OXYGEN ABUNDANCE MEASUREMENTS OF SHIELD GALAXIES

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ABSTRACT

We have derived oxygen abundances for eight galaxies from the Survey for H i in Extremely Low-mass Dwarfs (SHIELD). The SHIELD survey is an ongoing study of very-low-mass galaxies, with $M_{\text{HI}}$ between $10^6 - 5$ and $10^7.5 M_\odot$, that were detected by the Arecibo Legacy Fast ALFA survey. Ha images from the WIYN 3.5 m telescope show that these eight SHIELD galaxies each possess one or two active star-forming regions, which were targeted with long-slit spectral observations using the Mayall 4 m telescope at Kitt Peak National Observatory. We obtained a direct measurement of the electron temperature by detection of the weak [O ii] $\lambda$4363 line in two of the H ii regions. Oxygen abundances for the other H ii regions were estimated using a strong-line method. When the SHIELD galaxies are plotted on a B-band L-Z diagram, they appear to suggest a slightly shallower slope to the relationship than normally seen. However, that offset is systematically reduced when the near-infrared luminosity is used instead. This indicates a different mass-to-light ratio for the galaxies in this sample and we suggest that this may be indicative of differing star formation histories in the lowest luminosity and surface brightness dwarf irregulars.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: star formation

1. INTRODUCTION

Chemical abundance studies of the interstellar medium in galaxies allow a glimpse into the star formation and chemical enrichment history of these galaxies. The chemical evolution of local-universe galaxies with very-low-metallicity gas is particularly important as these galaxies may be objects of cosmological significance. These metal-poor systems represent potential local-universe analogs to galaxies in the early universe and can provide a better understanding of the processes of star formation and gas enrichment in the early universe. Additionally, in order for very metal-poor galaxies to exist in the local universe, processes of either enriched gas outflow or pristine gas inflow are usually invoked, and thus these galaxies can provide important constraints for understanding the role of gas inflows and/or outflows on galaxian evolution.

Many authors have searched for very-metal-poor or “extremely metal-deficient” (XMD; $12 + \log(O/H) \lesssim 7.65$) galaxies in the local universe (e.g., Kniazev et al. 2003; Ugrumov et al. 2003; Melbourne et al. 2004; Lee et al. 2004; Izotov et al. 2006; Brown et al. 2008; Papaderos et al. 2008; Guseva et al. 2011; Berg et al. 2012; Izotov et al. 2012). Some authors have extended the search out to intermediate redshift (Kakazu et al. 2007; Hu et al. 2009; Xia et al. 2012). Most of these studies have used emission-line surveys, seeking metal-poor galaxies from large samples of strong emission-line sources. While these searches have led to a significant increase in the number of known metal-poor galaxies, there have been relatively few discovered in the range qualifying as XMD. The seeming dearth of XMD galaxies has raised the question of whether they are intrinsically rare objects in the local universe or if they exist in large numbers but are mostly missed because emission-line surveys are biased toward systems with bright, high surface brightness H ii regions (i.e., systems that have recently undergone a very strong starburst) and are relatively insensitive to isolated low-mass, relatively quiescent star-forming galaxies.

A promising alternative method for finding XMD galaxies has been to study very-low-luminosity dwarfs since there is a historically well-established correlation between metallicity and luminosity among low-redshift dwarf galaxies (Lequeux et al. 1979; Skillman et al. 1989a; Pilyugin 2001; Melbourne & Salzer 2002; Tremonti et al. 2004; Salzer et al. 2005a; Lee et al. 2006; van Zee & Haynes 2006). This method has already led to the discovery of several XMD galaxies (Skillman et al. 1989a, 1989b; van Zee 2000; Pustilnik et al. 2005, 2011; Berg et al. 2012; Skillman et al. 2013). Despite the fact that there should be large numbers of low-luminosity galaxies according to the galaxy luminosity function, searching for these systems is very difficult as they tend to be very low surface brightness and difficult to detect optically. However, blind H i surveys do not suffer optical selection biases and thus can uncover low-mass H i sources that potentially have low-surface brightness optical counterparts that may be missed in optical studies.

It is particularly important to identify and study low surface brightness XMD sources because our current understanding of XMD galaxies is derived almost exclusively from blue compact dwarf galaxies (BCDs). However, normal low-luminosity star-forming galaxies should outnumber BCDs by at least an order of magnitude and thus should be more representative of the XMD population. The Arecibo Dual Beam Survey (ADBS; Rosenberg & Schneider 2000) detected many low-mass sources with low-surface brightness dwarf irregular optical counterparts. Of these ADBS galaxies, 12 were selected for spectroscopic follow-up by Haurberg et al. (2013) to determine their chemical abundances. While none of these galaxies were found to be XMD galaxies, the sample was generally low-metallicity and showed that

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H I-surveys can efficiently uncover metal-poor and potential XMD galaxies. The more recent Arecibo Legacy Fast ALFA (ALFALFA) blind H I-survey (Giovanelli et al. 2005; Haynes et al. 2011) has uncovered hundreds of low-mass H I sources, many with very-low-surface brightness optical counterparts. The ALFALFA catalog provides a promising target list of potential XMD galaxies.

The use of H I catalogs to search for low-luminosity XMD systems has already proven successful with the recent discovery of the Leo P dwarf. Leo P was selected as a candidate XMD from the ALFALFA catalog due to its low derived H I mass (Giovanelli et al. 2013) and very low stellar mass inferred from optical follow-up imaging (Rhode et al. 2013). Optical spectroscopy revealed an extremely low oxygen abundance of 12 + log(O/H) = 7.17 ± 0.04 (Skillman et al. 2013), confirming it as an XMD galaxy and one of the most metal-poor galaxies known.

In this paper, we report the findings from a program dedicated to determining and analyzing the nebular abundances of a set of low-luminosity, low surface-brightness, low H I mass galaxies selected from the ALFALFA catalog as part of The Survey for H I in Extremely Low-Mass Dwarfs (SHIELD). SHIELD is a comprehensive multi-wavelength project targeting 12 of the lowest H I mass galaxies discovered in the ALFALFA survey that have a clear optical counterpart (Cannon et al. 2011). The optical and H I properties of these galaxies (N. Hauberg et al., in preparation) make them prime candidates as XMDs.

In Section 2 we describe the sample selection in more detail and include the derived photometric and H I properties. The spectroscopic observations are described in Section 3 and the reduction and measurement processes are outlined in Section 4. Section 5 describes how we determined abundances for the H II regions and the abundance results. The analysis and discussion of the results are in Section 6, and our conclusions are in Section 8.

2. SAMPLE SELECTION

The ALFALFA survey includes hundreds of low-H I-mass objects with \( M_{\text{HI}} < 10^8 M_\odot \) and additionally has provided the first robust sample of galaxies at the very-low-mass end of the H I mass function with \( M_{\text{HI}} < 10^7 M_\odot \) (Martin et al. 2010). Of these galaxies, 12 with \( 10^{6.5} M_\odot < M_{\text{HI}} < 10^{7.5} M_\odot \) were selected for the SHIELD project (Cannon et al. 2011) from a preliminary ALFALFA catalog. The galaxies selected for SHIELD were those with the lowest H I mass that had apparent optical counterparts in Sloan Digital Sky Survey (SDSS) images. These galaxies represent the lowest mass potentially star-forming galaxies that have formed a significant number of stars. Thus, following the traditional luminosity–metallicity (L-Z) trend (or mass–metallicity (M-Z) trend), the galaxies in this sample should be some of the most metal-poor star-forming galaxies in the local universe.

The SHIELD project encompasses a complex multi-wavelength data set including detailed H I gas mapping from multi-configuration Expanded Very Large Array\(^5\) observations (Cannon et al. 2011), broadband \( BV R \) and narrowband \( H \alpha \) imaging from the Wisconsin–Indiana–Yale–NOAO (WIYN) 3.5 m telescope at Kitt Peak National Observatory\(^6\) (KPO; N. Hauberg et al., in preparation), 3.6 and 4.5 \( \mu m \) imaging with the InfraRed Array Camera (IRAC) on the Spitzer Space Telescope,\(^7\) Hubble Space Telescope (HST)\(^8\) Imaging with the Wide Field Camera 3 using the F606W (\( \sim R \)) and F814W (\( \sim I \)) filters, and long-slit optical spectra with the Ritchey–Chretien Focus Spectrograph on the Mayall 4 m at KPO (this work).

Since these galaxies were selected from a blind H I survey, the sample does not suffer any bias toward high surface brightness objects as is often present in optical catalogs. The only optical qualification for galaxies in the SHIELD sample is that there be some evidence of a stellar counterpart associated with the H I source in SDSS images. Low H I mass sources in the ALFALFA catalog with no apparent optical counterpart have been studied by Adams et al. (2013) and are also of great interest as these may represent sources with extremely low surface brightness counterparts or starless dark matter halos.

Thumbnail images showing the WIYN \( R \)-band and H\( \alpha \) images for the 12 SHIELD galaxies are shown in Figure 1. The H\( \alpha \) regions identified from the displayed H\( \alpha \) images were targeted for the long-slit spectroscopic follow-up that is the subject of this paper. Figure 1 also shows the approximate slit locations overlaid on each galaxy. A comprehensive set of general and photometric quantities that describe the SHIELD galaxies is compiled in Table 1. Column 1 lists the galaxies in the SHIELD sample with the coordinates for each source listed in Columns 2 and 3. The distance, calculated using HST optical imaging to determine the tip of the red giant branch (McQuinn et al. 2014), is given in Column 4 and is used as the assumed distance for the derivation of all distance-dependent quantities. The absolute \( B \)-band magnitude, from the WIYN 3.5 m (N. Hauberg et al., in preparation) images is listed in Column 5; the listed uncertainty includes the error in both the distance and photometric error. The \( B - V \) color and \( B \)-band central surface brightness not corrected for inclination effects (\( \mu_{B,0,n} \)) are listed in Columns 6 and 7, also from N. Hauberg et al (in preparation). Columns 8 and 9 contain the 4.5 \( \mu m \) and 3.6 \( \mu m \) flux (in mJy) from the Spitzer observations, and Column 10 lists the stellar mass estimate derived from the Spitzer data (J. Cannon et al., in preparation). The stellar masses presented in this table were calculated using the method of Eskew et al. (2012). The H I masses given in Column 10 are from Cannon et al. (2011), but have been adjusted for the updated distances. Column 11 lists the star formation rate (SFR) calculated from the H\( \alpha \) images (N. Hauberg et al., in preparation) using the standard prescription of Kennicutt (1998) to convert from H\( \alpha \) luminosity to SFR.

The optical images from the WIYN 3.5 m telescope confirmed the optical counterparts of the SHIELD H I sources as low surface brightness dIrrs with blue colors (Table 1). The H\( \alpha \) imaging revealed that the star formation in these galaxies was generally confined to one or two knots of star formation that were targeted with the long-slit spectroscopic follow-up observations presented in this work. Two of the SHIELD

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\(^6\) The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatory.

\(^7\) This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA.

\(^8\) Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program 12658.
Figure 1. Thumbnail images of the SHIELD galaxies, oriented so that north points up and east points to the left. On the left of each column are short exposure \( R \)-band images and on the right are continuum-subtracted \( \text{H} \alpha \) images from the WIYN 3.5 m (N. Haurberg et al., in preparation). Each thumbnail is approximately \( 50'' \times 50'' \). The approximate position of the slit is indicated for the eight SHIELD galaxies for which we obtained usable spectra. Those objects with no slit image superimposed either had no visible \( \text{H} \alpha \) emission or did not produce usable spectra.

galaxies, AGC 749241 and AGC 748778, were not included in this spectroscopic follow-up as the \( \text{H} \alpha \) imaging revealed no star-forming nebulae. AGC 749241 had no detected \( \text{H} \alpha \) emission associated with it and AGC 748778 displayed only very weak, diffuse \( \text{H} \alpha \) emission (2.6\( \sigma \) above the sky) with no discrete \( \text{H} \text{II} \) regions (see Figure 1). Additionally, \( \text{H} \text{II} \) regions were detected in AGC 174585 and AGC 174605, but they were too faint to provide useful spectra so they are not included in the following analysis. Hence, we were able to derive useful abundance estimates for 8 of the 12 SHIELD galaxies.

3. OBSERVATIONS

3.1. Optical and Near-infrared Imaging

Optical imaging observations were performed using the Mini-Mosaic Imager on the WIYN 3.5 m telescope at KPNO over four nights: 2010 October 7–8 and 2011 March 29–30. The two fall nights (2010 October) had fantastic seeing (\( \approx 0''.5 \)) and were done under photometric conditions, while the two nights in the spring (2011 March) had degraded seeing (\( \approx 1''.2 \)) and were not photometric. Short-exposure post-calibration observations for the spring targets were performed in 2011 April. The broadband Johnson \( B, V, R \), and W036 narrowband \( \text{H} \alpha \) filters were used. The nominal field of view was \( 9.6 \times 9.6 \) across two chips and four amplifiers.

Exposure times for the broadband images in the fall were 900, 720, and 600 s for \( B, V, \) and \( R \) bands, respectively. The narrowband imaging was taken in sets of two long narrowband \( \text{H} \alpha \) exposures (900 s) with a short (180 s) \( R \)-broadband image between them. Since the conditions were less ideal in the spring, longer exposure times were used. The spring broadband data were taken with 1200, 720, and 900 s exposures (for \( B, V, \) and \( R \), respectively) and 1200 s narrowband \( \text{H} \alpha \) exposures with a 240 s \( R \)-band exposure in between.
The broadband observation times were sufficiently long to have detected any diffuse emission from the galaxies. These optical broadband images were analyzed with both isophotal fitting techniques as well as large aperture photometry as discussed in detail in N. Haurberg et al. (in preparation). While we cannot rule out that there may be an extraordinarily low surface brightness component that was not detected in our images, comparison with the subsequent HST imaging used for McQuinn et al. (2014) shows no indication of such; thus, we remain confident that our images were sufficient at detecting all of the optical emission in these galaxies.

The near-infrared (NIR) observations were performed with the IRAC camera on Spitzer on the 3.6 \( \mu m \) and 4.5 \( \mu m \) channels in 2011 and 2012. Each galaxy was imaged with an exposure time of 4000 s, allowing for sufficiently deep imaging of all but one of the galaxies. The NIR emission from AGC 749241 was too close to the background level to obtain a reliable flux measurement. This galaxy also had no H\alpha emission detected in the optical study of N. Haurberg et al. (in preparation) and thus was not included in the spectroscopic sample as well. Additionally, the 3.6 \( \mu m \) and 4.5 \( \mu m \) fluxes for AGC 731457 were not able to be accurately determined due to significant stellar contamination.

3.2. Spectral Observations

The spectral observations presented in this work were carried out using the Mayall 4 m telescope at KPNO with the Richey-Chertien Focus Spectrograph and T2KA imager over the course of five nights: 2012 April 17–19 and 2012 October 15–16. The KPC-10A grating (316 lines mm\(^{-1}\)) and WG-345 blocking filter were used. The grating is blazed at 4000 \( \AA \) giving a dispersion of 2.78 \( \AA \) pixel\(^{-1}\) and total coverage from 2850–8550 \( \AA \) on the CCD. All spectra were taken with a slit-width of 1.5’ and the slit extended 324’ along the spatial direction. This instrumental setup delivered an effective spectral resolution of \(~5.6 \) \( \AA \). Most of the data were obtained under clear sky conditions, and with seeing ranging from 0.8’ to 1.5’. Each source was observed with three different exposures of 1200 s which were later combined into a final image with a total exposure time of 3600 s.

Target sources were too dim to be seen with the acquisition cameras, so nearby bright stars were used for blind-offsets. Offsets were checked by using multiple stars in the field, and were successful in aligning sources within the slit. The slit was positioned as nearly along the parallactic angle as possible to avoid the effects of differential refraction through the atmosphere. Since the star-forming regions in these galaxies are relatively isolated, usually only the target source fell in the slit, but in two cases an additional emission nebula ended up in the slit as well.

We observed several spectrophotometric standard stars throughout each night, which were used to calibrate the flux scale for our spectra. The standards were selected from the lists of Oke & Gunn (1983) and Massey et al. (1988). Each night we additionally took images of HeNeAr spectral lamps for wavelength calibration, zero-length exposure bias images, internal quartz lamps for flat field calibration, and twilight sky images to correct for slit-width variations.

4. SPECTRAL REDUCTION AND MEASUREMENT

Spectral images were processed through the standard spectral reduction routines in IRAF.\(^9\) The bias level was determined from the overscan region in each image and the mean bias image was used to account for any two-dimensional structure in the bias. Median combined quartz lamp flats were used to account for pixel-to-pixel variations and twilight sky flats were used to create an illumination function correcting for variations in the slit width. The science images were then processed through the LACOS_SPEC cosmic ray rejection routine of van Dokkum (2001) and the resultant “cleaned” images were examined carefully by eye in comparison with the original image to ensure that emission line pixels were not rejected as cosmic rays.

HI region spectra were extracted using the APALL package in IRAF. Since the diffuse background emission was typically very weak, local sky regions that closely bracketed the emission line source were selected for night-sky subtraction. The wavelength scale was determined for each night using the solution

\(^9\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Figure 2. Spectra of the H\textsc{ii} regions in the SHEILD galaxies that produced usable spectra for this project. AGC 110482\textit{b} and AGC 182595 display a measurable [O\textsc{iii}] $\lambda$4363 emission line and the location of this line is marked with a small arrow.

derived from HeNeAr lamp spectra. The spectrophotometric standard stars were then used to create a sensitivity function that was applied to all the spectra. After the spectra were wavelength and flux calibrated, standard stars were compared to a catalog spectrum in order to check the calibration, which appeared good in all cases. As a last step, telluric absorption features were removed.

Figure 2 shows the final spectra analyzed in this paper. Several important strong lines were present in all the extracted spectra, most notably H\textalpha, H\textbeta, the [O\textsc{ii}] doublet, and the strong lines from the [O\textsc{iii}] triplet. The weak, temperature sensitive, [O\textsc{iii}] $\lambda$4363 line was discernible in two of the H\textsc{ii} regions, AGC 110482\textit{b} and AGC 182595. The other extracted spectra were good quality but did not contain an unambiguous detection of the [O\textsc{iii}] $\lambda$4363 line. In total, we extracted 11 unique H\textsc{ii} regions from eight galaxies. Both of the H\textsc{ii} regions with discernible [O\textsc{iii}] $\lambda$4363 are distinguished in Figure 2 with a small arrow over the region of that line. We have plotted a version showing the full dynamic range of the emission and another version that displays only a small range in flux.

Once emission lines were identified, they were measured using the splot routine in IRAF. This routine allows interactive setting of the continuum level at each line. To decide on the correct location for the continuum, we used an average of the local continuum on either side of the emission line and assumed a linear fit for the continuum under the emission line. We generally assumed that the continuum remained at a constant level under the emission line except for those cases where the lines were very broad or the slope of the continuum was steep enough to change significantly through the line. In the cases of a very broad line or particularly steep continuum slope we retained a linear fit but chose a sloping continuum level consistent with the continuum emission on either side of the line.

Since we are measuring emission from regions of relatively recent star formation it is expected that the permitted Balmer lines are affected by underlying absorption from hot main-sequence stars. The underlying absorption was accounted for by first assuming that the equivalent width of absorption is the same for all the Balmer lines and then using multiple Balmer emission-line ratios (H\textalpha/H\textbeta, H\textgamma/H\textbeta, and H\textdelta/H\textbeta) to simultaneously estimate the amount of underlying absorption and $c$(H\textbeta) (i.e., the absorption coefficient at H\textbeta). We were able to estimate the proper absorption correction by determining where the $c$(H\textbeta) coefficients calculated from each Balmer ratio
converged. This correction was applied to the hydrogen lines so
that the relative Balmer intensities could be used to accurately
determine the reddening for each H\(\text{II}\) region. In cases where
only one Balmer ratio was available, an average absorption
correction of 1.0 Å was used since most H\(\text{II}\) regions showed
some absorption that we felt needed to be accounted for. The
reddening was determined using the reddening law of Cardelli
et al. (1989) and using the temperature derived from the [O\(\text{III}\)]
lines when possible. If the [O\(\text{III}\)] \(\lambda4363\) line was not detected,
we assumed an electron temperature of 10,000 K. Since the
Balmer decrement was used to calculate the reddening, there
is no distinction between intrinsic and foreground reddening.
The reddening corrected flux measurements (relative to H\(\beta\))
for each line we measured are tabulated for each H\(\text{II}\) region in
Table 2, along with the assumed equivalent width of underlying
absorption (\(W_{\text{abs}}\)), \(c(\text{H}\beta)\), and the assumed \(T_e\) and \(n_e\). The
electron temperature \(T_e\) and electron density \(n_e\) of the nebula were
estimated using the [O\(\text{III}\)] \(\lambda4363/[\text{O}\(\text{III}\)] \(\lambda\lambda4959, 5007\)
and [S\(\text{II}\)] \(\lambda\lambda6716, 6731\) ratios, respectively. For cases where the
[O\(\text{III}\)] \(\lambda4363\) line was measured, the temperature and density
calculation were performed with the Emission Line Spectrum
Analyzer (ELSA) program (Johnson et al. 2006) described
more completely in the following section. In cases where
there was not a reliable measurement of [S\(\text{II}\)] \(\lambda\lambda6716, 6731\)
a default electron density of 100 cm\(^{-3}\) was assumed. This
density is consistent with what is commonly observed for H\(\text{II}\)
regions. The errors given on the line fluxes were calculated by
fully propagating the derived errors from the relevant quantities (e.g.,
rms of the continuum, rms scatter in flux calibration, etc.).

### Table 2

| Line Identification | AGC 112521 | AGC 110482a | AGC 110482b | AGC 111946 | AGC 11977 | AGC 111164 |
|---------------------|-----------|------------|------------|-----------|-----------|------------|
| (Å)                 | \(F_{\text{ion}}/H\beta\) | \(F_{\text{ion}}/H\beta\) | \(F_{\text{ion}}/H\beta\) | \(F_{\text{ion}}/H\beta\) | \(F_{\text{ion}}/H\beta\) | \(F_{\text{ion}}/H\beta\) |
| [O\(\text{II}\)] \(\lambda3728\) | 0.809 ± 0.075 | 3.062 ± 0.217 | 1.306 ± 0.091 | 3.137 ± 0.282 | 1.965 ± 0.250 | 1.417 ± 0.095 |
| [Ne\(\text{II}\)] \(\lambda3869\) | ... | 0.300 ± 0.031 | 0.555 ± 0.044 | ... | 1.161 ± 0.150 | ... |
| He\(\text{II}\) | ... | 0.077 ± 0.023 | ... | ... | 0.152 ± 0.015 | ... |
| [Ne\(\text{II}\)] \(\lambda3970+\text{He}\) | ... | ... | ... | ... | 0.133 ± 0.013 | ... |
| H\(\alpha\) | 0.260 ± 0.027 | 0.432 ± 0.034 | 0.252 ± 0.027 | 0.298 ± 0.045 | ... | 0.249 ± 0.018 |
| H\(\beta\) | 0.387 ± 0.032 | 0.433 ± 0.031 | 0.520 ± 0.034 | 0.508 ± 0.052 | ... | 0.436 ± 0.025 |
| [O\(\text{I}\)] \(\lambda4363\) | ... | ... | 0.109 ± 0.021 | ... | ... | 0.109 ± 0.021 |
| H\(\beta\) | 1.000 ± 0.060 | 1.000 ± 0.051 | 1.000 ± 0.045 | 1.000 ± 0.068 | 1.000 ± 0.164 | 1.000 ± 0.044 |
| [O\(\text{I}\)] \(\lambda4959\) | 0.527 ± 0.036 | 0.939 ± 0.049 | 1.640 ± 0.066 | 0.276 ± 0.034 | 0.857 ± 0.090 | 0.750 ± 0.035 |
| [O\(\text{I}\)] \(\lambda5007\) | 1.701 ± 0.092 | 2.708 ± 0.124 | 5.189 ± 0.189 | 0.838 ± 0.061 | 3.375 ± 0.270 | 2.339 ± 0.096 |
| He\(\text{II}\) \(\lambda5876\) | 0.113 ± 0.017 | ... | 0.051 ± 0.014 | ... | ... | 0.051 ± 0.014 |
| He\(\beta\) | 2.860 ± 0.225 | 2.860 ± 0.201 | 2.785 ± 0.169 | 2.860 ± 0.237 | 2.860 ± 0.510 | 2.860 ± 0.183 |
| [N\(\text{II}\)] \(\lambda6583\) | 0.015 ± 0.012 | 0.080 ± 0.014 | ... | 0.226 ± 0.029 | 0.176 ± 0.044 | 0.062 ± 0.008 |
| [S\(\text{II}\)] \(\lambda6717\) | 0.143 ± 0.020 | 0.249 ± 0.024 | 0.157 ± 0.016 | 0.227 ± 0.029 | ... | 0.128 ± 0.002 |
| [S\(\text{II}\)] \(\lambda6731\) | 0.131 ± 0.019 | 0.179 ± 0.019 | 0.124 ± 0.015 | 0.153 ± 0.024 | ... | 0.094 ± 0.010 |
| [Ar\(\text{II}\)] \(\lambda7136\) | ... | ... | 0.060 ± 0.012 | ... | ... | 0.060 ± 0.012 |

**Notes:** 
** indicates a default \(n_e\) of 100 cm\(^{-3}\) was assumed. \(T_e\) values marked with * were not calculated directly, but were assumed to be 10,000 K. \(\delta\) next to the
value for \(W_{\text{abs}}\) indicates that the Balmer line data was not sufficient to derive a value for \(W_{\text{abs}}\) so an average absorption correction of 1.0 Å was used instead.
Figure 3. Emission-line diagnostic diagram with each H\textsc{ii} region plotted separately. The black points are from the SHIELD galaxies in this work, those with outer circles are H\textsc{ii} regions for which we obtained a measurement of the temperature sensitive [O\textsc{iii}] λ4363 line. The green triangles are galaxies from the ADBS survey (Haurberg et al. 2013) and the gray points are a large sample of emission line sources from the KISS survey (e.g., Salzer et al. 2000; Melbourne & Salzer 2002). The solid line traces the star-forming galaxy models of Dopita & Evans (1986), the dashed line (Kauffmann et al. 2003) delineates the region of high excitation star-forming regions that displayed a measurable [O\textsc{iii}] λ4363 flux. The green triangles represent H\textsc{ii} regions in low H\textsc{i} mass dIrr galaxies from the ADBS, which is a similarly selected, but more luminous, sample (Haurberg et al. 2013), and the gray points are galaxies from the KPNO International Spectroscopic Survey (KISS; e.g., Salzer et al. 2000; Melbourne & Salzer 2002; Salzer et al. 2005a). The dashed line differentiates active galactic nuclei (AGNs) from star-forming nebulae (Kauffmann et al. 2003) and the solid line represents the locus of high excitation star-forming nebulae from the models of Dopita & Evans (1986), which increase smoothly in metallicity from the upper left to the lower right.

It is clear that H\textsc{ii} regions from the SHIELD galaxies lie below and to the left of the majority of the KISS sample and the theoretical high-excitation star-forming model curve. This is consistent with the manner in which these galaxies were selected and indicates that the observed H\textsc{ii} regions in the SHIELD galaxies are generally low-excitation systems. Emission-line surveys like KISS are much less likely to include these types of low-excitation systems because the key emission lines used for selection in those surveys need to be strong, high equivalent-width lines in order to be detected. The relatively low-excitation of these systems indicates that either the initial mass function (IMF) was not fully populated or the most massive stars formed in these regions have already evolved off the main sequence. Both possibilities are consistent with the expectation for very-low-luminosity galaxies as either would lead to reduced luminosity and surface brightness in comparison to the more well-studied low-metallicity BCDs.

Three of the H\textsc{ii} regions that we observed, (AGC 110482b, AGC 112521, and AGC 111977'), had such weak [N\textsc{ii}] λ6583 lines that we were unable to determine an accurate measurement of [N\textsc{ii}] λ6583/Hα. Thus, these three H\textsc{ii} regions have been plotted with arrows indicating that the measured [N\textsc{ii}] λ6583/Hα is an upper limit. The lack of distinguishable [N\textsc{ii}] λ6583 emission is consistent with these being among the lowest metallicity regions (see Table 3). The H\textsc{ii} regions from the SHIELD galaxies all occupy the region of the diagnostic diagram expected for low-metallicity star-forming systems. However, the H\textsc{ii} regions spread over a significant portion of the low-metallicity region while the derived abundances in Table 3 cover a quite narrow range. This is consistent with the finding of Haurberg et al. (2013) that there is significant scatter in the position of similar metallicity H\textsc{ii} regions on the diagnostic diagram.

In order to accurately determine the chemical abundances for emission line nebulae, it is preferable to have a direct measurement of the electron temperature $T_e$. In the wavelength range covered by our observations, the best way to calculate $T_e$ is from measuring the [O\textsc{iii}] λ4363 line. The [O\textsc{iii}] λ4363 and [O\textsc{iii}] λλ4959, 5007 lines are produced by electronic transitions from different energy levels in the O\textsc{ii} ion. The relative strengths of the lines thus depend on the population of the different energy levels, which is strongly dependent on the temperature of the electrons (and to a lesser extent, the electron density). [O\textsc{iii}] λ4363 is usually a very weak line that is often difficult to detect. We were able to detect this line in two of our H\textsc{ii} regions, although the detection in AGC 182595 is noisy and thus fairly uncertain. In order to calculate the nebular abundances for these H\textsc{ii} regions we used the ELSA program, which is described in detail in Johnson et al. (2006).

ELSA uses a five-level atom routine with ionization correction factors and a two-region ionization model to calculate abundances. The five-level atom calculations are based on the work of Henry et al. (1989) but include multiple updates and improvements (see Johnson et al. 2006). The [O\textsc{iii}] λ4363/ [O\textsc{iii}] λλ4959, 5007 ratio is used to calculate temperature in the high-ionization region and the [S\textsc{ii}] λλ6716, 6731 ratio is used to calculate the electron density (in the low-ionization region) using an iterative process similar to that described in Izotov et al. (2006). The low-ionization region temperature would ideally be calculated from the ratio [N\textsc{ii}] λ5755/[N\textsc{ii}] λλ6548, 6583; however, [N\textsc{ii}] λ5755 is a weak line that is usually not detectable in star-forming regions. Therefore, the temperature of the low-ionization region is estimated using $T_e$, $n_{e,\text{O}^{2+}}$ and following the method of Pagel et al. (1992). The ionization correction factors are determined from lines with similar ionization potentials and then used to account for the unseen ionization states. Many uncertainties, including those in line fluxes, reddening correction, plasma diagnostics, and ionic abundances are carried through the ELSA program and propagated properly into the final uncertainties in the abundances.

In cases where $T_e$ is not directly measurable, strong-line calibrations must be used. These methods rely on ratios of strong emission lines to estimate an electron temperature and thus metallicity. Specifically, most strong-line abundance methods...
are calibrated to a specific oxygen abundance; we will use oxygen abundance to be synonymous with metallicity for the remainder of this paper. While these methods are very useful, some caution must be employed as they are reliant on both theoretical models and empirical calibration to arrive at an abundance.

One of the most robust strong-line methods for determining oxygen abundance is that of McGaugh (1991; henceforth the McGaugh method). The McGaugh method uses several key abundance ratios:

\[
\begin{align*}
[R_23]: & \log([O \text{ iii}] \lambda 4959, 5007+[O \text{ ii}] \lambda 3727)/H\beta \\
[O_23]: & \log([O \text{ iii}] \lambda 4959, 5007+[O \text{ ii}] \lambda 3727) \\
[[N \text{ ii}]/[O \text{ ii}]]: & \log([N \text{ ii}] \lambda 6583/[O \text{ ii}] \lambda 3727).
\end{align*}
\]

Each measured H ii region is placed on a grid of model emission nebula using the R_{23} and O_{23} parameters as shown in Figure 4. Since the models are degenerate (i.e., there are two possible oxygen abundances that can produce the same values for R_{23} and O_{23}) the value of [N ii]/[O ii] is used to break the degeneracy between high- and low-metallicity “branches.” H ii regions are placed on the low-metallicity branch if [N ii]/[O ii] < −1.0 and the high-metallicity branch if [N ii]/[O ii] > −0.9. If −1.0 < [N ii]/[O ii] < −0.9, the H ii regions are deemed to be in the “turn-around region” where precise determination of the abundance can be tricky. However, all the H ii regions in this work had very low [N ii] λ6583/[O ii] λ3727 placing them securely on the low-metallicity branch.

The degeneracy of the McGaugh models can be troublesome and lead to significant uncertainty when the branch is not well determined. However, the method is ideal for use with a sample like ours where the branch is unambiguous. The McGaugh method is a particularly robust strong-line calibration because it uses the total flux in the strong oxygen lines (the R_{23} parameter) to determine oxygen abundance, and also accounts for different hardness of the ionizing spectra by incorporating the O_{23} parameter, which greatly improves its accuracy. The precise value of the oxygen abundance derived from the McGaugh method depends not only on the values of R_{23} and O_{23} but also on the specifics of which models were used to create the grids. We have used the models described in McGaugh (1991) where the highest mass star produced from the IMF is 60 \(M_\odot\). The exact value of the oxygen abundance was determined by using the position of each H ii region and interpolating between the model points to estimate abundance more precisely.

A final table of abundances as well as key line ratios is presented in Table 3. Column 1 lists the galaxy and specific H ii region where applicable. Columns 2—4 contain the line ratios used to calculate the abundance via the McGaugh method. Column 5 gives the oxygen abundance determined via the McGaugh method (in terms of log(O/H)+12) while Column 6 gives the oxygen abundance determined via the T_c method.

![Figure 4](image-url)
Figure 5. Comparison of derived McGaugh and $T_e$ abundances. Black points within circles are H$\,\text{II}$ regions from galaxies in the SHIELD sample with $T_e$ derived abundances. Red diamonds represent galaxies from Berg et al. (2012); filled diamonds are those used to calibrate the empirical offset between the two abundance methods, and open diamonds are either obvious outliers or outside of the abundance range that we considered for the offset calculation.

when available. Column 7 lists the error-weighted mean oxygen abundance from the individual H$\,\text{II}$ regions in AGC 110482 and AGC 749237. The abundance listed in bold is the assumed abundance for each galaxy. We do not give explicit errors on the McGaugh abundances, but will assume an error of 0.10 dex consistent with that estimated for the upper branch in McGaugh (1991).

The abundances derived via the McGaugh and $T_e$ methods are not in perfect agreement with each other, which is consistent with what has been reported by other authors. The inconsistency is often considered an effect of intrinsic errors in the strong-line calibration methods since they rely on indirect determinations of $T_e$. While the $T_e$ method provides a direct measurement of the electron temperature it is also subject to some level of uncertainty and bias as it has been shown to favor higher temperature regions in the case that there are temperature fluctuations in the nebula being observed (Peimbert 1967). Thus, it can be difficult to determine which method more accurately yields the “correct” abundance.

Some authors (e.g., Kewley & Ellison 2008; Zahid et al. 2012) have suggested that empirical calibrations should be made to correct for systematic differences between various abundance determination methods. With only two $T_e$ abundances, we are unable to gauge whether we see a systematic offset in our data. However, if we use the sample of low-luminosity Local Volume Legacy (LVL) galaxies analyzed in Berg et al. (2012), which we will use as a comparison set in Section 6, we can determine a reasonable empirical correction and use it to reconcile the two abundance methods. We have assumed the $T_e$ abundances listed in Berg et al. (2012) then calculated McGaugh abundances from the fluxes given in that paper, using the same method and models used for our galaxies. When the two different abundance calculation methods are compared we can see that there does appear to be a systematic offset.

A plot of abundance difference (calculated as the McGaugh abundance minus the $T_e$ abundance) versus $T_e$ abundance for the Berg et al. (2012) sample is shown in Figure 5. The red diamonds are H$\,\text{II}$ regions from the LVL galaxies in Berg et al. (2012) and the black points are the H$\,\text{II}$ regions with $T_e$ abundances from the SHIELD galaxies. Since it is unclear whether this difference is a constant offset or if it varies with metallicity we have only used H$\,\text{II}$ regions within the range of metallicities that is consistent with our sample (7.4 ≤ log(O/H)+12 ≤ 8.1) and exclude the obvious outlier when finding the mean offset; however, all the Berg et al. (2012) galaxies are included on the diagram. The points from the Berg et al. (2012) sample that were used to calculate the mean offset are plotted as filled red diamonds and those that were excluded are plotted as open red diamonds. The mean offset that we calculated was 0.076 dex, indicating that on average the McGaugh abundances were 0.076 dex higher than those calculated using the $T_e$ method. This offset will later be used as a “correction” when comparing our sample to others from the literature.

“Corrected” average abundances for the SHIELD galaxies are compiled in Table 4. When more than one H$\,\text{II}$ region was measured a weighted mean of the multiple H$\,\text{II}$ region abundances was used. Notice that the abundances for AGC 112521 and AGC 111164 qualify them both as XMD galaxies, which is consistent with them being the two lowest luminosity galaxies for which we obtained usable spectra.

6. ANALYSIS

There is a well-established relationship between the luminosity and metallicity of galaxies, where lower luminosity corresponds to lower metallicity, which has been shown to extend down to low-luminosity dIrrs (e.g., Lequeux et al. 1979; Skillman et al. 1989a; Pilyugin 2001; Melbourne & Salzer 2002;
Tremonti et al. 2004; Salzer et al. 2005b; Lee et al. 2006; van Zee & Haynes 2006; Berg et al. 2012; Haurberg et al. 2013; Skillman et al. 2013). The underlying cause of this relationship is not fully understood, but it is believed to trace a more fundamental M-Z relationship, where luminosity is representative of stellar mass. Studies of the L-Z relationship that use NIR luminosities (which are better correlated with stellar mass) show decreased scatter (e.g., Lee et al. 2004; Salzer et al. 2005b; Lee et al. 2006), implying that the M-Z relationship is the more fundamental physical relationship. The origin of the relationship, however, is still unclear but is a key to understanding the star formation histories and chemical evolution of dwarf galaxies.

Low-luminosity galaxies (e.g., $M_B \gtrsim -13$), which should also be the most metal-poor galaxies, are a relatively understudied population, and thus the nature of the L-Z and M-Z relationships in the very-low-metallicity regime remains indeterminate. The XMD galaxies that have been studied are mostly BCDs with very high star formation densities and relatively high SFRs compared to other dIrrs and are not believed to be representative of the majority of the very-low-mass dIrr population. A much more in-depth analysis of extremely low-metallicity systems, including low surface brightness dIrrs, is necessary to characterize these relationships. In Figure 6 we have plotted the SHIELD sample in L-Z diagrams using oxygen abundance (plotted as log(O/H)+12) to represent metallicity with $M_B$ on the luminosity axis. On Figures 6(b) and (c) we have also included comparison galaxies from the literature, described in more detail in the paragraph below. The SHIELD galaxies (black points) within an outer circle represent galaxies where a $T_e$ abundance was measured. The $T_e$ abundance in Table 3 has been adopted for AGC 110482b and the weighted mean of the three H ii regions in AGC 749237 has been adopted for that system.
Table 4

| Galaxy     | log(O/H)+12 | Note                               |
|------------|-------------|------------------------------------|
| AGC 112521 | 7.33 ± 0.10 | Corrected McGaugh, XMD galaxy      |
| AGC 110482 | 7.79 ± 0.07 | Weighted mean of a (corrected) and b (T_e) |
| AGC 111946 | 7.86 ± 0.10 | Corrected McGaugh                  |
| AGC 111977 | 7.80 ± 0.10 | Corrected McGaugh                  |
| AGC 111164 | 7.59 ± 0.10 | Corrected McGaugh, XMD galaxy      |
| AGC 182595 | 7.75 ± 0.13 | T_e abundance                       |
| AGC 731457 | 8.00 ± 0.10 | Corrected McGaugh                  |
| AGC 749237 | 7.95 ± 0.06 | Weighted mean of a, b, and c (all corrected) |

Notes. Corrected abundances for SHIELD galaxies (see text for correction). For AGC 110482 and AGC 749237, a weighted mean of the abundances for each H_II regions was used. Both AGC 112521 and AGC 111164 qualify as XMD galaxies.

Our comparison sample is described in Table 5. It has been broken into two pieces: the "primary" sample (plotted as filled symbols) is composed of only those galaxies with velocity-independent distances and T_e abundances from Lee et al. (2006), van Zee & Haynes (2006), and Berg et al. (2012). The "expanded" sample (plotted as open symbols) includes galaxies from Berg et al. (2012) and van Zee & Haynes (2006) with velocity-based distances or strong-line abundances as well as the ADBS sample from Haurberg et al. (2013). The ADBS sample is of particular interest as it was chosen in a similar manner to the SHIELD sample (e.g., ADBS is a blind H I survey) and thus has similar selection biases. The ADBS galaxies have velocity-derived distances and the abundances were derived using the same techniques presented in this work with a mix of both the T_e and McGaugh methods used to derive the abundances (see Haurberg et al. 2013 for details).

Figure 6(a) shows only the SHIELD galaxies, while Figures 6(b) and (c) include comparison samples from the literature. Figure 6(b) includes the primary and expanded comparison samples while Figure 6(c) shows only the primary comparison sample and the SHIELD galaxies. As indicated, the abundances from the SHIELD galaxies in Figure 6(c) have been corrected, meaning that the McGaugh abundances have been adjusted by the offset calculated in Section 5 in order to be consistent with the T_e scale.

The data shown in Figure 6 were fit using a bivariate linear regression method weighting the errors in both x and y. The method we used is based on that outlined in Akritas & Bershady (1996) and references therein. The fit to the primary comparison sample is shown on all three panels in Figure 6 as a solid line. The dash-dotted line shown in Figure 6(b) is the fit to all of the comparison sample plus the SHIELD galaxies and the dashed line on Figure 6(c) is the fit to the primary comparison sample plus the SHIELD galaxies (using the corrected abundances). The XMD outlier, UGC 5340 (M_B = -15.83, log(O/H)+12 = 7.20), was excluded from all of the fits. The fit that is shown with a dotted line on Figure 6(b) was obtained by fitting only the H_I-selected galaxies (SHIELD and ADBS samples) and is interesting since it is notably different from the other fits. The fit parameters and samples that were used to obtain them are described in Table 6. The reduced x^2 values listed in that table are calculated for each fit and compared to the sample plotted in the indicated figure; x^2_red was calculated assuming abundance to be the dependent variable. We chose not to include a fit to the SHIELD sample alone because it is a statistically small sample that covers a limited luminosity range, thus it produced significant uncertainties in the quality of the fit.

The various fits are in general agreement within the errors (with the exception of the "H_I-sample" fit, which is discussed in the following paragraph). In all cases, the inclusion of the SHIELD sample results in a more shallow slope, as could easily be predicted from inspection of Figure 6. The SHIELD galaxies clearly lie above literature galaxies of similar luminosity even when the corrected abundances are used. This is certainly an intriguing trend, but since we have a relatively small sample it is possible that this is due to intrinsic scatter in the relationship owing to differing mass-to-light ratios in the B-band or uncertainty in the measurement of both luminosity and abundance. However, it may represent something more significant such as a fundamental difference in the samples or a flattening of the L-Z relationship at low-luminosity.

The fit obtained from the H_I-selected samples (dotted line) is interesting as it is significantly different from the other fits. It has a slope that is substantially shallower than the average slope of the other fits, but provides the best fit to the SHIELD sample according the reduced x^2 test. This indicates that the sample selection process may be a contributing factor and may suggest underlying physical differences between samples selected from H_I surveys and those selected from optical catalogs or emission line-surveys. For consistency, we used the uncorrected abundances for Figure 6(b) and when fitting this H_I selected sample since the ADBS galaxies have a mix of strong-line and T_e derived abundances. When the corrected abundances are used (Figure 6(c)), the obvious discrepancy between the SHIELD sample and the fit from the comparison sample is reduced. However, even when the corrected abundances are used, all but one of the SHIELD galaxies lie above the fit line, indicating some level of systematic difference that is unlikely to be due solely to intrinsic scatter in the relationship. These issues are further discussed in Section 7.

Figure 7(a) shows another version of the L-Z diagram. This version uses the corrected abundances for the SHIELD galaxies, like Figure 6(c), but uses the NIR luminosity (4.5 μm band;...
Figure 7. Symbols and colors are the same as in Figure 6. The two fits shown are the fit to the primary comparison sample only (solid line) and fits to the sample including the SHIELD galaxies (dashed line).

Table 6
L-Z and M-Z Relationship Fit Parameters

| Sample                        | Slope     | Intercept | Symbol   | Goodness of Fit (χ²/red) |
|-------------------------------|-----------|-----------|----------|--------------------------|
| log(O/H)+12 vs. \(M_B\)       |           |           |          |                          |
| Primary Comparison            | −0.125 ± 0.008 | 6.01 ± 0.12 | Solid 6a | 8.54 13.23 12.42         |
| SHIELD+ Primary + Expanded    | −0.110 ± 0.006 | 6.24 ± 0.10 | Dot-Dash | ... ... ... 11.43        |
| HI-Selected (SHIELD + ADBS)   | −0.061 ± 0.012 | 7.00 ± 0.24 | Dotted   | ... 12.91 ...            |
| SHIELD† + Primary             | −0.113 ± 0.007 | 6.21 ± 0.11 | Dashed   | ... ... 11.52            |
| log(O/H)+12 vs. \(M_{4.5}\)   |           |           |          |                          |
| Primary Comparison            | −0.112 ± 0.007 | 5.94 ± 0.13 | Solid 7a | 10.07                    |
| SHIELD† + Primary             | −0.110 ± 0.008 | 5.98 ± 0.14 | Dashed   | 9.76                     |
| log(O/H)+12 vs. \(\log(M_*)\)|           |           |          |                          |
| Primary Comparison            | 0.29 ± 0.09  | 5.64 ± 0.71 | Solid    | 11.42                    |
| SHIELD† + Primary             | 0.30 ± 0.25  | 5.60 ± 1.86 | Dashed   | 11.57                    |

Notes. The results of various fits to the L-Z and M-Z relationships. † indicates that corrected McGaugh abundances were used for the SHIELD galaxies. The “goodness of fit” parameter is the reduced χ² value for the given fit when compared with the data plotted on the indicated panel or figure. See the text for details of the fitting process and different samples.

\(M_{4.5}\) instead of the \(B\)-band luminosity as the luminosity metric. Since we do not have reliable 4.5 μm luminosities for one of the SHIELD galaxies for which we measured an abundance (AGC 731457), this version of the L-Z relationship only features seven of the galaxies in the SHIELD sample. The SHIELD galaxies are more coincident with the comparison data in the NIR version of the L-Z diagram than they are in Figure 6. The fits derived from fitting the comparison sample (solid line) are nearly identical to those calculated when the SHIELD data are added to the set (dashed line). Despite the similarity of the fits, the majority of the SHIELD galaxies still appear above the fit line on this diagram, again suggesting the possible presence of a systematic difference from the comparison sample. The fit parameters for Figure 7 are given in Table 6.
In Figure 7(b), the M-Z relationship is shown. For the comparison sample, stellar mass was derived using the 4.5 \( \mu m \) flux and the \( m_{4.5} - K \) (K-band magnitude) color following Lee et al. (2006). The SHIELD IR observations do not include the K-band, so stellar masses for the SHIELD sample had to be derived in a different manner. We used the 3.6 and 4.5 \( \mu m \) magnitudes and followed the method of Eskew et al. (2012). Since there can be significant uncertainties associated with stellar mass calculations, we performed an independent derivation to check against the mass obtained with the method of Eskew et al. (2012). As a check, we used a straight-forward conversion of 3.6 \( \mu m \) luminosity into mass, assuming a mass-to-light ratio of 0.5 (McGaugh & Schombert 2013) and \( M_{3.6,3.6} = 3.24 \) (Oh et al. 2008). The difference between the mass derived using Eskew et al. (2012) and that derived from our “straight-forward” conversion of 3.6 \( \mu m \) luminosity was very small; the average difference was only 0.008 dex. While we cannot confirm that our mass estimates are fully consistent with the Lee et al. (2006) method used by Berg et al. (2012), we do feel confident that the stellar-mass estimates from Eskew et al. (2012) for the SHIELD galaxies given in this paper are consistent with other IR-based mass derivation methods. Due to the use of different stellar-mass calculation methods and the inherently difficult nature of determining stellar masses, we proceed with some caution concerning the results derived using these mass estimates.

Similar to the \( L_{\text{NIR}} - Z \) relationship, the SHIELD galaxies appear consistent with the literature samples in the M-Z relationship shown in Figure 7(b) and the inclusion of the SHIELD data has very little effect on the results of the fit. The fit parameters and \( \chi^2_{\text{red}} \) for the M-Z relationship are included in Table 6.

7. DISCUSSION

Various physical mechanisms have been suggested to explain the origin of the M-Z relationship for dIrrs, but the ejection of enriched gas from low-mass galaxies via supernova and stellar winds is one of the most commonly invoked (e.g., Tremonti et al. 2006). The SHIELD IR observations do not include the K-band, so stellar masses for the SHIELD sample had to be derived in a different manner. We used the 3.6 and 4.5 \( \mu m \) magnitudes and followed the method of Eskew et al. (2012). Since there can be significant uncertainties associated with stellar mass calculations, we performed an independent derivation to check against the mass obtained with the method of Eskew et al. (2012). As a check, we used a straight-forward conversion of 3.6 \( \mu m \) luminosity into mass, assuming a mass-to-light ratio of 0.5 (McGaugh & Schombert 2013) and \( M_{3.6,3.6} = 3.24 \) (Oh et al. 2008). The difference between the mass derived using Eskew et al. (2012) and that derived from our “straight-forward” conversion of 3.6 \( \mu m \) luminosity was very small; the average difference was only 0.008 dex. While we cannot confirm that our mass estimates are fully consistent with the Lee et al. (2006) method used by Berg et al. (2012), we do feel confident that the stellar-mass estimates from Eskew et al. (2012) for the SHIELD galaxies given in this paper are consistent with other IR-based mass derivation methods. Due to the use of different stellar-mass calculation methods and the inherently difficult nature of determining stellar masses, we proceed with some caution concerning the results derived using these mass estimates.

Similar to the \( L_{\text{NIR}} - Z \) relationship, the SHIELD galaxies appear consistent with the literature samples in the M-Z relationship shown in Figure 7(b) and the inclusion of the SHIELD data has very little effect on the results of the fit. The fit parameters and \( \chi^2_{\text{red}} \) for the M-Z relationship are included in Table 6.

As an alternative to bursty star formation histories for isolated dIrrs, Gavilán et al. (2013) suggest that many observational features of isolated dIrrs can be explained without invoking winds or large-scale outflows, but instead rely on continuous infall or cooling of primordial gas and continuous star formation throughout the lifetime of the galaxy. This model provides interesting implications in the context of the results presented in this paper.

In the scenario proposed by Gavilán et al. (2013), the galaxies are modeled as a single region and the SFR is controlled only by the amount of gas available and an assumed star formation efficiency. This model does not allow for “bursts” of rapid star formation but instead produces a smooth, continuous (though not constant) star formation history for the galaxy. Their results suggest that with moderate to low star formation efficiencies this continuous type of evolution can plausibly reproduce the observed dIrr trends and the L-Z relationship. The Gavilán et al. (2013) models imply that the observed dispersion in abundance seen at a given \( B \)-band luminosity is a result of differing star formation histories, owing to different star formation efficiencies and/or different gas-collapse timescales. This is intriguing in the context of the work we have presented here, because it suggests the offset of the SHIELD sample seen in the \( B \)-band L-Z relationship may be indicative of different global star formation histories compared to optically selected samples. Since the SHIELD sample has specifically been chosen to represent some of the lowest-luminosity and lowest-surface-brightness galaxies, it is not unreasonable to assume that our selection may be biased to select galaxies with different star formation histories than those selected from optical catalogs.

Tassis et al. (2008) produced similar results to Gavilán et al. (2013), suggesting that galaxian outflow winds are not necessary to reproduce the observed L-Z trends and attribute the inefficient star formation in low-mass systems to inefficient gas cooling (i.e., longer collapse timescales) because of the more extended neutral gas distributions often observed in lower mass systems. Since there are only a limited number of low-mass dIrr samples where high-quality optical and H I data currently exist, it is very difficult to analyze whether this scenario is observationally consistent. However, we suggest that this is an idea worthy of further investigation. Further studies with the SHIELD project, and similar projects focusing on low-mass ALFALFA sources, should lead to a better understanding of the nature of the gas distributions in low-mass systems and the role that gas dynamics play in their chemical evolution.

The SHIELD galaxies all seem to be “offset” above the fit line from the comparison sample in the \( B \)-band L-Z relationship. When the “corrected” abundances are used, the offset, with respect to the fit from the comparison sample, is reduced, yet all but one of the SHIELD galaxies still appears above the fit line. This offset becomes even less pronounced when \( M_B \) is replaced with \( M_{4.5} \) and disappears when stellar mass (\( M_* \)) is used instead. This indicates that, on average, the mass-to-(\( B \)-band) light ratio for the SHIELD galaxies differs from the comparison sample. This is plausibly consistent with our previous suggestion, that our selection criteria may have biased our sample toward galaxies with a certain star formation history. However, the general trend simply suggests that the SHIELD galaxies are too massive for their \( B \)-band luminosity. This may arise because at least some portion of the SHIELD galaxies do not approach the quasi-continuous star formation history that has been suggested for more massive dIrrs by van Zee (2001). A stochastic star formation history that is similar to that suggested...
in van Zee (2001) but not as continuous (owing to the lower mass of the system) could cause the $B$-band luminosity to be less reflective of the current stellar mass in these galaxies.

Only 8 of the 12 SHIELD galaxies are included in this analysis and only 7 of those in the $M_*_Z$ relationship; thus, we must consider that there are possible biases introduced by not including the entire sample. Two of the galaxies from the SHIELD sample for which we were not able to obtain usable spectral data—AGC 748778 and AGC 749241—are the two lowest $B$-band luminosity galaxies in the sample and contained no detectable H$_\alpha$ emission. A fundamental question underlying the physical nature of the $L-Z$ and $M-Z$ relationships is whether the trends continue through this very-low-luminosity (and presumably low-mass) range, and further investigation of this issue is certainly warranted. However our results for this more moderately low-luminosity range would remain unaffected but we caution against extrapolation of $L-Z$ or $M-Z$ trends to lower luminosity ranges.

The other two SHIELD galaxies for which we did not obtain usable spectra are AGC 174585 and AGC 174605, which do not appear to be in any way anomalous. The relationships between $B$-band luminosity, stellar mass, and SFR in these systems are all consistent with others in the sample. AGC 174585 and AGC 174605 are among the lowest luminosity (as well as lowest $M_*$ and SFR) systems, but have clear knots of H\alpha emission (almost certainly associated with star formation) that can be seen in Figure 1. It seems that the distance to these systems resulted in them being too dim to produce useful spectra with the setup used for this work. These galaxies are within the luminosity range investigated in this paper and thus their inclusion could certainly affect some of the apparent trends discussed here. However, there is no reason to believe that their exclusion has introduced a bias into our analysis since their global properties appear consistent with others and their exclusion is simply due to distance. The final omitted galaxy is AGC 731457, for which we do not have a stellar mass estimate. This galaxy was observed in NIR by J. Cannon et al. (in preparation), but a reliable flux was not able to be determined due to stellar contamination.

Again, the reason for exclusion is not related to a fundamental property of the galaxy, meaning that there is no reason to believe a bias was introduced. While we do not believe that the absence of several SHIELD galaxies from our analysis has introduced significant biases in our results, given the relatively small number of well-studied dIrr systems in this luminosity and mass range the inclusion of more data is certainly necessary and will lead to a better understanding of our results.

The results presented in this paper do not necessarily clarify any of the issues associated with the chemical evolution of dIrrs, but they do suggest that varied star formation histories need to be considered along with the effects of enriched gas outflows in order to adequately explain the observed trends. Additionally, our data suggest that while the $M-Z$ relationship may be more fundamental, understanding the relationship of the mass-to-light ratio could reveal details of the star formation and chemical evolution in these systems. This sample is just a first step in beginning to fill in the very-low-luminosity range of dwarf irregulars.

8. CONCLUSIONS

We have used long-slit spectra from the Mayall 4m telescope at KPNO to determine the oxygen abundances for 8 of the 12 SHIELD galaxies. For two galaxies, we were able to measure the temperature sensitive $[\text{O\emissiontype{III}}]\lambda4363$ line and thus directly determine the electron temperature for at least one H\textsc{ii} region. We calculated abundances for the other six galaxies using the strong-line method of McGaugh (1991). We calculated an empirical correction to the McGaugh abundance scale using the dIrr sample from Berg et al. (2012), along with the two H\textsc{ii} regions for which we detected $[\text{O\emissiontype{III}}]\lambda4363$, allowing us to put our McGaugh abundances on a consistent scale with those that have a directly determined $T_e$. The galaxies in our sample have well-constrained distances ($HST$; McQuinn et al. 2014), optical luminosities ($WIYN$ $3.5\,m\,BVR$; N. Hauberg et al., in preparation), and NIR luminosities ($Spitzer$ 3.6 and 4.5$\mu$m; J. Cannon et al., in preparation). We compared the $L-Z$ and $M-Z$ relationships derived from our results with a substantial comparison set from the literature that also have well-determined abundances, distances, and optical and NIR luminosities (Lee et al. 2006; van Zee & Haynes 2006; Berg et al. 2012, and references therein). We additionally included dIrr galaxies with well-determined abundances that were selected from the ADBS blind H\textsc{ii}-survey (Hauberg et al. 2013) in our comparison sample. While more luminous than our data set, the latter sample is particularly interesting because the method of selection was very similar to that used for the SHIELD data set.

When the $L-Z$ relationship was examined using the $B$-band luminosity the SHIELD galaxies appear offset from the comparison sample, but that offset disappears when derived stellar mass is used instead. We suggest that this may indicate that a range of star formation histories and chemical evolution scenarios for dwarf irregulars should be considered. The possible effects that such scenarios may have on the $L-Z$ and $M-Z$ relationships warrant further examination and exploration. While the $M-Z$ relationship may be more well constrained, the $L-Z$ relationship may prove observationally important for disentangling the origins of that relationship. A larger and more comprehensive sample is needed and a more exhaustive comparison between an array of models and multiple observational parameters should be done before any model is too heavily favored. Such a comparison is beyond the scope of this work.

In this work, we identified two new XMD galaxies in the local universe, AGC 112521 and AGC 111164, and showed that blind H\textsc{ii}-surveys like ALFALFA are effective in providing candidate XMD dIrrs (e.g., Skillman et al. 2013). As follow-up studies of the low-H\textsc{ii} mass sources from the ALFALFA survey continue, a larger sample of low-luminosity gas-rich dIrrs will become available and allow us to start to unravel some of the puzzles concerning the chemical evolution of dwarf galaxies. Additionally, current work on resolved stellar populations in the SHIELD galaxies and the Leo P dwarf promise to further illuminate the star formation histories in these very-low-mass galaxies and lead to a deeper understanding of galaxian chemical evolution.

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