139 ± 0.009     |
| 12 + log (O/H)           | 7.511 ± 0.136 | 7.654 ± 0.049 | 7.713 ± 0.083 | 7.144 ± 0.028     |
| Ne$^{++}/H^+$ ($\times 10^5$) | 0.248 ± 0.132 | 0.430 ± 0.077 | 0.674 ± 0.187 | 0.168 ± 0.014     |
| ICF                     | 1.398       | 1.180       | 1.139       | 1.075             |
| log (Ne/O)               | −0.972 ± 0.674 | −0.948 ± 0.128 | −0.827 ± 0.187 | −0.888 ± 0.053    |
However, it should be kept in mind that the oxygen abundances derived with the direct method for the two H ii regions of J2238+1400 may be underestimated.

Examination of Table 5 shows that our sample contains at least 10 H ii regions with oxygen abundance less than 7.5. However, no H ii region with an oxygen abundance 12 + \log (O/H) < 7.1 has been found. This supports the idea discussed, for example, in Thuan et al. (2005) that the matter from which dwarf emission-line galaxies formed was preenriched to the level 12 + \log (O/H) \gtrsim 7.0 [or ~2% of the abundance 12 + \log (O/H) = 8.65 of the Sun; Asplund et al. 2005]. Based on spectroscopic data from the Far Ultraviolet Spectroscopic Explorer, Thuan et al. (2005) showed that BCDs spanning a wide range in ionized-gas metallicity all have H i envelopes with about the same neutral-gas metallicity of ~7.0. This is also the metallicity found in Ly\alpha absorbers. Taken together, the available data suggest that there may have been previous enrichment of the primordial neutral gas to a common metallicity level, possibly by Population III stars.

**TABLE 4—Continued**

| Property                      | J0956+2849 No. 2 | J0956+2849 No. 6 | J2238+1400 No. 1 | J2238+1400 No. 2 |
|-------------------------------|------------------|------------------|------------------|------------------|
| $T_e$(O iii) (K)              | 19913 ± 2184     | 22170 ± 4668     | 20975 ± 268      | 18580 ± 260      |
| $T_e$(O ii) (K)               | 16270 ± 1583     | 16396 ± 2938     | 16393 ± 183      | 15961 ± 201      |
| [O$^+$]/H ($\times 10^5$)     | 0.049 ± 0.012    | 0.096 ± 0.042    | 0.021 ± 0.001    | 0.043 ± 0.002    |
| [O$^+$]/H ($\times 10^6$)     | 0.676 ± 0.019    | 0.067 ± 0.030    | 0.257 ± 0.008    | 0.318 ± 0.011    |
| $\Delta$[12 + \log (O/H)]j   | 0.072            | 0.022            | 0.064            | 0.056            |
| log (O/H)                     | 8.608            | 8.608            | 8.608            | 8.608            |
| ICF                           | 1.173            | 1.275            | 1.030            | 1.042            |
| log (Ne/O)                    | -0.936 ± 0.189   | -1.132 ± 0.464   | -0.758 ± 0.019   | -0.757 ± 0.022   |
| Fe$^{++}$/H ($4658 \AA$ ($\times 10^5$)) | ...       | ...              | 0.052 ± 0.008    | ...              |
| Fe$^{++}$/H ($4988 \AA$ ($\times 10^5$)) | ...       | ...              | 0.088 ± 0.011    | ...              |
| ICF                           | ...              | ...              | 18.255           | ...              |
| log (Fe/O) ($4658 \AA$)       | ...              | ...              | -1.475 ± 0.068   | ...              |
| log (Fe/O) ($4988 \AA$)       | ...              | ...              | -1.244 ± 0.055   | ...              |

**TABLE 5**  
OXYGEN ABUNDANCES DERIVED BY DIFFERENT METHODS

| SDSS NAME   | DIRECT$^a$ | Equation (2)$^b$ | Equation (3)$^c$ | Equation (4)$^d$ | SEMIEMPIRIC$^e$ |
|-------------|------------|-----------------|-----------------|-----------------|-----------------|
|             | (1)        | (2)             | (3)             | (4)             | (5)             | (6)             |
| SDSS J0113+0052 No. 1       | 7.24 ± 0.05 | 7.35            | 7.16            | 7.25             | 7.29 ± 0.04     |
| SDSS J0113+0052 No. 2       | ...         | 7.48            | 7.16            | 7.25             | 7.34 ± 0.06     |
| SDSS J0113+0052 No. 4       | ...         | 7.44            | 7.20            | 7.30             | 7.35 ± 0.05     |
| SDSS J0204−1009 No. 1       | ...         | 7.52            | 7.19            | 7.29             | 7.37 ± 0.06     |
| SDSS J0204−1009 No. 2       | 7.56 ± 0.03 | 7.60            | 7.38            | 7.47             | 7.55 ± 0.05     |
| SDSS J0254−0035             | ...         | 7.45            | 7.11            | 7.20             | 7.28 ± 0.05     |
| SDSS J0301−0052             | 7.52 ± 0.06 | 7.44            | 7.44            | 7.52             | 7.59 ± 0.06     |
| SDSS J0313−0010             | ...         | 7.58            | 7.25            | 7.35             | 7.44 ± 0.06     |
| SDSS J0747+5111 No. 1       | 7.75 ± 0.04 | 7.96            | 7.70            | 7.68             | 7.84 ± 0.06     |
| SDSS J0747+5111 No. 2       | 7.75 ± 0.02 | 7.78            | 7.62            | 7.64             | 7.78 ± 0.06     |
| SDSS J0812−4836             | ...         | 7.35            | 7.08            | 7.16             | 7.28 ± 0.06     |
| SDSS J0859+3923             | ...         | 7.69            | 7.36            | 7.45             | 7.57 ± 0.06     |
| SDSS J0911+3135             | 7.51 ± 0.14 | 7.46            | 7.24            | 7.34             | 7.46 ± 0.05     |
| SDSS J0940+2935             | 7.65 ± 0.05 | 7.65            | 7.35            | 7.45             | 7.53 ± 0.04     |
| SDSS J0946+5452             | 7.71 ± 0.08 | 7.88            | 7.64            | 7.66             | 7.80 ± 0.06     |
| SDSS J0956+2849 No. 1       | 7.14 ± 0.03 | 7.16            | 7.04            | 7.12             | 7.13 ± 0.04     |
| SDSS J0956+2849 No. 2       | 7.13 ± 0.07 | 7.26            | 7.00            | 7.03             | 7.10 ± 0.03     |
| SDSS J0956+2849 No. 6       | 7.21 ± 0.14 | 7.45            | 7.12            | 7.21             | 7.28 ± 0.04     |
| SDSS J2238+1400 No. 1       | 7.45 ± 0.01 | 7.51            | 7.66            | 7.66             | 7.78 ± 0.07     |
| SDSS J2238+1400 No. 2       | 7.56 ± 0.01 | 7.57            | 7.66            | 7.66             | 7.79 ± 0.07     |

$^a$ $T_e$(O iii) derived from the [O iii] $\lambda4363/\lambda4365$ (4959 + 5007) ratio.

$^b$ Abundance 12 + \log (O/H) derived using the formula of Pilyugin & Thuan (2005).

$^c$ Abundance 12 + \log (O/H) derived using the formula of Nagao et al. (2006).

$^d$ Abundance 12 + \log (O/H) derived using the formula of Yin et al. (2007).

$^e$ $\Delta$(12 + \log (O/H)) derived from eq. (1).

$^f$ Average difference between the empirical abundances and those derived by the direct method, excluding the two H ii regions in J2238+1400.

[1127]
4. CONCLUSIONS

We have presented spectroscopic observations with the 6.5 m MMT of a sample of 20 H II regions in 13 dwarf emission-line galaxies. These galaxies were selected from Data Release 5 of the Sloan Digital Sky Survey using the two criteria \([\text{O III}] 4959/\text{H} \beta \leq 1\) and \([\text{N II}] 6583/\text{H} \beta \leq 0.05\). These spectral properties select out extremely low metallicity galaxies, with oxygen abundances comparable to those of the most metal-deficient emission-line galaxies known, SBS 0335–052W and I Zw 18. The above criteria selected \(\sim100\) galaxies from the DR5, of which the 13 objects discussed here form a subsample.

We find that 10 H II regions have oxygen abundances \(12 + \log (\text{O/H})\) lower than 7.5. We confirm the very low oxygen abundance found previously in two galaxies, J0113+0052 (UGC 772) and J0956+2849 (DDO 68), by Izotov et al. (2006a) and Pustil’nik et al. (2005), respectively. In particular, we find that the oxygen abundance in the brightest H II region of J0956+2849 is 7.14 \pm 0.03, making this galaxy the second most metal-deficient emission-line galaxy known, after SBS 0335–052W, and ahead of I Zw 18 NW, I Zw 18 SE, and SBS 0335–052E. However, no H II region with an oxygen abundance \(12 + \log (\text{O/H}) < 7.1\) has been found. The existing data on extremely metal-deficient emission-line galaxies appear to suggest the existence of an oxygen abundance floor. This supports the idea that the matter from which dwarf emission-line galaxies formed was preenriched to a level of \(12 + \log (\text{O/H}) \sim 7.0\) (e.g., Thuan et al. 2005).

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