Chapter 7: Conclusions and suggestions for future work

7.1 Large-scale environmental influence on the gas-phase chemical abundances in dwarf galaxies

We find that the large-scale environment influences the chemical evolution of dwarf galaxies by estimating the gas-phase oxygen (O/H) and nitrogen (N/H) abundances and the N/O ratio of star-forming dwarf galaxies in SDSS DR7 using the Direct T_e method and spectroscopic line flux measurements as reprocessed in the MPA-JHU catalog (Douglass & Vogeley, 2017a,b, Douglass et al., 2017, in prep). Due to the minimum redshift limit for detecting the [O II] λ3727 emission line in SDSS DR7 spectra, only 135 star-forming dwarf galaxies are available for analysis with the Direct T_e method. With this sample, we see no difference in the metallicity (O/H) between dwarf galaxies in voids and denser regions (Douglass & Vogeley, 2017a). Upon closer inspection, we find minor shifts in the distributions of gas-phase chemical abundances for void dwarf galaxies when compared to dwarf galaxies in denser regions: star-forming void dwarf galaxies have higher oxygen abundances (O/H), lower nitrogen abundances (N/H), and lower N/O ratios (Douglass & Vogeley, 2017b).

By deriving a relation between the doubly-ionized oxygen and total oxygen abundance in star-forming galaxies, we can expand our sample to consist of 1920 star-forming dwarf galaxies by removing the dependence on the [O II] λ3727 doublet. This larger sample exhibits the same shifts in the gas-phase chemical abundances as the smaller, 135 star-forming dwarf galaxy sample, but with a much higher statistical significance. We find that star-forming void dwarf galaxies have, on average, 7% higher oxygen abundances, 10% lower nitrogen abundances, and 17% lower N/O ratios than star-forming dwarf galaxies in denser regions. The large-scale ($\sim 10\ h^{-1}$Mpc) environment influences the chemical evolution of star-forming dwarf galaxies.

In addition to studying the large-scale environmental influence on the distribution of gas-phase chemical abundances in star-forming dwarf galaxies, we also investigate if and how the large-scale environment affects relationships between the chemical abundances and various other physical properties of the galaxies. We find that the N/O ratio decreases with increasing metallicity rather than a constant value for the N/O ratio as a function of O/H as observed in other studies. This is contrary to what we see in the M_*-N/O relationship, where we find that some of the star-forming dwarf galaxies have a constant value of N/O for a range of masses while the remainder exhibit a positive relationship between the stellar mass and N/O ratio. We make note of a different critical mass in the M_*-N/O relationship in the two environments, where the void dwarf galaxies begin to show evidence of secondary nitrogen synthesis at a stellar mass ~0.4 dex lower than for the galaxies in denser regions. Most of our star-forming dwarf galaxies follow the established mass-metallicity relation (e.g., Tremonti et al., 2004).

No relationship is observed between the metallicity and H I mass in our sample of star-forming dwarf galaxies, but we find that the N/O ratio decreases with increasing H I mass for a given stellar mass. The star-forming dwarf galaxies also exhibit an increase in the metallicity and N/O ratio with increasing color (both $u-r$ and $g-r$). We see very little correlation with SFR for either metallicity or the N/O ratio in dwarf galaxies, but the metallicity and N/O ratio decrease with increasing sSFR. Beyond the large-scale environmental influence on the distributions of the gas-phase chemical abundances and the critical mass in the M_*-N/O relationship, we do not observe any significant differences between the star-forming void and wall dwarf galaxies in any of these relationships.

We surmise that the differences in the distributions of metallicity and the N/O ratio seen in the sample of star-forming dwarf galaxies are due to a large-scale environmental influence on their star formation history and evolution. The shift in the gas-phase oxygen abundance distribution could be observational evidence for delayed star formation in void galaxies when compared to those in denser regions. This would result in a smaller ratio of stellar mass to dark matter halo mass in void galaxies than in dwarf galaxies in denser regions, as predicted in simulations by Jung et al. (2014) and Tonnesen & Cen (2015). If the void galaxies are retaining more oxygen as a result of their deeper potential wells, then they would be able to commence secondary nitrogen synthesis earlier, as seen in the M_*-N/O relation in Fig. **??**. In addition, the shift towards lower N/O ratios in the star-forming dwarf galaxies might be evidence that cosmological downsizing is environmentally dependent as predicted by Cen (2011). Our results provide evidence for delayed, ongoing star formation in void dwarf galaxies whose dark matter halos ceased coalescing earlier than for dwarf galaxies in denser regions.

It has been hypothesized that a special population of extremely metal-poor galaxies exist in void regions. We find no evidence for a special population of extremely metal-poor star-forming dwarf galaxies in the voids, as we note an equal fraction of low metallicity dwarf galaxies in both the void and denser regions. Due to their low gas-phase oxygen abundances, these 287 dwarf galaxies have some of the larger N/O ratios of the star-forming dwarf galaxies sample studied. While the metallicities of these galaxies cause them to stand out in the relationships between metallicity and other physical quantities (stellar mass, color, (s)SFR), they are not unusual when studying the relationships between the N/O ratio and these other quantities.

7.2 Small-scale environmental influence on dwarf galaxy evolution

In addition to the influence of the large-scale environment on the evolution of dwarf galaxies, we also study the effects of the small-scale environment on dwarf galaxies. We find that only the presence of a neighboring galaxy within 0.05 h^{-1}Mpc or $0.05r_{vir}$, or the presence of a group within 0.1 h^{-1}Mpc influences a dwarf galaxy's evolution. Dwarf galaxies with a nearest neighbor galaxy within 0.05 h^{-1}Mpc or $0.05r_{vir}$ are bluer, have a higher sSFR, and have higher oxygen and nitrogen abundances than average. This matches the results of Park & Choi (2009), who find that late-late type galaxy pairs within $0.05r_{vir}$ are bluer and have higher SFRs. In contrast, dwarf galaxies within 0.1 h^{-1}Mpc of the center of the closest group are redder, have lower oxygen abundances, and have higher N/O ratios than average. These results are independent of both the maximum relative velocity required to define a nearest neighbor and the sample (star-forming versus all dwarf galaxies).

When we incorporate the redshift into the distance calculations, we find that the galaxies within $0.05r_{vir}$ are most likely strongly interacting or merging with their nearest neighbor. These merging galaxies likely share the same dark matter halo, suggesting that the dark matter halo is more influential on a galaxy's evolution than the distance between a galaxy and its nearest neighbor.

7.3 Properties of green valley galaxies

Finally, we also investigate the properties of galaxies residing in the green valley of the color-magnitude diagram (CMD) in an effort to understand the role of the environment on a galaxy's evolution through the color-magnitude diagram. We discover that we can define galaxies which are transitioning through the green valley of the CMD by combining the galaxy's color, color gradient, and inverse concentration index. Galaxies with a value less than 25 for the morphological type as calculated in the KIAS-VAGC exist in the green valley portion of the UV-optical CMD. Galaxies defined as early types (morphological type values equal to 1 or 2) are in the red cloud, while those with morphological type values greater than 25 are in the blue sequence. With this quantitative definition for galaxies transitioning through the green valley, we can begin to understand the properties of green valley galaxies and their evolution.

Based on our analysis, green valley galaxies have stellar masses comparable to galaxies in the red cloud. They have intermediate SFRs and low-to-intermediate sSFRs. Green valley galaxies also have high gas-phase nitrogen abundances (N/H), resulting in high N/O ratios. While their SFRs show that their star formation has been quenched, their stellar masses inform us that this is not due to any premature quenching mechanism. The high nitrogen abundances in the green valley galaxies indicate that the galaxies are either no longer forming stars (since nitrogen is produced in lower mass stars than oxygen), or that the galaxies were able to synthesize both primary and secondary nitrogen (heavy elements were present during the last few star formation episodes to permit the CNO cycle to commence earlier). This chemical abundance pattern of normal oxygen (O/H), high nitrogen (N/H), and high N/O ratio is also seen in galaxies classified as AGN, indicating that galaxies in the green valley have an AGN.

There is a higher fraction of faint galaxies from denser regions than faint void galaxies in the green valley. Combined with the previous results about the large-scale environmental influence on the gas-phase chemical abundances, this indicates that void dwarf galaxies are less evolved than dwarf galaxies in denser environments.

7.4 Suggestions for future work

A critical problem in galaxy formation is understanding how galaxies transition from the blue sequence to the red cloud in the optical color-magnitude diagram. Star formation is thought to be quenching in galaxies moving through the green valley, but the relevant baryonic processes (gas cooling, feedback, etc.) are very complex and heavily independent. The enrichment of the interstellar medium (ISM) and circumgalactic medium (CGM) of a galaxy involves many complicated processes, the interplay of which is not yet well understood. Investigating the star formation history and chemical evolution of galaxies in the green valley should provide clues of the movement of a galaxy through the color-magnitude diagram.

With the advent of 2-dimensional spectroscopic data from SDSS MaNGA (Bundy et al., 2015; SDSS Collaboration et al., 2016), it is possible to examine how the ISM and CGM are enriched over time. MaNGA is the first large-scale survey using integral-field spectroscopy, which would permit the study of spatially-resolved physical properties of galaxies across many different environments, morphologies, and stages of evolution. In particular, it would be instructive to study the gradients of the gas-phase chemical abundances of galaxies in order to better understand their evolution through the CMD and also the influence of the environment in both large and small scales on the chemical evolution of these galaxies.

A better knowledge of the chemical abundances of galaxies with an AGN is also crucial to understanding the evolution of galaxies. Understanding how the presence of an AGN affects a galaxy's evolution is currently limited — at the moment, most research is concentrated on the physics within an AGN. Many simulations have been done to test different theories about the role of an AGN in a galaxy, and observations are now needed to test the results of the simulations.

The work done here on the small-scale environment is only the beginning of what can be done in this subject area. In addition to studying the relationship between a galaxy's physical parameters and its distance to the nearest neighbor, it is also important to look at the ratio of the galaxy's parameters to its neighbor's and the distance to the nearest neighbor — "galactic conformity." These comparisons should include a morphological comparison, similar to the analysis done by

Park & Choi (2009). We also find evidence of possible mergers when studying the influence of the small-scale environment. Visual inspection of these dwarf galaxies is imperative to confirming this conclusion.

Appendix A: The physics of the Direct T_e method

UV photons from young stars in an H II region keep the interstellar gas partially ionized. In an H II region, a photon with an energy $E_\gamma \gtrsim 13.6$ eV ionizes a hydrogen atom, producing an H^+ ion and an electron with some kinetic energy $K_{e^-} = E_\gamma - 13.6$ eV. As the free electron moves around in the gas, it loses some of its kinetic energy as it collisionally excites other ions in the gas. Because we are in a Strömgren sphere (an ionized region or an H II region), the cross-section for this electron scattering is much larger than the photoionization cross section, so the free electrons will thermalize quickly (De Robertis et al., 1987). Eventually, the free electron recombines with an H^+ ion, forming atomic hydrogen. The ions that are collisionally excited by the electron before its recombination eventually de-excite via forbidden transitions, emitting radiation that escapes the H II region.

In equilibrium, the total energy input into the gas via radiation from the star (that ionizes the hydrogen), $E_{photoionization}$, must be equal to the energy required to recombine the electron and the H^+ ion, $E_{recombination}$, and the energy radiated away from the H II region by the forbidden transitions, $E_{radiation}$. So

$$E_{photoionization} = E_{recombination} + E_{radiation} \tag{A.1}$$

For radiative de-excitation to dominate over collisional de-excitation, the electron density $n_e \ll 10^{8-10}$ cm^{-3} (De Robertis et al., 1987). Typical H II regions have an electron density $n_e \approx 100$ cm^{-3}, so radiative de-excitation dominates; this is why we observe forbidden transitions in outer space but not here on Earth.

A.1 Temperatures from the forbidden emission lines

Expanding the description in Sec. 2.2.2, we can define the ratio of the emission line strengths for [O III] λ4363 and [O III] $\lambda\lambda$4959,5007 as

$$\frac{j_{4959} + j_{5007}}{j_{4363}} = \frac{\Omega(^3\mathrm{P},^1\mathrm{D})}{\Omega(^3\mathrm{P},^1\mathrm{S})} \left[\frac{A_{^1\mathrm{S},^1\mathrm{D}} + A_{^1\mathrm{S},^3\mathrm{P}}}{A_{^1\mathrm{S},^1\mathrm{D}}}\right] \frac{\bar{\nu}(^3\mathrm{P},^1\mathrm{D})}{\nu(^1\mathrm{D},^1\mathrm{S})} e^{\Delta E/kT} \tag{A.2}$$

where j_λ is the emissivity of the emission line, $\Omega(i,j)$ is the collision strength between levels i and j, $A_{i,j}$ is the radiative transition probability between an upper level i and a lower level j, ν is the frequency of the transition, ΔE is the energy difference between the $^1\mathrm{D}_2$ and $^1\mathrm{S}_0$ levels, and T is the electron temperature (Osterbrock, 1989). The transition probabilities $A_{i,j}$ do not depend on the temperature, but the collision strength $\Omega(i,j)$ is temperature-dependent. We can define

$$\bar{\nu}(^3\mathrm{P},^1\mathrm{D}) = \frac{A_{^1\mathrm{D}_2,^3\mathrm{P}_2}\nu(5007) + A_{^1\mathrm{D}_2,^3\mathrm{P}_1}\nu(4959)}{A_{^1\mathrm{D}_2,^3\mathrm{P}_2} + A_{^1\mathrm{D}_2,^3\mathrm{P}_1}} \tag{A.3}$$

Inserting numerical values for the collision strengths and transition probabilities from Osterbrock (1989), the ratio becomes

$$\frac{j_{4959} + j_{5007}}{j_{4363}} = \frac{7.73\exp[(3.29\times 10^4)/T]}{1 + 4.5\times 10^{-4}(N_e/T^{1/2})} \tag{A.4}$$

By measuring the flux of these emission lines, we can then solve for the temperature of the gas.

A.2 [S II]

Similar to the sensitivity of the doubly-ionized oxygen ion transitions to the electron temperature of the surrounding gas, the transitions for singly-ionized sulfur are sensitive to electron number density. The relative excitation rates depend only on the ratio of the collision strengths when two emission lines (from the same ion) with nearly identical excitation energies are compared (Osterbrock, 1989). If the two levels have different transition probabilities and/or different collisional de-excitation rates, their ratio depends on the density.

The relative excitation rates of the two lines shown in Fig. 2.1 are proportional to their statistical weights; thus, the ratio of the line intensities is a constant in the low-density limit (Osterbrock, 1989). In the high-density regime, this ratio is best accurately described by a Boltzmann population ratio. There is a critical density for the energy levels which describes the turning point between these two extremes.

Appendix B: Simulations of dwarf galaxy formation and evolution

Numerous simulations have been performed over the years in an attempt to understand the formation and evolution of our universe. As observers, it is important to connect our observations with the theory in order to grow our ideas about the universe.

B.1 General dwarf galaxy formation and evolution

It is impossible to directly observe the formation of a galaxy. Based on detected merging galaxies, the astronomical community has surmised that galaxies have increased their mass largely due to the merging of smaller galaxies. ΛCDM simulations of hierarchical galaxy formation by de Rossi et al. (2007) find that the growth of systems by aggregation is responsible for the mass-metallicity relation. Less massive systems tend to increase their stellar mass by either gas-rich mergers or secular evolution, resulting in a stronger correlation between stellar mass and metallicity. Evidence of this is seen in the mass-metallicity relation of Tremonti et al. (2004), where there is little relationship between stellar mass and the metallicity for massive systems, but at intermediate and lower masses the correlation is strong between the two quantities.

The inflow and outflow of gas in galaxies are aspects of galaxy evolution that are not yet well understood. This is especially important when studying dwarf galaxies, since their gravitational potential wells may be shallow enough to be strongly influenced by star formation and/or supernovae. Simulations by Marcolini et al. (2004) find that when ram pressure from the intergalactic medium (IGM) is comparable to the thermal pressure of the central interstellar medium (ISM), stripping and superwind influence each other and increase the gas removal rate. They find that the amount of metal-rich ejecta is sensitive to the ram pressure. Simulations by Power et al. (2014) and Melioli et al. (2015) show that supernovae contain sufficient energy to unbind the gas in a low mass halo. Hu et al. (2016) show that supernova-driven galactic outflows push metal-rich gas into the halo. A small fraction of the gas eventually escapes the halo, while most falls back onto the disc. This results in the halo metallicity being about 20% higher than the disc metallicity. Likewise, Muratov et al. (2017) find that almost all metals produced in a Type II supernova are ejected from the galaxy. Unlike the supernovae, Melioli et al. (2015) finds that the ISM material does not have a strong likelihood of being expelled from a galaxy due to star formation. In contrast, Muratov et al. (2015) finds that a large portion of material is ejected in galactic outflows after a bust of star formation, which collects in the circumgalactic medium (CGM) and is sometimes recycled in later star formation episodes. In galaxies with $M_h < 10^{12} M_\odot$, a fraction of material is lost to the IGM.

Numerical simulations that study the properties of the ISM in an isolated, star-forming galaxy find that stellar feedback slowly increases the disc metallicity (Hu et al., 2016). The majority of outflows are enriched winds, which reduces the metallicity of the ISM. In dwarf galaxies at low redshifts, these outflows to the CGM are dominated by metal-poor gas (Muratov et al., 2017). While galaxies retain most of the metals they produce, a large fraction is in the CGM. By combining our observations with the results of these simulations, we can begin to understand how star formation and supernovae influence a dwarf galaxy's gas content.

B.2 Environmental differences

Unlike the simulations described above, simulations which investigate the influence of the large-scale environment on the formation and evolution of galaxies have presented a more uniform picture. Simulations by Jung et al. (2014); Xie et al. (2014) and Tonnesen & Cen (2015) show that dark matter halos assembled later in underdense regions for a given halo mass. For central galaxies, Jung et al. (2014) and Tonnesen & Cen (2015) find that the ratio of stellar mass to halo mass is larger in overdense regions because star formation rates were higher in these denser regions.

Cen (2011) studied cosmic downsizing with high-resolution large-scale hydrodynamic galaxy formation simulations based on the ΛCDM cosmology. He finds that cosmic downsizing is part of a trend where the sSFR is a function of halo mass such that lower-mass galaxies have higher sSFRs. The formation of large halos (groups and clusters) and the large-scale structure causes cosmic gas to heat beyond a critical temperature at which the gas's entropy is too high to cool to continue feeding the galaxies and their star formation. As the surrounding gas in the dense regions becomes heated beyond the critical limit, the sSFR of the affected galaxies decreases and the galaxies transition from the blue sequence to the red cloud. In the void environment, this heating does not occur, and so galaxies in the voids maintain a high sSFR in the present epoch. While this is the overall trend, there still exists some galaxies at $z = 0$ which have a high sSFR but reside in the more dense environments.