OXYGEN AND NITROGEN IN LEO A AND GR 8

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ABSTRACT

We present elemental abundances for multiple H II regions in Leo A and GR 8 obtained from long-slit optical spectroscopy of these two nearby low-luminosity dwarf irregular galaxies. As expected from their luminosities, and in agreement with previous observations, the derived oxygen abundances are extremely low in both galaxies. High signal-to-noise ratio (S/N) observations of a planetary nebula in Leo A yield 12 + log (O/H) = 7.30 ± 0.05; semi-empirical calculations of the oxygen abundance in four H II regions in Leo A indicate 12 + log (O/H) = 7.38 ± 0.10. These results confirm that Leo A has one of the lowest ISM metal abundances of known nearby galaxies. Based on results from two H II regions with high S/N measurements of the weak [O III] λ4363 line, the mean oxygen abundance of GR 8 is 12 + log (O/H) = 7.65 ± 0.06; using “empirical” and “semiempirical” methods, similar abundances are derived for six other GR 8 H II regions. Similar to previous results in other low-metallicity galaxies, the mean log (N/O) = −1.53 ± 0.09 for Leo A and −1.51 ± 0.07 for GR 8. There is no evidence of significant variations in either O/H or N/O in the H II regions. The metallicity-luminosity relation for nearby (D < 5 Mpc) dwarf irregular galaxies with measured oxygen abundances has a mean correlation of 12 + log (O/H) = 5.67M_B−0.151M_B, with a dispersion in oxygen about the relationship of σ = 0.21. These observations confirm that gas-rich, low-luminosity dwarf galaxies have extremely low elemental abundances in the ionized gas phase of their interstellar media. Although Leo A has one of the lowest metal abundances of known nearby galaxies, detection of tracers of an older stellar population (RR Lyrae variable stars, horizontal branch stars, and a well-populated red giant branch) indicate that it is not a newly formed galaxy, as has been proposed for some other similar low-metallicity star-forming galaxies.

Subject headings: galaxies: abundances — galaxies: dwarf — galaxies: evolution — galaxies: individual (Leo A, GR 8) — galaxies: irregular

1. INTRODUCTION

Understanding the evolution of dwarf galaxies, and in particular the chemical evolution of dwarf galaxies, has implications for our understanding of important processes in galaxy evolution, stellar nucleosynthesis, and the enrichment of the intergalactic medium. While a general relationship between galaxy luminosity and current metallicity has been well established for all galaxies, the fundamental underlying process (or processes) is still being debated. The star formation histories of dwarf galaxies are also far from being well understood. Is it possible for dwarf galaxies to form in the current epoch, or are the identities of all dwarf galaxies established at early times? Can massive star formation result in the instantaneous enrichment of the interstellar medium (ISM) of a dwarf galaxy, or is the bulk of the newly synthesized heavy elements released into a coronal gas phase that must cool before becoming incorporated into the other phases of the ISM and eventually the next generation of stars? By studying extreme dwarf irregular galaxies, i.e., the lowest luminosity, lowest metallicity, and lowest mass star-forming systems, we can extend the baseline for comparative studies of galaxies and test simple hypotheses of the formation of dwarf galaxies. This is particularly important for studying the chemical evolution of dwarf galaxies, as the impact of a given episode of star formation on a dwarf galaxy will be maximal for the lowest luminosity and metallicity systems. In principle, this could lead to the largest deviations from the luminosity-metallicity relationship, and this in turn may lead to a better understanding of that relationship.

Gas-phase abundances are one of the best measures of the intrinsic metallicity of low-mass galaxies. Here, we present new optical spectroscopy of Leo A and GR 8, two extremely low metallicity dwarf irregular galaxies in the Local Group (see van den Bergh 2000). Comparable nearby low-luminosity galaxies include DDO 210 (no usable H II regions; van Zee et al. 1997a), Sag DIG (empirical O/H only: Skillman et al. 1989b; Saviane et al. 2002; Lee et al. 2003a), and Peg DIG (faint H II regions with no detectable [O III] emission; Skillman et al. 1997). These (and other) observations indicate that it is often difficult to measure the gas-phase abundance of low-luminosity galaxies simply because there are few bright H II regions. Thus, accurate oxygen abundance measurements of multiple H II regions in Leo A and GR 8 have the potential to substantially further our understanding of chemical enrichment and mixing of enriched material in low-mass galaxies.

A summary of select global parameters of Leo A and GR 8 is presented in Table 1. At a distance of only 690 kpc, Leo A may be the nearest low-metallicity star-forming galaxy. Observations of the resolved stellar population in Leo A indicate an extremely
low metallicity (~3% of solar) for even the youngest stars (Tolstoy et al. 1998). However, accurate gas-phase metallicities have been difficult to obtain for this system, in part due to the low surface brightnesses of the faint \textsc{H}\textsc{ii} regions. The one exception is the bright planetary nebula (PN) in the northeastern quadrant of the galaxy. An oxygen abundance of ~2% of the solar value was derived from observations of this planetary nebula (Skillman et al. 1989a), but it was never certain if this value was representative of the galaxy as a whole, or just the gas ionized by the PN. We thus set out to observe several of the \textsc{H}\textsc{ii} regions in Leo A in order to obtain a more representative estimate of the gas-phase oxygen abundance.

GR 8 is slightly more luminous and metal-rich than Leo A, but it is also an extremely low metallicity system. Previous oxygen abundance measurements indicate that GR 8 has an oxygen abundance of approximately 5% of the solar value (Skillman et al. 1988; Moles et al. 1990). However, an unusually high N/O ratio and units of declination are degrees, arcminutes, and arcseconds. Previous oxygen abundance measurements indicate that GR 8 has an oxygen abundance of 12 + log(O/H) = 7.45 ± 0.07; Moles et al. 1990). However, it was never certain if this value was representative of the galaxy as a whole, or just the gas ionized by the PN. We thus set out to observe several of the \textsc{H}\textsc{ii} regions in Leo A and GR 8 in order to obtain a more representative estimate of the gas-phase oxygen abundance.

This paper is organized as follows. In § 2 we present spectroscopic observations of Leo A and GR 8. In § 3 we present the nebular abundance calculations and discuss direct and strong-line abundance calibrations. In § 4 we compare the abundance determinations of these two low-luminosity galaxies to values for other galaxies in the literature. In § 5 we demonstrate that, even though Leo A and GR 8 are among the lowest metallicity systems known, observations of resolved stars in these galaxies indicate that star formation in these galaxies has occurred throughout the age of the universe.

2. OBSERVATIONS

2.1. Optical Spectroscopy

Long-slit optical spectra of GR 8 and Leo A were obtained with the Double Spectrograph on the 5 m Palomar^2 telescope on the nights of 1999 February 18 and 19. The observations were obtained in long-slit mode; the 2′ long slit was set to an aperture 2′′ wide. Complete spectral coverage from 3600 to 7600 Å was obtained by using a 5500 Å dichroic to split the light to the two sides (blue and red) of the spectrograph. The red side was equipped with a 600 l/mm grating; the red side was equipped with a 300 l/mm grating. The effective spectral resolutions were well matched between the two sides, with a resolution of 5.0 Å (1.72 Å pixel^{-1}) on the blue side and 7.9 Å (2.47 Å pixel^{-1}) on the red side. Wavelength calibration was obtained by observations of arc lamps obtained before and after the galaxy observations. A hollow cathode (FeAr) lamp was used to calibrate the blue spectrum; a combination of He, Ne, and Ar lamps were used to calibrate the red spectra.

Stellar and \textsc{H}\textsc{ii} region coordinates were obtained from \textsc{H}\textsc{α} images kindly provided by E. Tolstoy^3 (Leo A) and J. J. Salzer^4 (GR 8). \textsc{H}\textsc{α} imaging of Leo A has previously been published by Strobel et al. (1991; but their field of view did not cover the westernmost \textsc{H}\textsc{ii} regions) and Hunter et al. (1993). \textsc{H}\textsc{α} imaging of GR 8 can also be found in Hodge et al. (1989) and references therein. Astrometric plate solutions for these images were calculated using the coordinates of bright stars in the Automated Plate Measuring (APM) catalog (Maddox et al. 1990), yielding positions accurate to within 0″. Optimum slit positions were determined so that the slit could cross several \textsc{H}\textsc{ii} regions during each observation while, at the same time, remaining close to the parallactic angle (Fig. 1). Due to the faintness of the \textsc{H}\textsc{ii} regions, all observations were conducted via blind offsets from nearby stars with typical offsets on the order of 30″–80″. The observations were broken into a series of 20 minute exposures; typical observations were sets of six or seven for \textsc{H}\textsc{ii} regions in Leo A and sets of two or three for \textsc{H}\textsc{ii} regions in GR 8 (Table 2).

As can be seen in Figure 1, in Leo A the three slit positions include a mixture of \textsc{H}\textsc{ii} region morphologies, while in GR 8 the four slit positions include all major \textsc{H}\textsc{ii} regions. Previous Keck 10 m observations of the two compact \textsc{H}\textsc{ii} regions in the northwestern quadrant of Leo A and the diffuse \textsc{H}\textsc{ii} region located north of slit A indicated that all of these \textsc{H}\textsc{ii} regions have weak or nondetectable [O \textsc{iii}] and [O \textsc{ii}] emission (H. A. Kobulnicky 1999, private communication). Thus, the present observations concentrate on diffuse \textsc{H}\textsc{ii} regions in Leo A, including the ring-like structure to the southwest (slit C), as well as observations of the planetary nebula (slit B). The \textsc{H}\textsc{ii} region observations also serendipitously included one background galaxy in each field. Observations of the compact \textsc{H}\textsc{ii} region south of slit C of Leo A were obtained on 1999 January 23 under very cloudy conditions; while these observations are not discussed here, since the target \textsc{H}\textsc{ii} region was only marginally detected (due to the clouds), this slit orientation included the background spiral galaxy at R.A. = 09^h 59^m 15.85^s, decl. = 30° 43′ 46.1″ (J2000.0), with z = 0.1467 ± 0.0002. Finally, slit C of GR 8 included the background spiral galaxy at R.A. = 12^h 58′ 39.95″, decl. = 14° 14′ 25.7″ (J2000.0), with z = 0.0642 ± 0.0002.

The spectra were reduced and analyzed with the IRAF^5 package. Spectral reduction followed standard practice, including bias

| Galaxy      | R.A. (J2000.0) | Decl. (J2000.0) | $D$ (Mpc) | $d_{25}$ (kpc) | $M_B$ | $(B-V)_0$ | $M_{H\alpha}$ (L$_\odot$) | 12 + log(O/H) | log(N/O) |
|-------------|----------------|-----------------|----------|---------------|-------|-----------|---------------------------|---------------|---------|
| Leo A       | 09 59 24.8     | 30 44 57        | 0.69     | 1.0           | -11.52| 0.26      | 1.3                       | 7.30 ± 0.05   | -1.53 ± 0.09 |
| GR 8        | 12 58 39.8     | 14 13 07        | 2.20     | 0.69          | -12.12| 0.38      | 0.76                      | 7.65 ± 0.06   | -1.51 ± 0.07 |

Notes.—All parameters except for 12 + log(O/H) and log(N/O) are from Dohn-Palmer et al. (1998) and references therein. The 12 + log(O/H) values are from direct abundance measurements (Table 5), and log(N/O) values are from semicircular measurements (Table 6). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

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2 Observations at the Palomar Observatory were made as part of a continuing cooperative agreement between Cornell University and the California Institute of Technology.

3 R-band and \textsc{H}\textsc{α} images of Leo A were obtained on the KPNO 2.1 m telescope as part of Hoessel & Saha’s KPNO 2.1 m Cepheid search key program (Hoessel et al. 1994).

4 R-band and \textsc{H}\textsc{α} images of GR 8 were obtained on the KPNO 0.9 m telescope as part of Salzer & Westpfahl’s survey of ionized gas in nearby galaxies (cf. Rhode et al. 1999).

5 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
subtraction, scattered light corrections, and flat fielding based on both twilight and dome flats. The two-dimensional images were rectified based on the arc lamp observations and the trace of stars at different positions along the slit. Multiple exposures were averaged together after the transformation. The sky background was removed from the two-dimensional images by fitting a low-order polynomial along each column of the spectra. One-dimensional spectra of the H\textsuperscript{ii} regions were then extracted from the images.

The one-dimensional spectra were corrected for atmospheric extinction and flux calibrated based on observations of standard stars from the list of Oke (1990); while the nights were not photometric, the relative line strengths should be robust. Representative spectra for Leo A and GR 8 are shown in Figures 2 and 3, respectively. Note the excellent agreement in the continuum level in the blue and red spectra, which confirms that

![Graphical representation of Leo A and GR 8 with slit positions marked. The pointings and orientations were optimized to include multiple H\textsuperscript{ii} regions while still maintaining a position angle close to the parallactic angle at the time of the observation.]

| Slit Position | R.A. (J2000.0) | Dec. (J2000.0) | P.A. (deg) | T\textsubscript{int} (s) |
|---------------|----------------|----------------|------------|------------------------|
| Leo A/A       | 09 59 31.8     | 30 44 37       | 92         | 7 x 1200               |
| Leo A/B       | 09 59 31.6     | 30 45 28       | 90         | 3 x 1200               |
| Leo A/C       | 09 59 17.2     | 30 44 07       | 73         | 6 x 1200               |
| GR 8/A        | 12 58 38.5     | 14 12 49       | 0          | 3 x 1200               |
| GR 8/B        | 12 58 40.1     | 14 13 01       | 45         | 2 x 1200               |
| GR 8/C        | 12 58 39.9     | 14 13 34       | 0          | 4 x 1200               |
| GR 8/D        | 12 58 40.4     | 14 12 56       | 45         | 2 x 1200               |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
The extraction regions were well matched on the two cameras. The H II regions in Leo A are generally low excitation, with weak [O III] lines and moderate-strength [O II] lines. The one exception is the spectrum of the planetary nebula (+089+031), which has strong [O III] and extremely weak [O II] lines. The weak [N II] and [S II] lines in these spectra clearly indicate that the H II regions in Leo A have low elemental abundances. The H II regions in GR 8 show higher excitation ([O III]/[O II]) than those in Leo A; the [O II] and [O III] lines are strong in all of the GR 8 H II regions. However, similar to Leo A, the weak [N II] and [S II] lines indicate that the H II regions in GR 8 have low elemental abundances.

2.2. Line Intensities

The emission-line strengths were measured in the one-dimensional spectra and then corrected for underlying Balmer absorption and reddening. Similar to the method described in van Zee et al. (1997a), the strengths of the Balmer emission lines were used to estimate the amount of reddening along the line of sight to each H II region using an iterative technique. The intrinsic Balmer line strengths were interpolated from the tabulated values of Hummer & Storey (1987) for case B recombination, assuming $N_e = 100 \text{ cm}^{-3}$ and $T_e = 15,000 \text{ K}$. Assuming a value of $R = A_V/E_B = 3.1$, the Galactic reddening law of Seaton (1979) as parameterized by Howarth (1983) was adopted to derive the reddening function normalized at H$\alpha$. For those H II regions with detected [O III] at 4363, the temperature was then recalculated from the corrected line strengths, and a new reddening coefficient was produced. An underlying Balmer absorption with an equivalent width of 2 Å was assumed in the few instances where the reddening coefficient was significantly different when derived from the observed line ratios of H$\alpha$/H$\beta$ and H$\gamma$/H$\beta$. The reddening coefficients, $c_{H\alpha}$, derived for each H II region are

Fig. 2.—Optical spectra of H II regions in Leo A. Most of the H II regions in Leo A are low excitation; the one high-excitation spectrum (+089+031) is a planetary nebula.

Fig. 3.—Optical spectra of H II regions in GR 8. The low-metallicity nature of GR 8 is clearly demonstrated by the weak [N II] and [S II] lines.
listed in Tables 3 and 4. These can be compared to the values of the foreground Galactic extinction derived by Schlegel et al. (1998) of $E(B-V) = 0.021$ for Leo A and 0.026 for GR 8, which correspond to $c(\text{H} \beta) = 0.03$ and 0.04, respectively. These very low values of foreground reddening are less than the errors on all of our reddening measurements. In several instances, the derived reddening coefficients were slightly negative (which is not physical), and in these cases zero reddening was assumed.

The measured intensities of emission lines for the H II regions in Leo A and GR 8 are tabulated in Tables 3 and 4, respectively. The first two columns in these tables give the ionic species and rest wavelength of the transition. The third and subsequent columns list the extinction-corrected line intensity relative to $\text{H} \beta$ for each detected transition. The $\text{H} \beta$ flux and equivalent width for each object are listed at the bottom of the tables; since the nights were nonphotometric, the $\text{H} \beta$ fluxes should only be taken as indicative values. The error associated with each relative line intensity was determined by taking into account the Poisson noise in the line, the error associated with the sensitivity function, the contributions of the Poisson noise in the continuum, read noise, sky noise, and flat fielding or flux calibration errors, the error in setting the continuum level, assumed to be at the 10% level, and the error in the reddening coefficient. Note that although the spectral coverage of the red camera allows for the measurement of the [O II] λ4363 line, these lines were not detected in any of the spectra due to a combination of intrinsic faintness and strong telluric emission. The spectral coverage of the red camera did not extend to the [S II] λ6716, 6731 lines.

### 3. Nebular Abundances

In this section we derive absolute and relative abundances from the emission-line spectra. In order to avoid confusion, we start with an overview of some nomenclature. In those cases where we have detected the temperature-sensitive [O II] λ4363 line, we can calculate abundances following the methods described in Osterbrock (1989), and following Dinerstein (1990) we refer to this as the “direct” method. In those cases where [O III] λ4363 is not observed, but [O II] λ5007 and [O II] λ3727 are observed, so-called empirical methods can be used to infer oxygen abundances (e.g., Pagel et al. 1979; McGaugh 1991), van Zee et al. (1997a) has introduced the “semiempirical” method, which uses the oxygen abundance and ionization parameter implied from photoionization models to infer a consistent electron temperature. That electron temperature can then be used to derive relative abundances with some degree of accuracy, since the relative abundances have a much lower sensitivity to the electron temperature than do the absolute abundances.

#### 3.1. Direct Abundance Measurements

Direct calculation of the oxygen abundance from the observed [O II] and [O III] emission-line strengths is possible if both the electron temperature ($T_e$) and electron density ($N_e$) are known. The procedure to calculate $T_e$ and $N_e$ is well described in Osterbrock (1989) and is not repeated here. A version of the FIVEL program of De Robertis et al. (1987) was used to compute $T_e$ and $N_e$ from the reddening-corrected [O III] and [S II] line ratios, respectively. In all cases, the observed [S II] line ratios indicated that the H II regions were within the low-density limit ($I(\lambda/6716)/I(\lambda/6731) > 1.35$). Thus, an $N_e$ of 100 cm$^{-3}$ was adopted for all H II regions. Unfortunately, calculating the electron temperature proved to be more difficult, since the weak [O III] λ4363 line was often contaminated by the nearby Hg $^6$4358 night-sky line. In Leo A, [O III] λ4363 was detected in only one nebula, which is almost certainly a planetary nebula. While a hint of the [O II] λ4363 line is visible in several of the GR 8 H II regions (Fig. 3), it was only detected solidly in two. Once the electron temperature of the O+ ionization zone is derived, the electron temperature of the O+ zone is estimated using the approximation given by Pagel et al. (1992). The emissivity coefficients for all of the detected emission lines were then calculated using the FIVEL code (De Robertis et al. 1987). For all atoms other than oxygen, the derivation of atomic abundances requires the use of ionization correction factors (ICFs)
TABLE 4
OPTICAL LINE INTENSITIES FOR H II REGIONS IN GR 8

| Ionic Species | Rest Wavelength | $[\lambda H(\text{H})]/[\text{H} ]$ | $[\lambda H(\text{H})]/[\text{H} ]$ | $[\lambda H(\text{H})]/[\text{H} ]$ | $[\lambda H(\text{H})]/[\text{H} ]$ | $[\lambda H(\text{H})]/[\text{H} ]$ | $[\lambda H(\text{H})]/[\text{H} ]$ |
|---------------|-----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| [O ii]......... | 3727            | 2.031 ± 0.084               | 2.581 ± 0.170               | 1.536 ± 0.068               | 2.305 ± 0.112               | 2.602 ± 0.109               | 2.362 ± 0.134               | 2.642 ± 0.106               | 2.160 ± 0.089               |
| [Ne iii]...... | 3869            | 0.157 ± 0.011               | ...                         | 0.228 ± 0.016               | ...                         | 0.169 ± 0.014               | ...                         | 0.093 ± 0.008               | 0.245 ± 0.013               |
| H\beta ........ | 4340            | 0.501 ± 0.019               | 0.467 ± 0.046               | 0.359 ± 0.018               | 0.381 ± 0.023               | 0.471 ± 0.020               | 0.566 ± 0.039               | 0.421 ± 0.016               | 0.427 ± 0.017               |
| [O iii]....... | 4363            | 0.045 ± 0.008               | ...                         | ...                         | ...                         | ...                         | ...                         | ...                        | 0.038 ± 0.008               |
| He i........... | 4471            | 0.023 ± 0.008               | ...                         | ...                         | ...                         | ...                         | ...                         | ...                        | ...                        |
| H\alpha ....... | 4861            | 1.000 ± 0.032               | 1.000 ± 0.061               | 1.000 ± 0.034               | 1.000 ± 0.040               | 1.000 ± 0.033               | 1.000 ± 0.049               | 1.000 ± 0.031               | 1.000 ± 0.032               |
| [O iv]........ | 4959            | 0.675 ± 0.022               | 0.613 ± 0.047               | 0.970 ± 0.034               | 0.419 ± 0.023               | 0.449 ± 0.018               | 0.537 ± 0.035               | 0.387 ± 0.014               | 0.619 ± 0.021               |
| [O iii]....... | 5007            | 2.103 ± 0.065               | 1.552 ± 0.084               | 2.951 ± 0.095               | 1.194 ± 0.046               | 1.444 ± 0.046               | 1.623 ± 0.072               | 1.131 ± 0.035               | 1.934 ± 0.059               |
| [S iv]........ | 6311            | 0.016 ± 0.003               | ...                         | 0.017 ± 0.003               | 0.023 ± 0.004               | ...                         | ...                         | 0.013 ± 0.002               | 0.014 ± 0.003               |
| H\alpha ....... | 6563            | 2.590 ± 0.113               | 2.786 ± 0.190               | 2.586 ± 0.118               | 2.502 ± 0.125               | 2.803 ± 0.125               | 2.872 ± 0.166               | 2.563 ± 0.110               | 2.712 ± 0.118               |
| [N ii]........ | 6584            | 0.078 ± 0.005               | 0.139 ± 0.013               | 0.076 ± 0.004               | 0.115 ± 0.007               | 0.084 ± 0.006               | 0.081 ± 0.008               | 0.109 ± 0.005               | 0.094 ± 0.005               |
| He i........... | 6678            | 0.021 ± 0.003               | ...                         | 0.019 ± 0.003               | 0.029 ± 0.004               | 0.026 ± 0.005               | ...                         | 0.021 ± 0.002               | 0.017 ± 0.003               |
| [S iv]........ | 6716            | 0.153 ± 0.008               | 0.298 ± 0.023               | 0.163 ± 0.008               | 0.274 ± 0.015               | 0.255 ± 0.013               | 0.173 ± 0.013               | 0.231 ± 0.011               | 0.165 ± 0.008               |
| [S iii]....... | 6731            | 0.102 ± 0.006               | 0.181 ± 0.016               | 0.113 ± 0.006               | 0.183 ± 0.011               | 0.165 ± 0.009               | 0.110 ± 0.010               | 0.163 ± 0.008               | 0.114 ± 0.006               |
| He i........... | 7065            | 0.021 ± 0.003               | ...                         | 0.015 ± 0.003               | ...                         | ...                         | ...                         | 0.017 ± 0.002               | 0.026 ± 0.003               |
| [Ar iv]....... | 7136            | 0.042 ± 0.004               | 0.043 ± 0.009               | 0.048 ± 0.004               | 0.045 ± 0.005               | 0.037 ± 0.007               | 0.042 ± 0.003               | 0.056 ± 0.004               |                   |

| \(\lambda([\text{H} ])/10^{15}\) | 0.00 ± 0.05 | 0.12 ± 0.07 | 0.00 ± 0.05 | 0.00 ± 0.06 | 0.15 ± 0.05 | 0.22 ± 0.06 | 0.00 ± 0.05 | 0.06 ± 0.04 |
| EW(\text{H} ) [\text{A}] | 2.87 | 1.57 | 4.95 | 2.12 | 3.73 | 0.78 | 7.46 | 5.98 |
| log([O ii] + [O iii]) / H\alpha | 0.682 ± 0.010 | 0.676 ± 0.018 | 0.737 ± 0.010 | 0.593 ± 0.014 | 0.653 ± 0.012 | 0.655 ± 0.015 | 0.619 ± 0.012 | 0.673 ± 0.010 |
| log([O iii] / [O ii]) | 0.136 ± 0.021 | -0.076 ± 0.035 | 0.407 ± 0.022 | -0.155 ± 0.025 | -0.138 ± 0.021 | -0.039 ± 0.029 | -0.241 ± 0.021 | 0.073 ± 0.021 |
| Slit | A | D | B | B | C | C | B | D |
to account for the fraction of each atomic species that is in an unobserved ionization state. To estimate the nitrogen abundance, we assume that N/O = N+/O+ (Peimbert & Costero 1969), which is probably accurate to ±20% for O/H < 25% solar (Garnett 1990). To estimate the neon abundance, we assume that Ne/O = Ne++/O+++ (Peimbert & Costero 1969). To determine the sulfur and argon abundances, we adopt an ICF from published H II region models to correct for the unobserved SIII and ArIV states (e.g., Thuan et al. 1995). In H II regions where S++/OIII was not detected, we do not calculate a sulfur abundance, as the ICF becomes too uncertain (Garnett 1989).

### 3.1.1. Leo A +089+031 (PN)

The highest surface brightness feature in the Hα image of Leo A is the bright planetary nebula in the northeastern part of the galaxy. Note that the Hα/Hβ ratio is close to the theoretical value, showing no evidence of the anomaly in the observations of Skillman et al. (1989a). The weak OIII λ4363 line is clearly detected in the high S/N spectrum of this region (Fig. 2). However, it should be noted that OIII λ3727 was not detected in this spectrum, and thus, in principle, the oxygen abundance derived from the OIII emission [12 + log (O/H) = 7.30 ± 0.05] is a lower limit (Table 5). However, an upper limit on the OIII λ3727 line, listed in Table 3, corresponds to an OIII/H abundance of less than 4% of the O++/H abundance, which is significantly smaller than the error on the total abundance. Thus, we treat this number as the best estimate of the oxygen abundance, noting that this result is similar to that derived previously for the PN (Skillman et al. 1989a) in this low-luminosity galaxy. Note that, unfortunately, it is not possible to measure the N/O, S/O, and Ar/O ratios directly in this object because the OIII λ3727 was not detected, which is required for the ionization correction schemes for these elements.

### 3.1.2. GR 8 −019−019 and +008−011

Two of the H II regions in GR 8 have solid OIII λ4363 detections. Following the procedure outlined above, the oxygen, nitrogen, neon, sulfur, and argon abundances were calculated for GR 8 −019−019 and +008−011. The electron temperatures derived from the [OIII] line ratios are listed in Table 5. The ion abundances relative to hydrogen were computed using the data listed in Table 4; if more than one line was observed for a given ion, the final ion abundances were calculated to be the weighted averages of the values for the different lines. The nebular abundances were then calculated based on the ion abundances and the ICFs, as described above. The derived 12 + log (O/H), log (N/O), log (Ne/O), log (S/O), and log (Ar/O) for these H II regions are listed in Table 6. The mean oxygen abundance for these two H II regions is 12 + log (O/H) = 7.65 ± 0.06, in excellent agreement with previous direct oxygen abundance measurements for GR 8 [12 + log (O/H) = 7.48 ± 0.14: 7.68, Skillman et al. 1988; Moles et al. 1990].

### 3.2. Strong-Line Oxygen Abundance Measurements

As first discussed by Pagel et al. (1979), the oxygen abundance of an H II region can be estimated from the strong-line ratio, R23 = ([OIII] + [OIII])/Hβ, since this parameter varies smoothly as a function of stellar effective temperature and oxygen abundance. Furthermore, while this ratio is double valued, the degeneracy of the R23 relation can be broken by examining the relative strengths of [NII] and [OIII]. If the nitrogen lines are extremely weak, as is the case for both Leo A and GR 8 (Figs. 2 and 3), only the lower oxygen abundance branch needs to be considered. However, an additional spread in the estimated oxygen abundance for a given R23 is introduced by the geometry of the H II region (e.g., Skillman 1989; McGaugh 1991); geometric effects can be
represented by the average ionization parameter, \( \bar{U} \), the ratio of ionizing photon density to particle density. This second parameter can be traced by the ratio of the abundance of atoms in different ionization states. Thus, both the sum of the oxygen lines (R_{23}) and the ratio of [O iii] to [O ii] need to be considered before an oxygen abundance can be determined from the strong lines. For example, the low-abundance branch of the model grid McGaugh (1991) generated for an initial mass function (IMF) with an upper mass limit of 60 \( M_{\odot} \) is shown in Figure 4. In this model (and other similar theoretical abundance calibrations; e.g., Kewley & Dopita 2002), the R_{23} value and [O iii]/[O ii] ratio are used to derive an empirical estimate of the oxygen abundance.

As illustrated in Figure 4, the H II regions in GR 8 cluster around an oxygen abundance of \( 12 + \log(O/H) = 7.8 \) in the McGaugh (1991) calibration, indicating that all of these H II regions have a similar oxygen abundance. However, there is a troubling discrepancy between the oxygen abundances derived from the McGaugh (1991) calibration and those obtained by direct calculation based on measured \( T_e \) and individual line strengths (e.g., Pilyugin 2000; Pérez-Montero & Díaz 2005; van Zee & Haynes 2006). In general, the McGaugh (1991) calibration appears to yield abundances that are systematically 0.1–0.2 dex higher than direct calculations; this discrepancy is also found for the H II regions in GR 8 [direct abundance calculations yield \( 12 + \log(O/H) = 7.65 \pm 0.06; \text{§ 3.1.2} \)].

An alternative empirical calibration scheme was proposed by Pilyugin (2000) based on H II regions where [O iii] \( \lambda 4363 \) has been detected (the \( p \)-method). The Pilyugin (2000) relations for \( 12 + \log(O/H) \) between 7.4 and 8.2 are shown in Figure 4. In the high-ionization regime \( (\bar{U} \sim 0.01–0.1) \), the shapes of the McGaugh curves and the Pilyugin relations are reasonably similar, but the Pilyugin relations give oxygen abundances \( -0.12–0.15 \) dex lower for the same \( R_{23} \) value. However, as discussed in Skillman et al. (2003) and van Zee & Haynes (2006), and as is also clear from Figure 4, the empirical relations of Pilyugin (2000) are only valid in this high-ionization regime, where there were sufficient \( T_e \) measurements in the literature to enable such a calibration. In the low-ionization regime, the regime of most of the H II regions in GR 8 and Leo A, the empirical relations of Pilyugin (2000) clearly deviate from results of photoionization models and physical intuition. Indeed, van Zee & Haynes (2006) demonstrate that the empirical abundances derived from the \( p \)-method have a clear systematic offset that correlates with ionization parameter.

Thus, the empirical oxygen abundances listed in Table 6 for the H II regions in Leo A and GR 8 are based on the McGaugh (1991) model grid, despite the inherent uncertainties and possible systematic errors. The empirical abundances of Pilyugin (2000) will not be discussed further.

While the GR 8 H II regions clearly outline a common locus in Figure 4, the H II regions in Leo A appear to be more widely

### Table 6

| Galaxy     | Offsets (East, North) | 12 + log(O/H) (Empirical) | 12 + log(O/H) (Semiempirical) | log(N/O) | log(Ne/O) | log(S/O) | log(Ar/O) |
|------------|-----------------------|---------------------------|-------------------------------|----------|-----------|----------|-----------|
| Leo A      | -101–052              | 7.48                      | 7.44 ± 0.10                   | -1.66 ± 0.18 | ... | ... | ... |
|            | -091–048              | 7.45                      | 7.36 ± 0.11                   | -1.45 ± 0.17 | ... | ... | ... |
|            | +099–018              | 7.70                      | 7.36 ± 0.10                   | -1.44 ± 0.12 | ... | ... | ... |
|            | +112–020              | 7.65                      | 7.38 ± 0.11                   | -1.56 ± 0.16 | ... | ... | ... |
| (Leo A)    | ...                   | 7.58                      | 7.38 ± 06                     | -1.53 ± 0.09 | ... | ... | ... |
| GR 8       | -019–019              | 7.78                      | 7.67 ± 0.10                   | -1.61 ± 0.15 | -0.85 ± 0.28 | -1.53 ± 0.23 | -2.27 ± 0.18 |
|            | -013–032              | 7.85                      | 7.69 ± 0.10                   | -1.37 ± 0.16 | ... | ... | ... |
|            | -012–022              | 7.77                      | 7.70 ± 0.10                   | -1.41 ± 0.16 | -0.83 ± 0.28 | -1.50 ± 0.23 | -2.24 ± 0.19 |
|            | -002–012              | 7.75                      | 7.64 ± 0.10                   | -1.40 ± 0.16 | ... | ... | ... |
|            | +001–008              | 7.83                      | 7.70 ± 0.10                   | -1.59 ± 0.16 | -0.64 ± 0.29 | ... | -2.24 ± 0.18 |
|            | +001+027              | 7.80                      | 7.66 ± 0.10                   | -1.57 ± 0.16 | ... | ... | ... |
|            | +004–006              | 7.83                      | 7.66 ± 0.10                   | -1.49 ± 0.14 | -0.82 ± 0.29 | -1.55 ± 0.20 | -2.17 ± 0.18 |
|            | +008–011              | 7.78                      | 7.67 ± 0.10                   | -1.46 ± 0.14 | -0.62 ± 0.28 | -1.56 ± 0.22 | -2.14 ± 0.18 |
| (GR 8)     | ...                   | 7.80                      | 7.67 ± 0.04                   | -1.51 ± 0.07 | -0.78 ± 0.17 | -1.52 ± 0.12 | -2.23 ± 0.08 |

**Notes:** Empirical oxygen abundances are derived from the strong-line diagnostics of McGaugh (1991) and have typical uncertainties of 0.1–0.2 dex. The abundance ratios and semiempirical oxygen abundances are calculated by adopting \( T_e(\text{ion}) = 15,000 ± 2500 \) K as a typical electron temperature for low-metallicity H II regions.

![Figure 4](image_url)
scattered in ionization parameter and, perhaps, oxygen abundance. Two of the observed H II regions have extremely low ionization parameters (Leo A +069–018 and +112–020); both are extremely diffuse H II regions located in the eastern half of the galaxy. For +069–018, [O III] λ5007 is barely detected, indicating that this H II region has an extremely low ionization parameter.

Similar low-excitation spectra were seen in the faint H II region of another Local Group galaxy, Peg DIG (Skillman et al. 1997). For Peg DIG, the morphology (compact) and spectrum of the H II region is consistent with an ionizing flux of a single B0 star. In Leo A, the Balmer line flux that is observed corresponds to ionization by B0–O9.5 zero-age main sequence (ZAMS) stars for each of the four H II regions. It is thus possible that the IMF is truncated (or incompletely sampled) or that these H II regions are evolved (aged). However, unlike Peg DIG, the low-excitation H II regions in Leo A are diffuse, amorphous structures; thus, it is also possible that the long-slit observations do not sample fully the different ionization zones of these H II regions. In particular, if the observations are missing a significant fraction of the O II ionization zone, these H II regions may be displaced significantly in Figure 4; with additional [O III], their location would shift significantly upward and slightly to the right, possibly moving them into the same metallicity regime as the other two H II regions.

Nonetheless, since the Balmer line fluxes of the H II regions in Leo A are consistent with radiation from lower mass, cooler O and B stars, we examine further the effect of aging in the abundance diagnostic diagram. In Figure 5 we place the low-metallicity models [12 + log (O/H) = 7.33] of Stasinska & Leitherer (1996) in the diagnostic grid of Figure 4. As can be seen in Figure 5, aging of H II regions introduces significant scatter in the abundance diagnostic diagram as both the ionization parameter and shape of the ionizing spectrum evolve (e.g., Stasinska & Leitherer 1996; Olofsson 1997). Thus, once one allows for a large range of ionizing spectra and ionization parameter, H II regions of a single oxygen abundance can populate a large range of positions in this diagnostic diagram. This is further emphasized in the bottom panel of Figure 5, where the positions of theoretical H II regions with the same oxygen abundance as the models in the top panel of the figure are shown with varying values of the electron temperature and ionization fraction.

While the results of Figure 5 may appear to suggest that strong-line ratios alone are not adequate to determine an empirical oxygen abundance, it is important to recall that the empirical scheme of McGaugh (1991) (and others) relies on a limited range of radiation field and a tight coupling between electron temperature and ionization fraction. Since both the spectrum of the ionizing radiation and the ionization parameter affect the ionization fraction, if the ionizing radiation is not held fixed (e.g., ZAM stars with a fully populated IMF), then there is a larger scatter for a given abundance. However, these parameters are likely a reasonable approximation for most high surface brightness H II regions, and thus the photoionization models do yield reasonable estimates of the oxygen abundance in most instances. Rather, the issue of varying the ionizing radiation only becomes significant for low-excitation H II regions. In fact, the tight correspondence between the isommetallicity contours and the location of the H II regions in GR 8 in Figure 4 suggests that log (O/32) ≥ −0.4 could serve as a guideline for a lower limit of the utility of the R23 calibration.

In any event, whether the H II regions in Leo A are evolved, were formed with a truncated IMF, or were incompletely sampled by the observations, it is likely that the model grid shown in Figure 4 is not optimal for their analysis and interpretation. Thus, we caution that it is premature to speculate on possible oxygen abundance variations in Leo A; in particular, the planetary nebula has an oxygen abundance similar to the estimated abundances of the other two (higher excitation) H II regions [12 + log (O/H) ~ 7.46]. In fact, while we cannot rule out oxygen abundance variations, all of the H II region spectra in Leo A are consistent with the oxygen abundance determined in the bright planetary nebula (see § 4.1).

3.3. Semiempirical Relative Abundance Measurements

3.3.1. H II Regions in Leo A

The [O III] λ4363 line was not detected in any of the other Leo A H II region spectra. Thus, we adopt a “typical” electron temperature of 15,000 ± 2500 K to enable analysis of nitrogen, neon, sulfur, and argon abundances. While we have no representative H II regions with measured T_e in this galaxy to use as a basis for this value, there is a general anticorrelation between electron temperature and oxygen abundance because low-metallicity gas is cooled less efficiently (e.g., McGaugh 1991). Thus, even...
with their low-ionization parameters, we expect the electron temperature to be reasonably high in these H regions. Adopting this electron temperature and using the emission-line strengths tabulated in Table 3, the oxygen, nitrogen, and argon abundances were calculated for each H region (Table 6). The derived mean oxygen abundance for these four H regions is $7.38 \pm 0.06 \pm 0.10$, where the first error is the weighted error in the mean and the second is the systematic uncertainty due to the assumed electron temperature. This value is in excellent agreement with both the planetary nebula abundance ($\S 3.1$) and the low end of those derived from semiempirical methods ($\S 3.2$). Furthermore, we emphasize that even if the derived oxygen abundances are only rough estimates, the relative elemental abundances are less sensitive to choice of electron temperature.

The mean $\log(N/O)$ for all four H regions in Leo A is $-1.53 \pm 0.09$; [Ar] was detected in only one H region (at a low S/N), with a value of $\log(\text{Ar/O}) = -2.25 \pm 0.25$. Finally, since [S] and [Ne] were not detected, S/O and Ne/O values were not measured for the Leo A H regions.

3.3.2. H Regions in GR 8

For six of the H regions observed in GR 8, the $[O\,\text{ii}]$ 4363 line was too weak to be detected or was contaminated by the nearby Hg 4358 night-sky line. In the absence of a direct measurement of the electron temperature, we chose to adopt a typical electron temperature of $15,000 \pm 2500$ K to enable analysis of nitrogen, neon, sulfur, and argon abundances. This electron temperature is similar to those determined in the GR 8 H regions $-019-019$ and $+008-011$, and is approximately what is necessary to reproduce the empirical oxygen abundances of these H regions (Table 6). The uncertainty associated with the adopted electron temperature includes the possibility that the spread of ionization parameters seen in Figure 4 corresponds to a spread in electron temperatures as well. Fortunately, the relative enrichment of nitrogen (and the other elements) is less sensitive to the electron temperature to be reasonably high in these H regions. Thus, we are forced to use our alternative method of comparing Ne, Ar, and S abundances to determine if the PN abundance is representative of the present-epoch ISM abundance. Unfortunately, the lack of [O] and [S] detection in the PN and the lack of [Ne] detections in the Leo A H regions prevents a direct comparison within the galaxy. However, if we compare the Leo A PN abundances to the average of the GR 8 H regions, we find that the Ne abundance is lower by $0.51 \pm 0.17$ dex and that Leo A H region abundance measurements appear to confirm those early results. However, it is possible that the agreement is coincidental. In this section, we examine the inferred properties of the PN to determine whether it is justifiable to use the abundances from the PN to represent the ISM abundance at the present epoch. We also compare the complete set of abundances of the PN to those of the Leo A and GR 8 H regions to search for systematic offsets in O, Ne, and Ar abundances.

There are two main concerns with using PN nebula abundances as an indicator of ISM abundances. First, if the PN is from a low-mass progenitor, and there has been significant chemical evolution since the formation of the original star, then the PN abundances reflect the lower abundances of a preenriched ISM (e.g., Richer & McCall 1995). In fact, with several PNs, one can establish the history of chemical enrichment (e.g., Dopita et al. 1997). Second, the evolution of the progenitor star may have significantly altered the abundances of certain species (typically, He, C, and N). If O is not significantly affected by the evolution of the progenitor star, then the PN O abundance serves as a lower limit to the ISM abundance; furthermore, if a main-sequence age can be estimated for the progenitor star, then the younger the age, the better the estimate of the ISM O abundance.

It is possible to estimate an age for a PN progenitor star by making estimates of its central star $T_{\text{eff}}$ and $L$. For example, Kniazev et al. (2005) have recently presented abundance measurements of a PN in the nearby low-metallicity galaxy Sextans B and find good agreement between the PN O abundance and two of the three H regions observed. For the PN central star, they estimate a Zanstra temperature using equation (1) of Kalber & Jacoby (1989) and a total luminosity using equation (9) of Zijlstra & Pottasch (1989; see also Gathier & Pottasch 1989). It is then possible to use the models of Vassiollis & Wood (1994) to estimate a progenitor mass and corresponding main-sequence age. Although this requires absolute photometry and our observations were obtained in nonphotometric conditions, the H$\alpha$ flux reported here is in good agreement with that of Magrini et al. (2003). Following this methodology for the Leo A PN, we derive values of $T_{\text{eff}} = 125,000$ K and log ($L/L_{\odot}$) = 3.6, resulting in a progenitor mass of $\sim 0.1 M_{\odot}$ and thus a correspondingly very old age. At face value, the agreement between the PN O abundance and those inferred from the H regions implies very little chemical evolution in Leo A over most of the lifetime of the universe.

However, recent interest in the evolution of very low metallicity stars present in the early universe has prompted new generations of stellar evolution models at low metallicities. One of the results of these calculations is that oxygen can be enhanced in the envelopes of extremely metal-poor AGB stars by efficient third dredge-up (Herwig 2004a, 2004b). Indeed, Kniazev et al. (2005) discovered a PN in Sextans A with a 0.5 dex oxygen overabundance with respect to its H regions. With an estimated age of $\sim 1.6$ Gyr, this PN might be expected to have an oxygen abundance equal to or slightly lower than the surrounding ISM, but that expectation is clearly ruled out. Based on this observation, Kniazev et al. (2005) argue that oxygen abundances from metal-poor planetary nebula should not be used as reliable ISM abundance indicators.

Thus, we are forced to use our alternative method of comparing Ne, Ar, and S abundances to determine if the PN abundance is representative of the present-epoch ISM abundance. Unfortunately, the lack of [O] and [S] detection in the PN and the lack of [Ne] detections in the Leo A H regions prevents a direct comparison within the galaxy. However, if we compare the Leo A PN abundances to the average of the GR 8 H regions, we find that the Ne abundance is lower by $0.51 \pm 0.17$ dex and that
the Ar abundance is lower by 0.20 ± 0.14 dex. These are in general agreement with the average offset in the semiempirical oxygen abundances of 0.29 dex.

In summary, it would appear that the PN in Leo A probably has a low-mass progenitor and therefore is less than ideal for making an estimate of the present-day ISM oxygen abundance. It is also clearly a very low metallicity PN and thus subject to oxygen enrichment through stellar evolutionary processes. Nonetheless, the abundances derived from the PN agree with those of the H ii regions and have the benefit of having [O iii] λ4363 detected. While a higher S/N spectrum that detects the lower ionization species and the near-IR [S ii] lines remains highly desirable, we adopt the PN abundance as representative of the ISM abundance in Leo A for the remainder of this paper.

4.2. Oxygen in Leo A and GR 8: Global Abundance Values and Chemical Mixing

Both Leo A [12 + log (O/H) = 7.30] and GR 8 [12 + log (O/H) = 7.65] have extremely low oxygen abundances,² on the order of 3%–5% of the solar value (using the old oxygen scale; Lambert 1978) or 5%–10% (using the new scale: Allende Prieto et al. 2001; Asplund et al. 2004; Meléndez 2004). Similar extremely low oxygen abundances are seen in other low-luminosity galaxies, such as UGCA 292 [12 + log (O/H) = 7.30; van Zee 2000], Sag DIG [12 + log (O/H) = 7.44; Skillman et al. 1989a; Saviane et al. 2002], and UGC 4483 [12 + log (O/H) = 7.56; Skillman et al. 1994; van Zee & Haynes 2006]; however, all are more metal-rich than I Zw 18 [12 + log (O/H) = 7.20; Searle & Sargent 1972; Skillman & Kennicutt 1993].

At these very low abundances, and given the lack of shear that would lead to more efficient mixing, it would be natural to expect significant chemical inhomogeneities in the ISM of these dwarf galaxies (Skillman et al. 1989a). Indeed, one of the motivations for this study was the anomalously high N/O ratio observed in one of the H ii regions in GR 8 by Moles et al. (1990). However, we find no evidence of N/O enrichment in any of the H ii regions observed. Furthermore, the derived oxygen abundances appear to be uniform in both galaxies (within the measurement errors), indicating that the enriched material is well mixed in both of these low-mass systems. In fact, within the accuracy of the measurements, we find no evidence of abundance variations in any of the elements observed in either of the two galaxies. Perusal of Tables 5 and 6 indicates that excursions from the average O/H and N/O of more than 0.1 and 0.15 dex (respectively) seem unlikely. Within errors, all of the abundance measurements appear to be consistent with uniform abundances.

In the past, there have been insufficient H ii region measurements to provide a robust test for abundance dispersions in low-luminosity dwarf irregular galaxies. However, with the availability of spectrographs on larger telescopes, the situation is improving (e.g., Miller 1996; Kobulnicky & Skillman 1996, 1997; Vilchez & Iglesias-Páramo 1998; Lee & Skillman 2004; van Zee & Haynes 2006; Lee et al. 2005a, 2005b). In addition, abundances for individual young stars are now becoming available (e.g., Venn et al. 2001, 2003; Kaufer et al. 2004). Interestingly, based on observations of only three H ii regions in Sextans B, Kniazev et al. (2005) have identified an oxygen abundance difference of ~0.3 dex. Nonetheless, at present, it appears that significant departures from a uniform ISM abundance are the exception and not the rule (e.g., NGC 5253; Kobulnicky et al. 1997). The lack of significant dispersion in abundance even at these extremely low metallicities supports the picture of efficient mixing of newly synthesized elements into the hot phase of the ISM before cooling back down to the observable warm phase of the ISM (e.g., Tenorio-Tagle 1996; Kobulnicky & Skillman 1997; Legrand et al. 2000).

4.3. The Metallicity-Luminosity Relationship

Leo A and GR 8 contribute significantly to the number of low-luminosity, low-metallicity galaxies known. Using the compilation of Karachentsev et al. (2004) to identify galaxies within the local 5 Mpc volume, we have compiled a list of all nearby low-luminosity galaxies with known oxygen abundances. The 5 Mpc volume was chosen to include several of the nearest dwarf-rich groups (e.g., Local Group, M81, Sculptor, and Centaurus). Of the 163 gas-rich galaxies (morphological type >0) in this volume, 144 have $M_B > -18$. Of these, only 50 have measured oxygen abundances in the literature (Table 7). Also included in Table 7 are the optical magnitudes and distances compiled by Karachentsev et al. (2004) and an indication of the methods used to calculate the distance (Karachentsev et al. 2004) and the oxygen and nitrogen abundances. The luminosity-metallicity relationship for the local volume is shown in Figure 6. In creating Figure 6, we have excluded Peg DIG because the oxygen abundance is based on measurements of only [O iii] and thus may not be consistent with the other abundance calibrations.

A weighted least-squares fit to the data yields

$$12 + \log (O/H) = 5.67M_B - 0.151M_B,$$

with an error in the slope and zero point of 0.014 and 0.21, respectively. This result is remarkably similar to that presented by Skillman et al. (1989a); the slight difference in the zero point (5.67 instead of 5.60) can easily be attributed to the slightly different distance scales used for the compilations. Similar results are also found by Richer & McCall (1995), van Zee et al. (1997b), Lee et al. (2003b), and van Zee & Haynes (2006).

Figure 6 gives the impression that the dispersion is larger for the empirically derived oxygen abundances relative to those derived via the direct method. Statistically, this is correct. For the 33 galaxies with direct oxygen abundances, the dispersion about the relationship is $\sigma = 0.17$ dex, and for the 16 galaxies with empirical oxygen abundances, the dispersion is $\sigma = 0.29$ dex. However, this could be misleading. Three of the galaxies in the compilation have empirical oxygen abundances based on relatively lower quality spectra (UGC 86, DDO 168, and NGC 5264). (Note that when [O iii] λ4363 is measured in a spectrum, it is, by definition, a higher quality spectrum.) When these three galaxies are removed from the empirical oxygen abundance sample, the dispersion decreases to $\sigma = 0.19$ dex—nearly identical to that of the direct abundance sample. This implies that the intrinsic scatter in the metallicity-luminosity relationship is at least of order the size of the uncertainty in the abundance measurements. Given their apparent uncertainties, we delete these three galaxies from subsequent analysis of the metallicity-luminosity relationship.

Richer & McCall (1995) found an increased scatter in the metallicity-luminosity relationship at lower luminosities, with an abrupt onset at $M_B = -15$. If we divide our data into a high-luminosity sample ($M_B \leq -15$) and a low-luminosity sample, for the 21 high-luminosity galaxies we calculate a dispersion of $\sigma = 0.19$ dex and for the 25 low-luminosity galaxies a dispersion of $\sigma = 0.16$ dex. Thus, we find no evidence for an increased dispersion at lower luminosities (see also Lee et al. 2003b).
TABLE 7
OXYGEN AND NITROGEN ABUNDANCES FOR LOW-LUMINOSITY GALAXIES (D < 5 Mpc)

| Galaxy     | Distance (Mpc) | D method | Mα   | 12 + log(O/H) | log(N/O) | (O/H) method | Reference |
|------------|----------------|----------|------|--------------|----------|----------------|-----------|
| G020       | 14.44          | h        | -14.15 | 8.75 ± 0.20  | -1.62 ± 0.20 | Empirical 8     | 23        |
| G020       | 13.10          | rgb      | -14.18 | 7.95 ± 0.03  | -1.60 ± 0.06 | Direct 4, 11    |
| G293       | 14.22          | rgb      | -14.43 | 8.00 ± 0.03  | -1.45 ± 0.08 | Direct 4        |
| G293       | 15.22          | rgb      | -14.48 | 7.65 ± 0.20  | ...        | Empirical 19    |
| IC 1613    | 11.74          | h        | -15.07 | 8.17 ± 0.04  | -1.50 ± 0.05 | Direct 27, 28, 29   |
| G043       | 13.58          | rgb      | -14.64 | 7.72 ± 0.03  | -1.41 ± 0.02 | Direct 25, 26    |
| G206       | 12.17          | rgb      | -14.04 | 7.67 ± 0.06  | -1.68 ± 0.13 | Direct 13, 22   |
| G104       | 14.44          | rgb      | -14.51 | 7.62 ± 0.05  | -1.13 ± 0.18 | Direct 8        |
| G020       | 11.03          | h        | -15.16 | 8.19 ± 0.06  | -1.37 ± 0.08 | Direct 8        |
| G043       | 9.32           | ceph     | -15.20 | 8.11 ± 0.05  | -1.60 ± 0.10 | Direct 2, 30     |
| G104       | 12.97          | rgb      | -15.28 | 7.50 ± 0.20  | ...        | Empirical 11    |
| G043       | 10.39          | rgb      | -15.52 | 7.73 ± 0.33  | -1.32 ± 0.20 | Direct 8, 31    |
| G104       | 12.20          | cep      | -15.55 | 8.19 ± 0.14  | ...        | Direct 31       |
| G025       | 12.73          | rgb      | -15.57 | 7.70 ± 0.10  | -1.27 ± 0.10 | Direct 25, 29    |
| G025       | 11.06          | rgb      | -15.63 | 7.92 ± 0.07  | -1.05 ± 0.12 | Direct 8        |
| G291       | 13.20          | rgb      | -15.88 | 8.30 ± 0.10  | -1.3 ± 0.1   | Empirical 8     |
| G291       | 12.60          | rgb      | -15.90 | 8.66 ± 0.20  | -0.57 ± 0.20 | Empirical 8     |
| G043       | 11.68          | rgb      | -16.00 | 7.91 ± 0.05  | ...        | Direct 32       |
| G043       | 2.75           | ceph     | -16.31 | 8.13 ± 0.10  | -1.58 ± 0.15 | Direct 38       |
| G043       | 12.21          | rgb      | -16.60 | 8.00 ± 0.03  | -1.46 ± 0.05 | Direct 27, 33   |
| G043       | 11.59          | rgb      | -16.53 | 8.10 ± 0.10  | -1.25 ± 0.03 | Direct 26       |
| G043       | 11.90          | rgb      | -16.60 | 8.10 ± 0.20  | ...        | Empirical 31     |
| G043       | 13.09          | rgb      | -16.70 | 7.92 ± 0.10  | ...        | Direct 31, 32   |
| G043       | 10.24          | rgb      | -17.19 | 8.25 ± 0.10  | -1.30 ± 0.15 | Direct 32, 34   |
| G043       | 10.84          | rgb      | -17.34 | 8.09 ± 0.07  | -1.52 ± 0.13 | Direct 24, 32   |
| G043       | 10.87          | rgb      | -17.38 | 8.15 ± 0.10  | -0.84 ± 0.10 | Direct 35       |
| G043       | 8.84           | t'        | -17.50 | 8.35 ± 0.10  | ...        | Empirical 36     |
| G043       | 13.50          | rgb      | -17.68 | 7.80 ± 0.20  | ...        | Empirical 19     |
| G043       | 8.95           | rgb      | -17.77 | 8.73 ± 0.04  | ...        | Empirical 36     |
| G043       | 10.61          | rgb      | -17.78 | 8.45 ± 0.20  | -1.52 ± 0.20 | Direct 37       |
| G043       | 0.90           | rgb      | -17.91 | 8.37 ± 0.22  | -1.30 ± 0.20 | Direct 38       |

Notes.—Optical parameters and distances are taken from the compilation of Karachentsev et al. (2004). References for oxygen and nitrogen abundances are indicated below (see References note).

References.—(1) This paper; (2) Skillman et al. 1989a; (3) van Zee 2000; (4) van Zee & Haynes 2006; (5) Skillman et al. 1997; (6) Skillman et al. 1989b; (7) Saviane et al. 2002; (8) Lee et al. 2003a; (9) Skillman et al. 1988; (10) Molaro et al. 1990; (11) Hidalgo-Gámez & Olofsson 2002; (12) Silva et al. 2005; (13) van Zee et al. 1997a; (14) van Zee et al. 1997b; (15) Skillman et al. 1994; (16) Rönnback & Bergvall 1995; (17) Guseva et al. 2000; (18) Kniavzev et al. 2005; (19) Hodge & Miller 1995; (20) Lee et al. 2005a; (21) Izotov et al. 1997; (22) Kennicutt & Skillman 2001; (23) Werl et al. 1983; (24) Miller & Hodge 1996; (25) Miller et al. 1996; (26) Skillman et al. 2003; (27) Slavinska et al. 1868; (28) Heydari-Malayeri et al. 1990; (29) Hidalgo-Gámez et al. 2002; (30) Hidalgo-Gámez et al. 2001a; (31) Lee et al. 2003b; (32) Masegosa et al. 1991; (33) Masegosa et al. 1994; (34) Kobulnicky & Skillman 1996; (35) Kobulnicky et al. 1997; (36) Zaritsky et al. 1994; (37) van Zee et al. 1998; (38) Russell & Dopita 1990.
O AND N IN LEO A AND GR 8

5. LOW O/H AS A YOUNG GALAXY HYPOTHESIS

Based on spectroscopic observations of H II regions in low-metallicity blue compact galaxies, Izotov & Thuan (1999) hypothesized that \( \text{galaxies with } 12 + \log (O/H) \leq 7.6 \) are now undergoing their first burst of star formation, and that they are therefore young, with ages not exceeding 40 Myr. This hypothesis is based on observations of nearly constant N/O and C/O ratios for their sample of galaxies. The reasoning holds that these galaxies have not had sufficient time for the intermediate-mass stars to deliver their time-delayed production of N and C. In Leo A, we have excellent evidence that \( 12 + \log (O/H) \leq 7.6 \), and the value of \( \log (N/O) = -1.53 \pm 0.09 \) is consistent with their remarkably narrow plateau of \( -1.60 \pm 0.02 \) (Fig. 7). Leo A thus provides an excellent test case for the young galaxy hypothesis.

There is abundant evidence that Leo A is not a young galaxy. The Hubble Space Telescope (HST) color-magnitude diagram presented by Tolstoy et al. (1998) shows very well populated red giant branch and red clumps, indicative of intermediate and old age stars. Furthermore, Dolphin et al. (2002) discovered eight RR Lyrae stars indicative of a \( \sim 10 \) Gyr old stellar population. Thus, although Leo A has not necessarily been forming stars at a constant rate over the lifetime of the universe (Tolstoy et al. 1998), it clearly has stars with a wide variety of ages.

Momany et al. (2005) come to a very similar conclusion in their study of Sag DIG. In fact, an ancient stellar population has been detected in all low-metallicity dwarf galaxies with sufficiently deep observations of their resolved stellar populations (Mateo 1998). The one possible exception has been I Zw 18; Izotov & Thuan (2004) claim an absence of any old stellar population based on new HST imaging. However, Momany et al. (2005) have reanalyzed the same HST observations and, based on photometry that reaches roughly 1 mag deeper than that of Izotov & Thuan (2004), find evidence consistent with the detection of a red giant branch tip corresponding to a distance of 15 Mpc. Although not noted, the extended red supergiant branch is also not consistent with an age of less than 40 Myr for all of the resolved stars. Thus, it would appear that, to date, there is no evidence in support of dwarf galaxies being formed for the first time in the current epoch.

6. CONCLUSIONS

We present the results of optical spectroscopy of four H II regions and one planetary nebula in Leo A and eight H II regions in GR 8. Observations of the planetary nebula in Leo A yield \( 12 + \log (O/H) = 7.30 \pm 0.05 \), in agreement with semiempirical calculations of the oxygen abundance in its H II regions yielding \( 12 + \log (O/H) = 7.38 \pm 0.10 \). These results confirm that Leo A has one of the lowest ISM metal abundances of known nearby galaxies. From two H II regions with [O III] \( \lambda 4363 \) detections, the mean oxygen abundance of GR 8 is \( 12 + \log (O/H) = 7.65 \pm 0.06 \), in agreement with "empirical" and "semiempirical" abundances for the six other H II regions. Similar to previous results in other low-metallicity galaxies, the mean log (N/O) = \(-1.53 \pm 0.09 \) for Leo A and \(-1.51 \pm 0.07 \) for GR 8. There is no evidence of significant variations in either O/H or N/O in the H II regions.

The metallicity-luminosity relation for nearby \((D < 5 \text{ Mpc})\) dwarf irregular galaxies with measured oxygen abundances has a mean correlation of \( 12 + \log (O/H) = 5.67M_B - 0.151M_B \),
with a dispersion in oxygen about the relationship of $\sigma = 0.21$. These observations confirm that gas-rich, low-luminosity galaxies have extremely low elemental abundances in the ionized gas phase of their interstellar media.

Although Leo A has one of the lowest metal abundances of known nearby galaxies, detection of tracers of an older stellar population (RR Lyrae variable stars, horizontal branch stars, and a well-populated red giant branch) indicate that it is not a newly formed galaxy, as has been proposed for some other similar low-metallicity star-forming galaxies (e.g., I Zw 18 and SBS 0335–052). Because Leo A has ISM abundances very similar to these systems, it could be taken as evidence against the hypothesis that these are young galaxies.

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