Large-scale Environmental Dependence of the Abundance Ratio of Nitrogen to Oxygen in Blue, Star-forming Galaxies Fainter than $L^*$

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Abstract
We examine how the cosmic environment affects the chemical evolution of galaxies in the universe by comparing the N/O ratio of dwarf galaxies in voids with that of dwarf galaxies in denser regions. Ratios of the forbidden [O III] and [S II] transitions provide estimates of a region’s electron temperature and number density. We estimate the abundances of oxygen and nitrogen using these temperature and density estimates and the emission-line fluxes [O II] $\lambda 3727$, [O III] $\lambda\lambda 4959, 5007$, and [N II] $\lambda\lambda 6548, 6584$ with the direct $T_e$ method. Using spectroscopic observations from the Sloan Digital Sky Survey Data Release 7, we are able to estimate the N/O ratio in 42 void dwarf galaxies and 89 dwarf galaxies in denser regions. The N/O ratio for void dwarfs ($M_r > -17$) is slightly lower ($\sim$12%) than for dwarf galaxies in denser regions. We also estimate the nitrogen and oxygen abundances of 2050 void galaxies and 3883 galaxies in denser regions with $M_r > -20$. These somewhat brighter galaxies (but still fainter than $L_*$) also display similar minor shifts in the N/O ratio. The shifts in the average and median element abundance values in all absolute magnitude bins studied are in the same direction, suggesting that the large-scale environment may influence the chemical evolution of galaxies. We discuss possible causes of such a large-scale environmental dependence of the chemical evolution of galaxies, including retarded star formation and a higher ratio of dark matter halo mass to stellar mass in void galaxies.

Key words: galaxies: abundances – galaxies: active – galaxies: dwarf – galaxies: evolution – galaxies: ISM

Supporting material: machine-readable tables

1. Introduction
The measurement of the abundance of heavier elements relative to hydrogen in a galaxy can indicate the galaxy’s evolutionary stage. As stars evolve, they slowly convert hydrogen into heavier elements, increasing the ratio of the heavier elements (oxygen, nitrogen, etc.) to hydrogen. The ratio of oxygen to hydrogen is often used to determine the chemical evolution of a galaxy because oxygen is the most abundant element in the universe (after hydrogen and helium) and because oxygen has very strong emission lines in the optical regime that cover a range of ionization states (Kewley & Dopita 2002).

It is instructive to also study the relative abundances of the heavy elements in a galaxy. Rather than indicating the amount of hydrogen converted to heavier elements, the ratio of two heavy elements can reveal important details about the nucleosynthesis process and the chemical conditions of the galaxy when the last star formation episode occurred (Izotov & Thuan 1999). One of the easiest and most informative ratios to study is nitrogen to oxygen.

From what we currently understand of stellar nucleosynthesis, we can group its products into two classes: primary and secondary elements. The yields of primary elements (carbon and oxygen, for example) are independent of the initial metallicity of the star, while the yields of secondary elements depend on the initial abundance of heavy elements in the star. Nitrogen is unique—it can behave as both a primary and a secondary element (Matteucci 1986). Nitrogen is produced during the CNO cycle, which is one of the two main processes of hydrogen burning in a star. The CNO cycle fuses four protons into a helium atom with two positrons and two electron neutrinos as by-products. It tends to occur in more massive stars than our Sun, due to the higher temperature required for the fusion processes involved. Carbon is a catalyst of the CNO cycle, not a product. As a result, if carbon is not initially present within the star, then nitrogen is produced in the same relative abundance as carbon and oxygen—nitrogen behaves as a primary element. However, if the interstellar medium (ISM) has a relatively high abundance of heavier elements from previous star formation episodes, then nitrogen behaves as a secondary element, since its production is based on carbon and oxygen produced prior to the star’s creation.

The majority of the production of oxygen and nitrogen is thought to occur in different mass stars—nitrogen is produced in the CNO cycle of intermediate-mass stars ($4M_\odot < M_* < 8M_\odot$), while oxygen is primarily produced in the helium-, carbon-, and neon-burning stages of higher-mass stars ($M_*>4M_\odot$) (Henry et al. 2000, 2006). The CNO cycle can occur in lower-mass stars (the minimum temperature is only $1.5 \times 10^7$ K), but it requires carbon as a catalyst. If there is already carbon present in a star at its birth, the CNO cycle can commence much earlier in the star’s lifetime than if it is composed primarily of hydrogen at its birth.

A measurement of the N/O ratio indicates where a galaxy is in its chemical evolution. The relative amounts of these two elements can be influenced by nucleosynthesis, a galaxy’s star formation history, and/or a varying initial mass function (IMF), for example. The star formation history of a galaxy can be strongly influenced by the galaxy’s environment. Galactic interactions can cause bursts of star formation in addition to secular star formation. Due to the time delay in the release of nitrogen and oxygen from the stellar population, galaxies that have more recently experienced star formation will result in lower N/O ratios (since oxygen is released sooner than nitrogen, due to higher-mass stars being responsible for the production of oxygen). In addition to this time delay, if a
galaxy has enough heavy elements present in its gas at the time of the stars’ births, secondary nitrogen will be produced in addition to primary. This would result in higher N/O ratios, and there would be a correlation between the metallicity and the N/O ratio in the galaxies.

Large galaxy redshift surveys have shown that the large-scale structure of galaxies is similar to that of a three-dimensional cosmic web (Bond et al. 1996), where voids (large, underdense regions that occupy approximately 60% of space) separate galaxy clusters that are connected by thin filaments of galaxies. These cosmic voids are an important environment for studying galaxy formation (see van de Weygaert & Platen 2011, for a review), as the ΛCDM cosmology predicts void galaxies to have lower mass and be retarded in their star formation when compared to those in denser environments (e.g., Gottlöber et al. 2003; Goldberg et al. 2005; Cen 2011). Because dwarf galaxies are sensitive to many astrophysical effects, including cosmological reionization, internal feedback from supernovae and photoheating from star formation, external effects from tidal interactions and ram pressure stripping, small-scale details of dark matter halo assembly, and properties of dark matter, they should be the most sensitive to the effects of the void environment.

Previous work by Douglass & Vogeley (2017, hereafter Paper I) shows that there is no large-scale environmental dependence of the amount of oxygen in dwarf galaxies, in contrast to earlier studies by Pustilnik et al. (2006), Cooper et al. (2008), Deng (2011), and Filho et al. (2015), for example. One of the main arguments for the existence of an environmental dependence of the metallicity of galaxies centers around the idea that void galaxies are surrounded by pristine hydrogen that is unavailable to galaxies in denser regions. By looking at just N/O, we remove the hydrogen dependence of the relative abundances. Detecting a difference in the N/O ratio due to the large-scale environment would indicate that the cosmic environment has some influence on the nucleosynthesis of secondary elements. In addition, if the environment does have some very minor effect on the metallicity of a galaxy, removing the hydrogen dependence could amplify this effect above the noise of the data. Combined with the metallicity results in Paper I, we might be able to discern a large-scale environmental effect on the chemical evolution of galaxies.

Large-scale sky surveys like the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009) contain a large sample of dwarf galaxies, allowing us to analyze the dwarf galaxy population in the nearby universe with more statistical significance. Over 1000 voids have been identified in SDSS DR7 (Pan et al. 2012), and SDSS provides spectroscopy to permit abundance estimates of those dwarf galaxies found in these voids. Thus, we are able to estimate the N/O ratio as a function of large-scale environment for the largest sample of dwarf galaxies to date.

We make use of the MPA-JHU catalog’s reprocessed spectroscopic data to study the N/O abundance ratio of a large collection of dwarf galaxies in SDSS DR7. Because our analysis depends on the weak [O III] λ4363 auroral line, the MPA-JHU catalog’s more detailed treatment of the stellar continuum permits the weaker emission lines to become more apparent. As a result, using this catalog’s flux measurements should improve the accuracy of our results. We study the N/O abundance ratio of these dwarf galaxies as a function of large-scale environment to discern whether the large-scale environment has an effect on the relative abundance of heavier elements in dwarf galaxies.

Our paper is organized as follows. Section 2 describes the method used to estimate the chemical abundances in galaxies. We remind the reader of the source of our data in Section 3. Section 4 includes the results of our analysis, and Section 5 is a discussion of the implications of our results on the large-scale environmental effects on galaxy evolution. Finally, Section 6 summarizes our conclusions and discusses future work.

2. Estimation of Gas-phase Chemical Abundances from Optical Spectroscopy

We study a galaxy’s oxygen and nitrogen abundances because they are relatively abundant elements, they emit strong lines in the optical regime (including for several ionization states in oxygen), and a ratio of some of the oxygen lines provides a good estimate of the electron temperature (Kewley & Dopita 2002). What follows is a description of the theory and methods we employ to estimate the oxygen and nitrogen abundances in dwarf galaxies.

2.1. [N II]

The energy-level diagram for the various transitions of [N II] is very similar to that of [O III], since they have the same electron ground-state configuration ((1s)2(2s)2(2p)2). The similarities can be seen in Figure 1. Therefore, an estimate of the electron temperature can be made from the [N II] λ5755 emission line. However, this line is weaker than the [O III] λ4363 auroral line (since there is less N than O in galaxies), so we use the [O III] auroral line for our temperature estimates, as in Paper I. After obtaining a temperature and density estimate, we use the [N II] λλ6548, 6584 doublet to estimate the abundance of singly ionized nitrogen in a galaxy.

![Energy-level diagram for [O III] and [N II] ions.](image)
2.2. Direct $T_e$ Method

We use the same method to calculate the nitrogen abundance as that used in Paper I to estimate the oxygen abundance. However, here we use the [N II] $\lambda\lambda6548,6584$ doublet instead of the [O II] $\lambda\lambda3727$ and [O III] $\lambda\lambda4959,5007$ doublets. Because the temperature estimate depends on the auroral line [O III] $\lambda4363$, this method is often difficult to employ. As a result, it works best with low-redshift, low-metallicity galaxies. The electron temperature is derived by solving the following system of equations:

$$
t_3 = \frac{1.432}{\log[( \lambda4959 + \lambda5007)/\lambda4363] - \log C_T},
$$

where $t_3 = 10^{-4}T_e(p++)$, and

$$
C_T = (8.44 - 1.09t_3 + 0.5t_3^2 - 0.08t_3^3) \frac{1 + 0.0004x_3}{1 + 0.044x_3},
$$

where $x_3 = 10^{-4}n_e t_3^{-0.5}$. The ionic abundances are then found with the equations

$$
12 + \log\left(\frac{O^{++}}{H^+}\right) = \log\left(\frac{\lambda4959 + \lambda5007}{H\beta}\right) + 6.200
+ \frac{1.251}{t_3} - 0.55 \log t_3
- 0.014t_3,
$$

$$
12 + \log\left(\frac{O^+}{H^+}\right) = \log\left(\frac{\lambda3727}{H\beta}\right) + 5.966 + \frac{1.676}{t_2}
- 0.40 \log t_2 - 0.034t_2
+ \log(1 + 1.35x_2),
$$

$$
12 + \log\left(\frac{N^+}{H^+}\right) = \log\left(\frac{\lambda6548 + \lambda6584}{H\beta}\right) + 6.234
+ \frac{0.950}{t_2} - 0.42 \log t_2 - 0.027t_2
+ \log(1 + 0.116x_2),
$$

where $t_2 = 10^{-4}T_e(p++)$ and $x_2 = 10^{-4}n_e t_2^{-0.5}$. We assume that $T_e(N^+) = T_e(O^+)$. The signal-to-noise ratio of the SDSS spectra is too low to directly estimate the temperature of the gas in the low-ionization zone. As a result, we use the relation $t_2 = 0.7t_3 + 0.3$ by Garnett (1992). This relation has been shown to overestimate this temperature (Andrews & Martini 2013). Since the metal emission lines are the primary method of cooling for the gas, a high temperature corresponds to a low metallicity. Therefore, an overestimate of the temperature results in an underestimated abundance. As shown in Paper I, this only affects perhaps 15 of the dwarf galaxies in our sample and does not influence our conclusions.

The sum of the abundances of each of the element’s ionization states is equal to the total abundance of any element, whether or not all ionization states are observed. Most of the oxygen exists as either singly or doubly ionized, so the total oxygen abundance is

$$
\frac{O}{H} = \frac{O^{++}}{H^+} + \frac{O^+}{H^+}.
$$

Since we can only observe the nitrogen abundance in one of the main ionization states, we use an ionization correction factor (ICF) to account for the missing states. For any element X, the total abundance is

$$
\frac{X}{H} = \sum_i ICF_i \frac{X_i}{H}.
$$

For nitrogen, we employ the ICFs as defined in Izotov et al. (2006):

$$
ICF(N^+) = \begin{cases} 
-0.825v + 0.718 + \frac{0.853}{v} & \text{low Z} \\
-0.809v + 0.712 + \frac{0.852}{v} & \text{intermed Z}, \\
1.467v + 1.752 + \frac{0.688}{v} & \text{high Z},
\end{cases}
$$

where $v = O^+/O^{++}$. The range for low Z covers galaxies with $12 + \log(O/H) \leq 7.2$, while high Z includes galaxies with $12 + \log(O/H) \geq 8.2$. For galaxies with $7.2 < 12 + \log(O/H) < 7.6$, values for the ICFs are a linear interpolation between the low-Z and intermediate-Z values, while the ICFs for galaxies with $7.6 < 12 + \log(O/H) < 8.2$ are a linear interpolation between the intermediate-Z and high-Z values.

The N/O ratio can be found from the O/H and N/H ratios:

$$
\log\left(\frac{N}{O}\right) = \left[12 + \log\left(\frac{N}{H}\right)\right] - \left[12 + \log\left(\frac{O}{H}\right)\right].
$$

3. SDSS Data and Galaxy Selection

The SDSS Data Release 7 (DR7; Abazajian et al. 2009) uses drift scanning to map approximately one-quarter of the northern sky; it is a wide-field multiband imaging and spectroscopic survey. A dedicated 2.5 m telescope at the Apache Point Observatory in New Mexico (Tremonti et al. 1996; Gunn et al. 1998) takes the photometric data in the five-band SDSS system—$u, g, r, i,$ and $z$. Galaxies selected for spectroscopic analysis must have a Petrosian $r$-band magnitude $m_r < 17.77$ (Lupton et al. 2001; Strauss et al. 2002). Two double fiber-fed spectrographs and fiber plug plates take the spectra in an observed wavelength range of 3800–9200 Å with a resolution $\lambda/\Delta\lambda \sim 1800$ and a minimum fiber separation of 55″ (Blanton et al. 2003). As in Paper I, we use the emission-line flux data from the MPA-JHU value-added catalog, which is based on the SDSS DR7 sample of galaxies. Total star formation rates (SFRs) and total specific star formation rates (sSFRs) are also from the MPA-JHU value-added catalog, following the technique discussed in Brinchmann et al. (2004). The MPA-JHU catalog is also the source of the stellar mass estimates used, as calculated in Tremonti et al. (2004), following the method outlined in Kauffmann et al. (2003). The KIAS value-added galaxy catalog (Choi et al. 2010) is our source of the absolute magnitudes and colors of the galaxies.

3.1. Spectroscopic Selection

The following requirements are implemented on the SDSS DR7 main spectroscopic galaxy sample described above. We use the same requirements for our sample as in Paper I: all galaxies must have

1. $M_r > -17$ (dwarf galaxies);
2. a minimum $5\sigma$ detection of $H\beta$.  

3. a minimum 1σ detection of [O III] λλ4363;
4. a flux >0 for all other required lines;
5. $T_e$ (O III) < $3 \times 10^4$ K;
6. a star-forming BPT classification by Brinchmann et al. (2004).

We also use the oii_flux value from the MPA-JHU catalog in place of their [O II] λλ3726, 3729 flux measurement since we are working at such low redshifts ($0.02 < z < 0.03$). Detailed descriptions of these criteria can be found in Section 3.1 of Paper I.

### 3.2. Void Classification

The large-scale environment of the galaxies was determined using the void catalog constructed by Pan et al. (2012), which is based on the galaxies in the SDSS DR7 catalog. The VoidFinder algorithm of Hoyle & Vogeley (2002) removes all isolated galaxies with absolute magnitudes $M_r < -20$ (a galaxy is defined to be isolated if its third nearest neighbor is more than 7 $h^{-1}$ Mpc away). Placing a grid over the remaining galaxies, VoidFinder grows spheres in the centers of all grid cells that contain no galaxies. The spheres expand until they encounter four galaxies on the surface. To be considered part of a void, a sphere must have a minimum radius of 10 Mpc; two spheres that overlap by more than 10% are considered part of the same void. We refer the reader to Hoyle & Vogeley (2002) for a more detailed description of the VoidFinder algorithm. Using these voids, galaxies that live within any void spheres are classified as a void galaxy; those that are outside the spheres are considered wall galaxies. Due to the construction of the void spheres, we cannot identify any voids within 10 Mpc of the edge of the survey. As a result, the large-scale environment of any galaxy within this boundary is uncertain.

A total of 9519 of the ~800,000 galaxies with spectra available in SDSS DR7 are dwarf galaxies ($M_r > -17$). Of these, 42 void dwarf galaxies, 89 wall dwarf galaxies, and 4 dwarf galaxies with uncertain large-scale environments are left to analyze after applying the spectroscopic cuts (or 135 dwarf galaxies in total, 131 of which are used in the environmental study).

### 4. Abundance Analysis and Results

Our primary objective is to perform a relative measurement of the N/O ratio of dwarf galaxies to discern how the large-scale environment affects their chemical evolution. As discussed in Paper I, multiple methods have been developed for metallicity calculations based on the quality of the spectra. We use only the direct $T_e$ method for our abundance calculations, due to the limited galaxy types used in the calibration or theoretical development of other methods.

For reference, the solar metallicity $Z_\odot = 8.69 \pm 0.05$ (Asplund et al. 2009).

#### 4.1. Estimation of Uncertainties and Comparison of N/O and N\(^+\)/O\(^+\)

We estimate uncertainties in the computed abundances using a Monte Carlo method. We calculate 100,000 abundance estimates using the measured line fluxes and scaled uncertainty estimates. A new positive “fake” line flux is drawn from a normal distribution for each abundance estimate. The standard deviation in the sets of 100,000 calculated abundance values is used for the error in the abundance calculation. A more in-depth description of this process can be found in Paper I.

It has been common practice to assume that N/O $\approx$ N\(^+\)/O\(^+\), thus eliminating the need for the ICF in Equation (7). We find that this is a reasonable but slightly biased approximation, agreeing with the results of Nava et al. (2006). A comparison of the N/O ratio and the N\(^+\)/O\(^+\) ratio for our dwarf galaxies can be seen in Figure 2; galaxies with absolute magnitudes $M_r > -20$ roughly follow the approximation that N/O $\approx$ N\(^+\)/O\(^+\), which is often assumed in other studies of the abundance ratio of nitrogen to oxygen. In this paper, we will use the abundance ratio N/O for our analysis.

#### 4.2. Sources of Systematic Error

There is a radial dependence of many physical properties of galaxies (Bell & de Jong 2000). Consequently, abundance estimates may depend on the locations of the spectroscopic fiber on the galaxy. If all of the galaxy’s light is not contained within the fiber of the spectrograph, the estimated abundances will not necessarily be representative of global abundance values. For example, Bell & de Jong (2000) show that the metallicity is not constant throughout a galaxy. Due to the spatially resolved spectra produced by MaNGA of SDSS-IV (SDSS Collaboration et al. 2016), a statistically significant measure of the radial dependence of a galaxy’s metallicity should soon be possible (Wilkinson et al. 2015). In SDSS DR7, the fiber diameter is $3'$, corresponding to a physical diameter between 1.29 and 1.93 kpc at redshifts $0.02 < z < 0.03$. This covers a majority of most dwarf galaxies’ luminous surfaces.
Table 1

| Index | R.A.       | Decl.      | Redshift | $M_r$ | $12 + \log \left( \frac{O}{H} \right)$ | $12 + \log \left( \frac{N}{H} \right)$ | $\log \left( \frac{O}{N} \right)$ | Void/Wall |
|-------|-----------|------------|----------|-------|--------------------------------|--------------------------------|--------------------------------|-----------|
| 63713 | 09°20′04″27 | −00°30′08″79 | 0.0257 | −16.73 | 7.80 ± 0.41 | 6.83 ± 0.28 | −0.97 ± 0.49 | Wall |
| 73537 | 09°25′24″23 | +00°12′40″39 | 0.0250 | −16.94 | 7.94 ± 0.34 | 6.76 ± 0.24 | −1.18 ± 0.41 | Wall |
| 75442 | 13°13′24″25 | +00°15′02″95 | 0.0264 | −16.81 | 7.55 ± 0.35 | 6.73 ± 0.24 | −0.82 ± 0.42 | Void |
| 168874 | 11°45′13″16 | −01°48′17″68 | 0.0273 | −16.99 | 8.16 ± 0.31 | 6.94 ± 0.21 | −1.21 ± 0.37 | Wall |
| 184308 | 09°39′09″18 | +00°59′04″15 | 0.0244 | −16.73 | 7.36 ± 0.43 | 6.71 ± 0.31 | −0.65 ± 0.53 | Wall |

Note. Five of the 135 dwarf galaxies analyzed from SDSS DR7. The flux values for all required emission lines can be found in the MPA-JHU value-added catalog. Metallicity values are calculated using the direct $T_e$ method, with error estimates via a Monte Carlo method. The void catalog of Pan et al. (2012) is used to classify the galaxies as either Void or Wall. A galaxy is located too close to the boundary of the SDSS to identify whether or not it is inside a void, it is labeled as Uncertain.

(This table is available in its entirety in machine-readable form.)

The fiber is almost always placed on the brightest spot of the galaxy, which is often the center of the galaxy for spiral and ellipticals. Since the metallicity has been shown to decrease at large radius, these abundance values may be overestimates of the global abundances. Since many dwarf galaxies are irregular galaxies, the fiber is instead focused on a bright H II region. As a result, we are estimating the abundances of the gas from which stars recently formed.

We are implicitly limiting our sample of galaxies to only blue, star-forming dwarf galaxies as a result of our selection criteria outlined in Section 3.1. Consequently, this is not a representative sample of the full dwarf galaxy population. In this study we are only able to discuss the large-scale environmental influence on blue, star-forming dwarf galaxies within a narrow redshift range. It is impossible to use the direct $T_e$ method to measure the chemical abundances of red dwarf galaxies because the UV photons from young stars are needed to excite the interstellar gas.

4.3. Galaxy Abundances

Abundances estimated using the direct $T_e$ method for our dwarf galaxy sample are listed in Table 1, along with other important characteristics and identification for the galaxies (including their large-scale environment classification).

4.3.1. Oxygen and Nitrogen Abundances

Histograms of the resulting oxygen and nitrogen abundances are shown in Figures 3 and 4, respectively. Both figures show very little difference in the distribution of abundance values in dwarf galaxies between voids and walls. A two-sample Kolmogorov–Smirnov (K–S) test quantifies this observation—it produced a test statistic of 0.13 for oxygen and 0.11 for nitrogen, corresponding to a probability of 67.1% and 83.8%, respectively, that a test statistic greater than or equal to this calculated test statistic will be measured if the void sample were drawn from the wall sample. The cumulative distribution function (CDF) of these samples can be seen in the right panel of Figures 3 and 4. The K-S test quantifies the visual impression in these figures that the distributions of oxygen and nitrogen abundances are similar for dwarf galaxies in voids and walls.

The average and median values of the dwarf galaxy abundances indicate very little large-scale environmental influence on the oxygen and nitrogen abundances. The average oxygen abundance for void dwarf galaxies is 7.99 ± 0.049 and the median is 8.04, while the average for wall dwarf galaxies is 7.93 ± 0.036 with a median value of 8.01. This implies that the wall dwarf galaxies have lower oxygen abundances by an average of 0.07 ± 0.060 relative to the void dwarf galaxies; the shift in the median values is 0.03 for the dwarf galaxies, with
As can be seen in Figure 7, there is a shift in the N/O ratio to lower values in the void dwarf galaxies than in the wall dwarf galaxies. This difference is quantified in the K-S test—the test returned a probability of 11.1% that a test statistic greater than or equal to 0.22 will be measured if the void sample was drawn from the wall sample. The void dwarf galaxies have lower N/O ratios by an average of 0.05 ± 0.074 than the wall dwarf galaxies; the difference in the median values of the N/O ratio in the void and wall dwarf galaxy samples is 0.07. However, like the shifts seen in the oxygen and nitrogen abundances, the shift in the N/O ratio for dwarf galaxies is not statistically significant.
We perform the same analysis with the N/O ratio on somewhat brighter galaxies, up through $M_r > -20$; the results of this analysis can be seen in Figure 8 and in Table 2. The shift toward lower N/O ratios for the void galaxies is small for all magnitude bins. The direction of the shift between environments for the N/O ratio is consistent for all absolute magnitude bins: void galaxies have slightly lower N/O ratios than wall galaxies. This is only very weak evidence of a large-scale environmental influence on the relative abundances of elements in galaxies, but it is worth testing for in larger samples.

Figure 8 indicates a shift toward higher values in the peak of the N/O distribution as the absolute magnitude of the galaxies increases. There is a known positive correlation between the N/O ratio and the stellar mass of a galaxy, as discussed in Section 4.5 below. To test whether this relation is causing the shift seen in Figures 7 and 8, we downsamplled the wall galaxies in each magnitude bin to match the void sample. The original shifts in the N/O ratio seen were still present after the downsampling; the observed shift in the N/O ratio is not due to any variations in the distribution of the stellar masses between the two environments. In addition, if we are overestimating the temperatures in these galaxies as a result of an incorrect measurement of [O III] $\lambda$4363 (discussed above in Section 4.3.1), that effect should cancel when we look at the ratio of nitrogen to oxygen. This shift toward higher N/O values as a function of absolute magnitude indicates that brighter galaxies produce more nitrogen than fainter galaxies (relative to their oxygen abundance). This result is consistent with the theory that nitrogen behaves as a secondary element in galaxies with high enough metallicity, if we assume a positive correlation between absolute magnitude and metallicity.

### 4.4. O/N versus O/H

Comparing the N/O ratio with the gas-phase oxygen abundance in a galaxy can help us understand the nucleosynthesis of nitrogen in galaxies. When the metallicity of a galaxy is low, stars created from this gas do not have enough carbon to efficiently produce helium via the CNO cycle. As a result, any nitrogen produced in these stars will behave as a primary element—it will be produced in the same relative quantity as oxygen. However, when the metallicity of a galaxy is high enough, stars are created with enough seed carbon to initiate the CNO cycle at an earlier stage in the star’s life. As a result, nitrogen will behave as a secondary element and will be produced in a larger quantity relative to the primary elements (like oxygen and carbon). By studying the relation between N/O and the metallicity of a galaxy, we should be able to discern the critical metallicity at which nitrogen switches from a primary to a secondary element.

Our results for N/O versus metallicity can be seen in Figure 9. Unlike many previous comparisons of N/O and...
for any of the somewhat brighter galaxies.

For example, Vila Costas & Edmunds (1993; Thuan et al. 1995; Henry et al. 2000; Pilyugin et al. 2002; Lee et al. 2004; Pilyugin et al. 2004; Nava et al. 2006; van Zee & Haynes 2006; Pérez-Montero & Contini 2009; Amorín et al. 2010; Berg et al. 2012), we do not find a constant value for N/O as a function of O/H for dwarf galaxies (nor for any of the somewhat brighter galaxies). Shields et al. (1991), Contini et al. (2002), and Nicholls et al. (2014) also find little or no evidence of a plateau in their study. Instead of a constant value for N/O as a function of O/H at low metallicities, we find a slight decrease in the N/O ratio as the metallicity increases; a linear fit to the dwarf galaxies reveals a slope of $-0.38 \pm 0.078$. This is close to the footnoted results of Andrews & Martini (2013), who find a slope of $-0.21$ for their stellar-mass-binned galaxies with metallicities $12 + \log(O/H) < 8.5$. The average value of $\log(N/O)$ for the void dwarf galaxies is $-1.25 \pm 0.060$ with a median value of $-1.28$, while the average value for the wall dwarf galaxies is $-1.21 \pm 0.044$ with a median of $-1.22$. As shown in Figure 7, the void dwarf galaxies have slightly less nitrogen relative to oxygen than do dwarf galaxies in denser regions.

Both these median values are higher than that of Andrews & Martini (2013), and these average values are higher than that of Izotov & Thuan (1999) and Nava et al. (2006).

If a plateau in the O/H–N/H relation exists, then we should see a slope of 1 in the O/H–N/H relation. When looking at N/H as a function of O/H in Figure 10, we see that there is a correlation between the nitrogen and oxygen abundances. However, a best fit to the dwarf galaxies reveals a slope of only $0.62 \pm 0.078$—the nitrogen abundance increases at a slower rate than the oxygen abundance. This result matches the negative relationship between the metallicity and the N/O ratio seen in Figure 9. If we examine only the low-metallicity ($12 + \log(O/H) < 7.6$) star-forming galaxies with $M_r > -20$, a linear fit produces a slope of $0.05 \pm 0.019$ in Figure 10 and a slope of $-0.94 \pm 0.019$ in Figure 9. This is in sharp contrast to the star-forming galaxies with $M_r > -20$ that have metallicities $12 + \log(O/H) > 7.6$, where their slope in Figure 10 is $0.60 \pm 0.022$ and $-0.39 \pm 0.023$ in Figure 9. It appears that the nitrogen production is independent of the amount of oxygen produced in low-metallicity systems. At normal metallicities ($7.6 < 12 + \log(O/H) < 8.5$), there exists a positive relationship between the production of nitrogen and oxygen, although the ratio of N/O produced depends on the galaxy’s metallicity.
There is no difference between void and wall galaxies in the relationship of oxygen and nitrogen production in the low-metallicity sample. There is a slight difference in slopes between the void and wall galaxies with normal metallicities, where the void galaxies have a larger slope in the relationship between O/H and N/H and a smaller slope in the relationship between O/H and N/O. While statistically significant, the difference in the slopes between the two environments is not large enough to be physically relevant. The significant scatter in both Figures 9 and 10 indicates that the described relationships between the production of nitrogen and oxygen are only global trends in the nucleosynthesis of the galaxies.

### 4.5. Mass–N/O Relation

Just as there is a well-known mass–metallicity relation for galaxies (where the metallicity increases with stellar mass; see,
there is also a mass–N/O relation. We expect to see a primary N/O plateau in the mass–N/O relation, since galaxies with lower stellar masses have not yet produced enough heavy elements to synthesize more nitrogen than oxygen. Beyond the low-mass limit, there should be a steady increase in the N/O ratio as a function of stellar mass, due to secondary nitrogen enrichment. Our dwarf galaxies in Figure 11 show a steady increase in N/O as a function of stellar mass; there is a hint of the beginnings of a plateau for $M_r > -20$. To place the dwarf galaxies in the context of the general galaxy population, we also plot (gray stars) all star-forming galaxies with $M_r > -20$.

As a result, nitrogen behaves as a primary element at galactic metallicities less than approximately 8.5. To place the dwarf galaxies in the context of the general galaxy population, we also plot (gray stars) all star-forming galaxies fainter than $M_r > -20$.

There is a positive correlation between the two abundances. With a best-fit slope less than 1, we see that the synthesis of nitrogen in these galaxies is primary.

e.g., Tremonti et al. 2004), there is also a mass–N/O relation. We expect to see a primary N/O plateau in the mass–N/O relation, since galaxies with lower stellar masses have not yet produced enough heavy elements to synthesize more nitrogen than oxygen. Beyond the low-mass limit, there should be a steady increase in the N/O ratio as a function of stellar mass, due to secondary nitrogen enrichment. Our dwarf galaxies in Figure 11 show a steady increase in N/O as a function of stellar mass; there is a hint of the beginnings of a plateau for $\log(M_*/M_\odot) \lesssim 8$. The lack of a plateau here could be a result of our limited stellar mass range for the dwarf galaxies. A linear fit to our dwarf galaxies reveals a slope of $0.6 \pm 0.12$, which is much stronger than the slope of 0.30 found by Andrews & Martini (2013).
Figure 12. Color ($u - r$ and $g - r$) vs. N/O ratio for star-forming void (red circles) and wall (black triangles) dwarf galaxies. Error bars have been omitted for clarity. N/O is expected to increase as galaxies become redder if there is a time delay between the release of oxygen and nitrogen. To place the dwarf galaxies in context, we also plot the star-forming galaxies with $M_*>-20$ (gray stars).

From Figure 11, we conclude that the N/O plateau, if one exists, starts around $\log(M_* / M_\odot) \approx 8$. This is at a much lower mass than that found by Andrews & Martini (2013)—they claim that the N/O plateau exists for galaxies with $\log(M_* / M_\odot) < 8.9$. However, our relationship between stellar mass and N/O matches Figure 3 of Amorín et al. (2010), as well as the results of Pérez-Montero & Contini (2009) and Pérez-Montero et al. (2013). None of our data samples display an obvious N/O plateau above a stellar mass $\log(M_* / M_\odot) > 8$, indicative of primary nitrogen versus secondary nitrogen production in galaxies. This could indicate that the switch from primary to secondary nitrogen production occurs at a much lower stellar mass than found by Andrews & Martini (2013). More low-mass galaxies are needed to extend this relation below $\log(M_* / M_\odot) < 8$.

4.6. Color–N/O Relation

As van Zee & Haynes (2006) and Berg et al. (2012) discuss, a time delay between the release of nitrogen and oxygen will result in a positive relationship between the N/O ratio and the color of a galaxy. If oxygen is primarily produced in higher-mass stars (and since these stars die earlier than the intermediate-mass stars responsible for the synthesis of nitrogen), then, for a given star formation episode, the oxygen produced will be released on a shorter timescale than the nitrogen. As a result, the amount of nitrogen relative to oxygen should increase as the hotter, more massive stars die and the galaxy becomes redder. This is exactly what we see in Figure 12. We use rest-frame colors $K$-corrected to a redshift of 0.1; they are corrected for galactic extinction and calculated with model magnitudes (Choi et al. 2010). Van Zee & Haynes (2006) and Berg et al. (2012) also found an increase in the N/O ratio as a function of color.

4.7. (s)SFR–N/O Relation

We expect there to be a correlation between SFR or sSFR (per unit stellar mass) and the N/O ratio in galaxies as a result of the positive correlations between the SFR and stellar mass of a galaxy (Brinchmann et al. 2004) and between the sSFR and the color of a galaxy (Figure 13). As shown in Figure 11, the N/O ratio increases with increasing stellar mass. As a result, we expect there to be a positive correlation between the SFR and N/O ratio in our galaxies. This can be seen in the sample of star-forming galaxies with $M_* > -20$ in the left panel of Figure 14. Due to the large scatter in this relation, the blue star-forming dwarf galaxies exhibit a negative correlation between their N/O ratios and their SFRs. These SFRs are aperture corrected to estimate the total SFR in the galaxy (not just within the SDSS fiber).

The N/O ratio is expected to decrease as sSFR increases in galaxies, as is shown in the right panel of Figure 14. Bluer galaxies have higher sSFR. Figure 12 shows that there is a positive correlation between the color and the N/O ratio, such that bluer galaxies have lower N/O ratios. As a result, we are not surprised to see that the N/O ratio decreases as the sSFR increases.

5. Large-scale Environmental Influence

The majority of the shifts in the gas-phase abundances of oxygen, nitrogen, and the N/O ratio seen in galaxies fainter than $L_*$ are small and statistically insignificant. However, they occur in almost the same direction across all magnitude bins. This trend suggests that the gas-phase abundances may be influenced by the galaxies’ large-scale environments. Shields et al. (1991) find no offset in the N/O ratio between cluster and field galaxies, despite the difference in O/H they observe. Similar to us, Contini et al. (2002) and Pilyugin et al. (2002) also find a statistically insignificant shift in the N/O ratio of cluster galaxies, although they find that these galaxies have lower N/O ratios than field spiral galaxies. Based on Figure 7 and the statistics in Table 2, we find weak evidence that void dwarf galaxies have a smaller N/O ratio than dwarf galaxies in denser regions. This means that void dwarf galaxies may have more oxygen than wall dwarf galaxies, and/or void dwarf galaxies could have less nitrogen than wall dwarf galaxies. Here we discuss these possibilities and explore their implications for the large-scale environmental impact on the formation and evolution of galaxies.

Table 2 suggests a slight large-scale environmental dependence of the oxygen and nitrogen abundances (relative to
hydrogen), where void galaxies have slightly more O/H and N/H than wall galaxies. This small difference is not apparent when looking at Figures 3 and 4. However, the N/O ratio amplifies this large-scale environmental effect so that a shift in the mean (or median) of the two populations can be seen in Figure 7. We hesitate to combine the results across all magnitude bins in an effort to improve their significance. Instead, we look toward the future to analyze a larger sample of galaxies to increase the statistical significance of these results.

5.1. Higher Metallicities in Void Dwarf Galaxies

A slightly higher metallicity in void dwarf galaxies than wall dwarf galaxies may be evidence of a difference in the ratio of dark matter halo mass to stellar mass between the two environments. Simulations by Jung et al. (2014) and Tonnesen & Cen (2015) have shown that the dark matter halo masses of void central galaxies are larger than those of wall central galaxies for a given stellar mass. Due to their environment, void dwarf galaxies are more likely to be in the center of their own dark matter halo. Wall dwarf galaxies, on the other hand, are much more likely to be a satellite galaxy within a much larger dark matter halo; the simulation results mentioned above would not apply to these wall dwarf galaxies. However, because the wall dwarf galaxies studied here have sufficiently high sSFRs, they most likely live in a small-scale environment very similar to that of the void dwarf galaxies, as discussed in Paper I. As a result, it is likely that (and should be tested to see whether) the wall dwarf galaxies in this study are actually central galaxies.

Applying the results of these simulations to our dwarf galaxy sample, if the ratio of dark matter halo mass to stellar mass is larger in void galaxies, the metals ejected from a void galaxy’s ISM into its circumgalactic medium are more likely to fall back onto the ISM than in a wall galaxy with the same stellar mass, since the void galaxy’s virial radius and potential well are larger. As a result, two dwarf galaxies with the same stellar mass in these two different large-scale environments can have different metallicities—void dwarf galaxies would have higher
metallicities than wall dwarf galaxies, matching what we see in Table 2.

5.2. Lower N/O Ratios in Void Dwarf Galaxies

A difference in the N/O ratio between void dwarf galaxies and wall dwarf galaxies could be a result of the difference in the synthesis of nitrogen in galaxies within these two large-scale environments. If void galaxies are retarded in their star formation (as simulations of the ΛCDM cosmology suggest), then cosmic downsizing would reduce the SFR at late times much more in wall galaxies than in void galaxies. As a result, the minimum gas-phase metallicity required for the production of secondary nitrogen in walls would be achieved at an earlier time in the galaxy’s lifetime than in a void galaxy. This would cause the N/O ratio in wall galaxies to be larger than that in voids. Van Zee & Haynes (2006) suggest that a galaxy with a declining SFR (wall galaxies) will have a higher nitrogen-to-oxygen yield than a galaxy with a constant SFR (void galaxies). This is due to more oxygen being released into the ISM as a result of the ongoing star formation in the void galaxies. This explanation is supported by the color–N/O diagram in Figure 12, which reveals that redder galaxies have higher N/O ratios. The correlation between color and the N/O ratio found in van Zee & Haynes (2006), Berg et al. (2012), and Figure 12 is a result of declining SFRs (van Zee & Haynes 2006). Therefore, the shift in the N/O ratio we see between void and wall galaxies may be observational evidence of retarded star formation in void galaxies as a result of cosmic downsizing.

Another explanation that would lead to a shift in the N/O ratio between environments is a difference in the ratio of intermediate- and high-mass stars produced in void and wall dwarf galaxies. For there to be more oxygen relative to nitrogen in void dwarf galaxies, the percent of higher-mass stars produced in a star formation episode would be higher than that in wall dwarf galaxies. This would indicate a varying IMF as a function of large-scale environment. Previous studies have been inconclusive when testing for a varying IMF (see Kroupa 2001, 2002;Hoversten & Glazebrook 2008; Meurer et al. 2009, for example). It is beyond the scope of this paper to elaborate on this explanation.

5.3. N/O Ratio for Extremely Low Metallicity Galaxies

While Paper I shows that there is not a special population of extremely low metallicity dwarf galaxies residing in voids, we want to look in particular at the N/O ratio of extremely low metallicity galaxies. For the 21 dwarf galaxies with 12 + log(O/H) < 7.6 identified in Paper I, we see from Figure 10 that their N/H ratios are also some of the lowest in the dwarf galaxy sample. However, as shown in Figure 9, their N/O ratios cover the range of N/O ratio values of all the dwarf galaxies studied. This is consistent with the expectation that nitrogen behaves as a primary element for galaxies with low and moderate metallicities. Details of these 21 dwarf galaxies with extremely low metallicities are listed in Table 3, including their gas-phase chemical abundances.

6. Conclusions

The nucleosynthesis of nitrogen is a vital component of the chemical evolution of galaxies in our universe. We estimate the nitrogen abundance and N/O ratio of dwarf galaxies using the direct T_e method and spectroscopic line flux measurements from the SDSS DR7 sample as reprocessed in the MPA-JHU catalog. The 135 galaxies analyzed suggest a slight large-scale environmental dependence of the N/O ratio, where void dwarf galaxies could have a lower N/O ratio than dwarf galaxies in denser environments. Thus, the large-scale (~10 Mpc) environment might influence the chemical evolution of dwarf galaxies.

We find small, statistically insignificant shifts in the mean (or median) N/O ratio for galaxies between the void and denser regions across all blue, star-forming galaxies with M_r > −20. These shifts are somewhat more significant, however, when we look at the entire sample of galaxies. Each magnitude bin is shifted in the same direction, and they are potentially very interesting, as they might indicate delayed star formation histories, more constant SFRs, and larger ratios of dark matter halo mass to stellar mass in void galaxies, as discussed in Section 5. A larger sample would help test these results. We look to increase the sample and probe a larger magnitude (and mass) range of dwarf galaxies in K. A. Douglass & M. S. Vogeley (2017, in preparation).

In addition, we look at the relationship between the N/O ratio and other physical characteristics of our dwarf galaxies. In the relation between N/O and O/H, our galaxies all reside on the so-called “nitrogen plateau,” where the N/O ratio is predicted to be constant for low and intermediate metallicities. However, instead of a constant value for these galaxies, we find a negative correlation between the N/O and O/H ratios. Our dwarf galaxies show a positive correlation between stellar mass and the N/O ratio. These dwarf galaxies have some of the lowest N/O ratios for both their color and (s)SFR. Beyond the suggestive large-scale environmental dependence of the N/O ratio, there is no clear large-scale environmental dependence in any of these relationships.

The N/O ratios of the extremely metal-poor dwarf galaxies are no different than those of the remaining dwarf galaxy sample, though their N/H abundance is also extremely low. A more detailed study of these 21 extremely metal-poor dwarf galaxies is recommended to confirm their abundance values and discover any characteristics shared by the population.

Although SDSS provides spectroscopic observations for over 800,000 galaxies, only 135 are dwarf galaxies with emission-line fluxes necessary to estimate the gas-phase chemical abundances using the direct T_e method. The greatest limiting factor in this sample is the requirement of the [O II] λ3727 doublet in the abundance calculations. We seek to develop a work-around for this emission line in K. A. Douglass & M. S. Vogeley (2017, in preparation) to greatly increase our sample of dwarf galaxies with abundance estimates. These estimated ionic abundances can then be compared with environmental dependence of star formation and abundance predictions from high-resolution hydrodynamic simulations.

Further tests may refine our understanding of the environmental scale that is important for determining the chemical evolution of dwarf galaxies. In particular, it will be important to examine whether the influence of relatively small-scale (~2 Mpc) environments is more significant to a dwarf galaxy’s chemical evolution than the larger-scale environment investigated here. In previous work, both Kreckel et al. (2015) and Beygu et al. (2017) find little evidence to support a significant large-scale environmental influence on the gas content, chemical content, or SFR of void galaxies. Future work will expand on these studies with a larger sample and the possible influence they might have on the dwarf galaxies’ chemical
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