Chapter 5: The influence of the small-scale environment on dwarf galaxy evolution

This work was done in collaboration with Daniele Schneider for her senior thesis "The effects of small-scale environment on dwarf galaxies."

5.1 Introduction

Large galaxy redshift surveys have shown that the large-scale structure of the distribution of galaxies in the universe is similar to that of a three-dimensional cosmic web (Bond et al., 1996), where galaxy clusters are connected by thin filaments of galaxies and are separated by voids (large, underdense regions that occupy close to 60% of space). Over the last few decades, the Sloan Digital Sky Survey (Abazajian et al., 2009; Ahn et al., 2012) has accelerated the research into the influence of the large-scale environment on the formation and evolution of galaxies.

Because gravitational clustering within a void proceeds as if in a very low-density universe, cosmic voids are an important environment for studying galaxy formation (see van de Weygaert & Platen, 2011, for a review). The ΛCDM cosmology predicts that galaxies formed in voids have lower masses and are retarded in their star formation when compared to those in more dense environments (Gottlöber et al., 2003; Goldberg et al., 2005; Cen, 2011). The effects of the void environment should be most obvious in dwarf galaxies due to their minimal gravitational potential. As a result, they are more sensitive to astrophysical effects such as cosmological reionization, internal feedback from supernovae and photoheating from star formation, small-scale details of dark matter halo assembly, and the properties of dark matter.

Observations have shown that the properties of dwarf galaxies vary dramatically with the environment (e.g., Ann et al., 2008; Geha et al., 2012). Void galaxies have been found to have lower stellar mass (Hoyle et al., 2005; Croton et al., 2005; Moorman et al., 2015), be bluer and of a later type (Grogin & Geller, 2000; Rojas et al., 2004; Patiri et al., 2006; Park et al., 2007; von Benda-Beckmann & Müller, 2008; Hoyle et al., 2012), have higher star formation rates (Rojas et al., 2005;

Moorman et al., 2015; Beygu et al., 2016), and be more gas rich (Kreckel et al., 2012; Moorman et al., 2016; Jones et al., 2016) than galaxies in denser regions.

In conjunction with the large-scale environment, the small-scale environment ($\sim 1\ h^{-1}$Mpc) has also been found to influence a galaxy's evolution. A well-established morphology-density relation exists (Dressler, 1980), where the fraction of late-type galaxies is inversely proportional to the local density. Ellison et al. (2009) determined that a galaxy's local environment influences a galaxy's evolution more than its large-scale environment. Likewise, Rupke et al. (2008) concluded that interacting galaxies have suppressed metallicities, because interactions induce flows of hydrogen. Park & Choi (2009) found that, for galaxies with $M_r < -19$, galaxy interactions out to the virial radius of the nearest neighbor influence the evolution of the target galaxy. They determine that the large-scale environment has a minimal effect on the evolution of a galaxy once the luminosity and morphology are taken into account.

We want to understand if the small-scale environment is more influential in a galaxy's evolution than its large-scale environment. One important question within the small-scale environment asks if tidal influences due to the nearest neighbor galaxy or gravitational potentials from the nearest galaxy group are more influential in a galaxy's evolution. A group consists of multiple galaxies that share the same dark matter halo. A group member will interact gravitationally with all other group members, not just its nearest neighbor. And a galaxy near a group, but not within it, may also experience strong tidal effects from the group similar to and stronger than those from a neighboring galaxy.

5.2 Calculating distances

We employ two different spatial metrics to determine the best way to locate a galaxy's nearest neighbor. Within a relative velocity $v_{rel} < 300$ km/s, we use either the physically closest galaxy in units of h^{-1}Mpc or the galaxy within the smallest fraction of its virial radius; both these methods are described below in further detail. The two methods result in different neighboring galaxies for about 40% of our dwarf galaxy sample.

5.2.1 Peculiar velocity

A galaxy's redshift is composed of both the expansion of the universe and the galaxy's peculiar velocity (its motion relative to its surrounding galaxies and environment). Known as the "Finger of God" effect, the peculiar velocity causes galaxy groups and clusters to appear extended along the line of sight when using redshift as a distance measurement. When we calculate distances on large scales, the peculiar velocity is negligible. However, when we study the distance between two objects in the universe on a small scale (within a few h^{-1}Mpc), the peculiar velocity dominates. The relative velocity v_{rel} between galaxies a and b is defined as

$$v_{rel} = |z_a - z_b|c \tag{5.1}$$

where z is the redshift. We require all neighbors to have a maximum relative velocity $v_{rel} <$ 300 km/s. We show in Sec. 5.4.3 that our results are insensitive to this value.

5.2.2 Sky separation in h^{-1}Mpc

The projected distance between two galaxies is found by projecting the two galaxies onto a sphere of radius $\bar{r}$, where $\bar{r}$ is the average distance from Earth of the two galaxies. This assumes that two galaxies which are gravitationally bound are in a system where the relative velocity between us and it is 0 and that $\bar{r}$ is the distance to the center of the system. The distance to the system is calculated as

$$\bar{r} = \frac{\bar{z}c}{H_0} \tag{5.2}$$

where $\bar{z}$ is the average redshift of the two galaxies, c is the speed of light, and H_0 is the Hubble constant. Each galaxy's right ascension (RA) and declination (dec.) are converted to Cartesian coordinates to find their sky separation.

5.2.3 Fractional virial radii

From Hwang & Park (2010), we calculate the virial radius of a galaxy to be

$$r_{vir} = (3L\gamma/4\pi/200\rho_c)^{1/3} \tag{5.3}$$

where L is the galaxy's luminosity, γ is the mass-to-light ratio, and ρ_c is the critical density of the universe. The critical density is the density at which evenly distributed gas would collapse to form a galaxy. The mass-to-light ratio depends on the galaxy's morphology type, where $\gamma_{early} = 2\gamma_{late}$. Hwang & Park (2010) defines $200\rho_c = 740\bar{\rho}$, where $\bar{\rho} = (0.0223 \pm 0.0005)(\gamma_{late} L_{-20})(h^{-1}\mathrm{Mpc})^3$. We can then rewrite Eqn. 5.3 as

$$r_{vir} = \left(\frac{3}{4 \times 740 \times 0.0223\pi} \frac{\gamma}{\gamma_{late}} \frac{L}{L_{-20}} \right)^{1/3} \tag{5.4}$$

where L_{-20} is the luminosity of a galaxy with $M_r = -20$. We can then use the virial radius to scale the distance between two galaxies as a fraction of the neighbor's virial radius.

Rather than using a measure of the virial radius for the group analysis, we scale the distance as a fraction of the group's root mean square (rms) radius.

5.2.4 Absolute distance to nearest neighbor

We can also calculate the distance between two galaxies by ignoring the effects of their relative velocities. Instead of projecting both galaxies onto a sphere with radius $\bar{r}$, we instead project each onto its own sphere of radius

$$r = \frac{cz}{H_0} \tag{5.5}$$

We then convert to Cartesian coordinates and use the three-dimensional Pythagorean theorem to calculate the distance between the two galaxies.

5.3 SDSS Data and galaxy selection

The Sloan Digital Sky Survey Data Release 7 (SDSS DR7; Abazajian et al., 2009) is a wide-field multiband imaging and spectroscopic survey which maps approximately one-quarter of the northern sky using a drift scanning technique. Photometric data in the five-band SDSS system — u, g, r, i, and z — is taken on a dedicated 2.5m telescope at the Apache Point Observatory in New Mexico (Fukugita et al., 1996; Gunn et al., 1998). Galaxies with Petrosian r-band magnitudes $m_r < 17.77$ are selected for follow-up spectroscopic analysis (Lupton et al., 2001; Strauss et al., 2002). The galaxy colors are taken from the Korean Institute for Advanced Study Value-Added Galaxy Catalog (KIAS-VAGC; Choi et al., 2010), which contains galaxies from the SDSS DR7 main sky survey based on the New York University Value-Added Galaxy Catalog Data Release 7 (NYU-VAGC; Blanton et al., 2005). Total star formation rates (SFR) and total specific star formation rates (sSFR) are from the MPA-JHU value-added catalog[1], calculated using the technique described in Brinchmann et al. (2004). The gas-phase chemical abundances used are from Douglass & Vogeley (2017, in prep.), which are calculated using the Direct T_e method. The galaxies' large-scale environments are based on the void catalog compiled by Pan et al. (2012), which is constructed from SDSS DR7 using the VoidFinder algorithm of Hoyle & Vogeley (2002). Galaxies which are located within identified voids are labeled as void galaxies, and those which do not fall within a void are designated as a wall galaxy. The large-scale environment within 5 h^{-1}Mpc of the edge of the main SDSS DR7 footprint cannot be described using the VoidFinder algorithm because the minimum diameter of a void is 10 h^{-1}Mpc. Therefore, the large-scale environment for galaxies within 5 h^{-1}Mpc of the edge of the main footprint in SDSS DR7 is designated as unknown.

5.3.1 Various samples

Two galaxy samples are used in this analysis. The largest one contains the 11,845 dwarf galaxies spectroscopically observed in SDSS DR7. The second sample contains those star-forming dwarf galaxies from the first set which have gas-phase chemical abundances in Douglass & Vogeley (2017, in prep.), totaling 2506 dwarf galaxies. While this subset of galaxies contains only star-forming

[1] Available at `http://www.mpa-garching.mpg.de/SDSS/DR7/`

galaxies and is not representative of all dwarf galaxies, we show in Section 5.4.3 that this does not affect our results.

5.3.2 Group catalog

In addition to comparing the target galaxies to their nearest neighbor, we also look at the relationship between the dwarf galaxies' properties and their proximity to the nearest galaxy group. We use the Mr18 Berlind group catalog Berlind et al. (2006) as our source of groups, which is built on the galaxies in the NYU-VAGC. The catalog identifies groups using a friends-of-friends algorithm (Huchra & Geller, 1982) to connect galaxies with $M_r < -18$.

5.4 Distance analysis and results

Our primary objective is to compare various physical characteristics of dwarf galaxies against their nearest neighbors or groups to discern how the small-scale environment affects their evolution.

5.4.1 Parameter – distance relations

The relationships between various physical parameters and the distance to the nearest neighbor or group for our sample of star-forming dwarf galaxies are shown in Figs. 5.1–5.5. In each of the four plots within each figure, we bin the galaxies in distance-space and show the average parameter value in each bin, to see any overall trends in the data. We also fit a linear line to the data; the output of these fits are in Table 5.1. Each of these four plots probes this distance relationship from a different angle. The top left plots in Figs. 5.1–5.5 relate the target dwarf galaxy's parameter to the distance to its nearest neighbor, as defined by the the closest galaxy on the sky in h^{-1}Mpc with a velocity difference less than 300 km/s. The bottom left plots relate the target dwarf galaxy's parameter to the distance to its nearest neighbor, as defined by the closest galaxy on the sky in units of the virial radius of the neighbor galaxy with a velocity difference less than 300 km/s. The nearest galaxy is not necessarily the same for these two distance measurements, as explained in Sec. 5.2.

We repeat this same analysis on the nearest groups to the target dwarf galaxy. The top right plots in Figs. 5.1–5.5 relate the target dwarf galaxy's parameter to the distance to the center of the nearest group, as defined as the closest group in the sky in h^{-1}Mpc with a velocity difference less than 300 km/s. The bottom right plots in Figs. 5.1–5.5 relate the target dwarf galaxy's parameter to the distance to the nearest group as defined by the closest group on the sky in units of the group's rms radius with a velocity difference of less than 300 km/s. Groups are very rare in the void environment (by nature of the void environment), so the uncertainty in the binned values shown in these plots is much larger than in the galaxy neighbor plots.

These figures reveal influences from both the large-scale and small-scale environments, since we are identifying which galaxies reside in void regions and which do not.

Color

Because of the known morphology-density relation, we expect to find that a dwarf galaxy's color became more blue as the distance to its nearest neighbor increased. Fig. 5.1 shows very little relationship between the distance and color, except at the smallest distance bin. The linear fits quantify this observation — the slopes are on the order of 10^{-3}. However, within a distance of 0.05 h^{-1}Mpc or $0.05 r_{vir}$, dwarf galaxies tend to be bluer than at further distances from their nearest neighbor. At distances less than 0.1 h^{-1}Mpc from the center of the nearest groups, the dwarf galaxies are redder than average. However, there does not appear to be any relationship between a dwarf galaxy's color and its distance to the center of the nearest group in units of the group's rms radius. It has been well-established that void galaxies tend to be bluer than galaxies in denser environments (Grogin & Geller, 1999; Rojas et al., 2004; Patiri et al., 2006; von Benda-Beckmann & Müller, 2008; Hoyle et al., 2012); this shift is apparent in Fig. 5.1, where the void dwarf galaxies are slightly bluer than the wall dwarf galaxies.

sSFR

Following our prediction for the color-distance relations, we expect that the sSFR to increase with distance from the nearest neighbor. We also see very little relationship between the distance and sSFR in Fig. 5.2, except in the smallest distance bin. The linear fits quantify this observation — the slopes are on the order of 10^{-3}. Within a distance of 0.05 h^{-1}Mpc or $0.05 r_{vir}$, dwarf galaxies tend to have higher sSFRs than at further distances from their nearest neighbor. There does not appear to be any relationship between a dwarf galaxy's sSFR and its distance to the center of the nearest

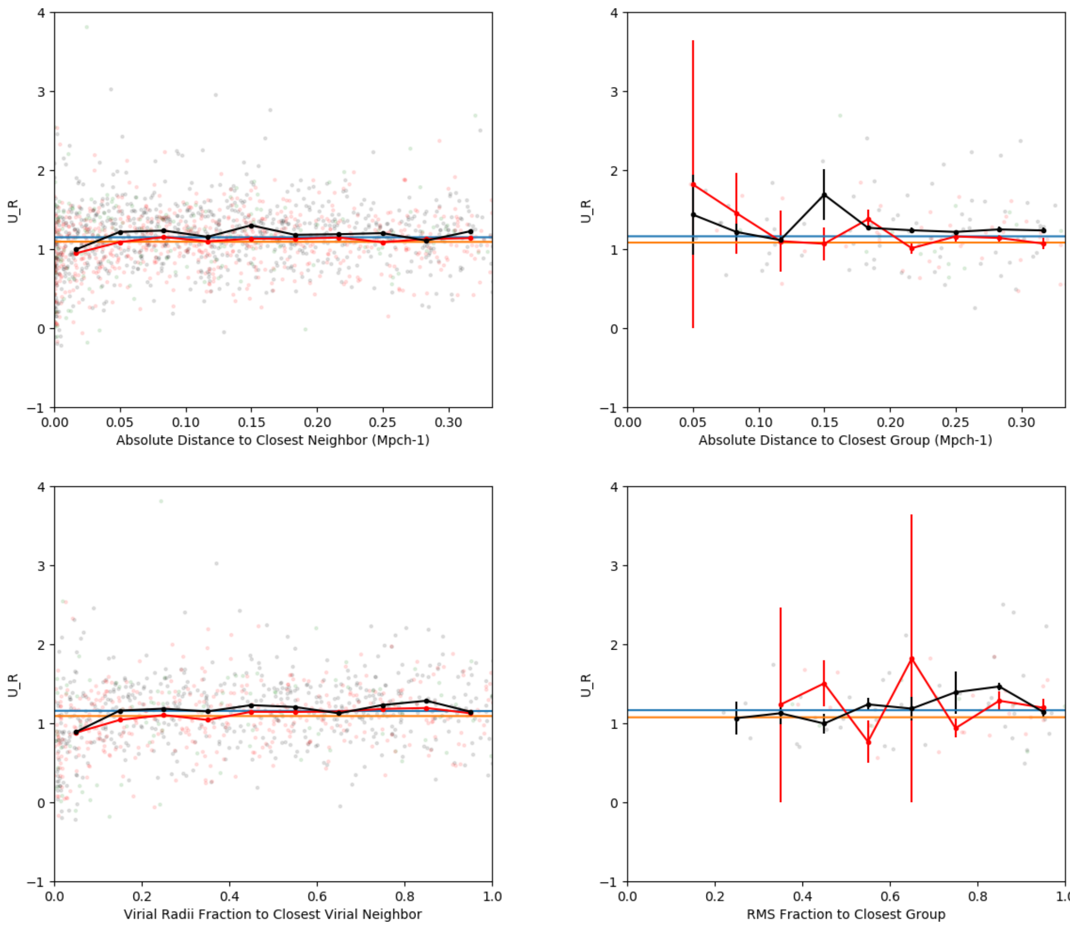

Figure 5.1: Color $(u-r)$ versus distance to the nearest galaxy (on the left) and nearest group (on the right). The top panel shows the color as a function of the sky separation in h^{-1}Mpc between the target dwarf galaxy and the neighbor, while the bottom panel shows the color as a function of the closest virial neighbor. Void galaxies are shown in red, while wall galaxies are shown in black and unknown in green. We have also included the average color for the galaxies after binning by distance, to discern any finer behavior in the relationships. Linear fits to the void and wall galaxies are shown in orange and blue, respectively. It is clear that the void dwarf galaxies are bluer than the wall dwarf galaxies. The nearest galaxies appear to only have some affect on the dwarf galaxy's color at separations less than 0.05 h^{-1}Mpc, or $0.05r_{vir}$. The closest group appears to have some affect on the target dwarf galaxy's color at distances less than 0.1 h^{-1}Mpc to the group's center; there appears to be no relationship between a dwarf galaxy's color and its distance to the nearest group as represented by the fraction of the group's radius.

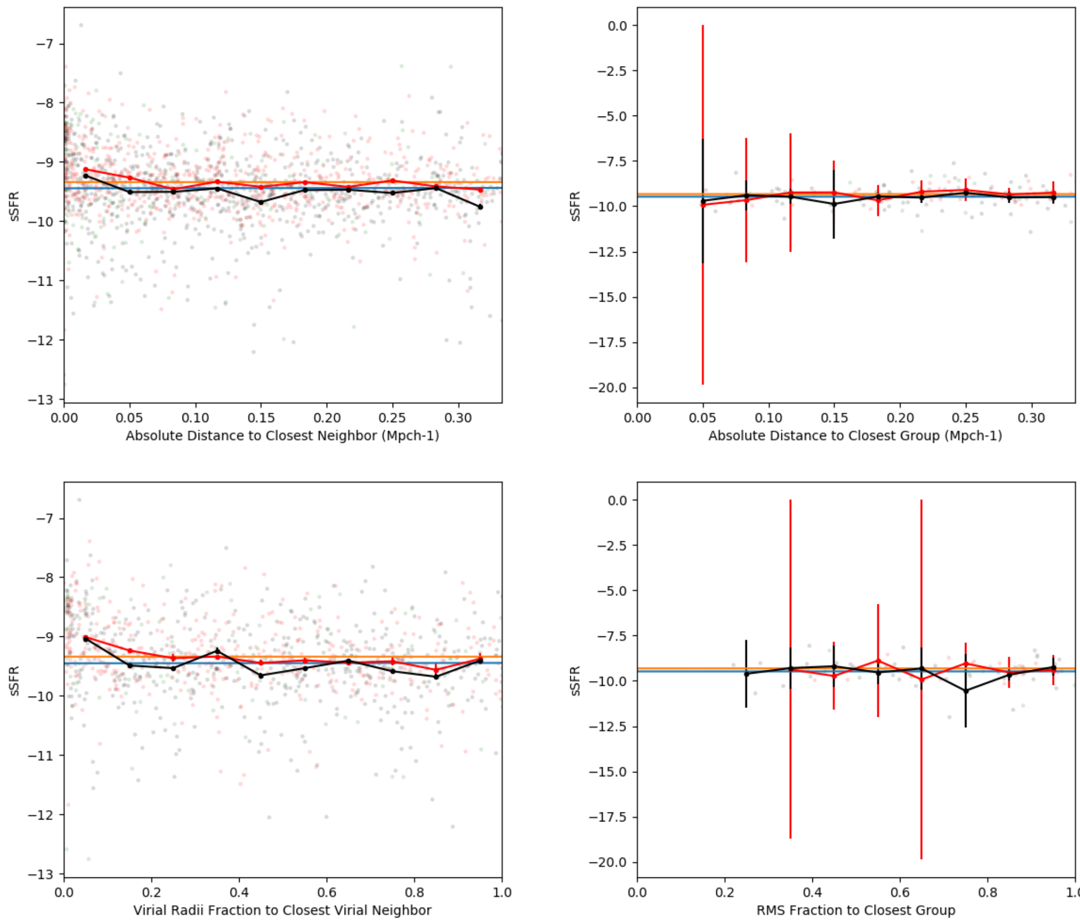

Figure 5.2: sSFR versus distance to the nearest galaxy (on the left) and nearest group (on the right). The top panel shows the sSFR as a function of the sky separation in h^{-1}Mpc between the target dwarf galaxy and the neighbor, while the bottom panel shows the sSFR as a function of the closest virial neighbor. Void galaxies are shown in red, while wall galaxies are shown in black and unknown in green. We have also included the average sSFR for the galaxies after binning by distance, to discern any finer behavior in the relationships. Linear fits to the void and wall galaxies are shown in orange and blue, respectively. It is clear that the void dwarf galaxies have higher sSFRs than the wall dwarf galaxies. Only the neighbor galaxies at separations less than 0.05 h^{-1}Mpc or $0.05r_{vir}$ appear to have some affect on the dwarf galaxies' sSFR. There appears to be no relationship between a dwarf galaxy's sSFR and its distance to the nearest group.

group in either distance metric. In these distance comparisons, there is a shift towards higher sSFRs in the void dwarf galaxies when compared to the wall dwarf galaxies, as has been observed many times before (Rojas et al., 2005; von Benda-Beckmann & Müller, 2008; Moorman et al., 2015; Beygu et al., 2016).

Metallicity

Based on our hypothesis that galaxies would be redder and have lower sSFRs at small distances to their nearest neighbors, we anticipated that the metallicity of the galaxies would decrease with increasing distance. As before, we only see a relationship between the distance and metallicity in the smallest distance bin in Fig. 5.3. The linear fits quantify this observation — the slopes are on the order of 10^{-2}. Within a distance of 0.05 h^{-1}Mpc or $0.05r_{vir}$, dwarf galaxies tend to have higher metallicities than at further distances from their nearest neighbor. At distances less than 0.1 h^{-1}Mpc from the center of the nearest group, dwarf galaxies might have lower than average metallicities. However, this could be an erroneous conclusion due to low-number statistics. In these distance comparisons, there is a shift towards higher metallicities in the void dwarf galaxies when compared to the wall dwarf galaxies, as has been observed by Douglass & Vogeley (2017b) and Douglass & Vogeley (2017, in prep).

Nitrogen abundance

It was expected that the gas-phase nitrogen abundance would follow the same trend as the metallicity, to decrease with increasing distance. As observed with the other parameters, Fig. 5.4 shows very little relationship between the distance and N/H, except in the smallest distance bin for the closest virial neighbor. The linear fits quantify this observation — the slopes are on the order of 10^{-2}. Within a distance of $0.05r_{vir}$, dwarf galaxies tend to have higher nitrogen abundances than at distances further from their nearest neighbor. There does not seem to be any relationship between the nitrogen abundance of the star-forming dwarf galaxies and distance to the center of the nearest group. Unlike the shifts seen with the other parameters and what is observed in Douglass & Vogeley (2017b) and Douglass & Vogeley (2017, in prep), we see no significant difference in the nitrogen abundance resulting from the large-scale environment.

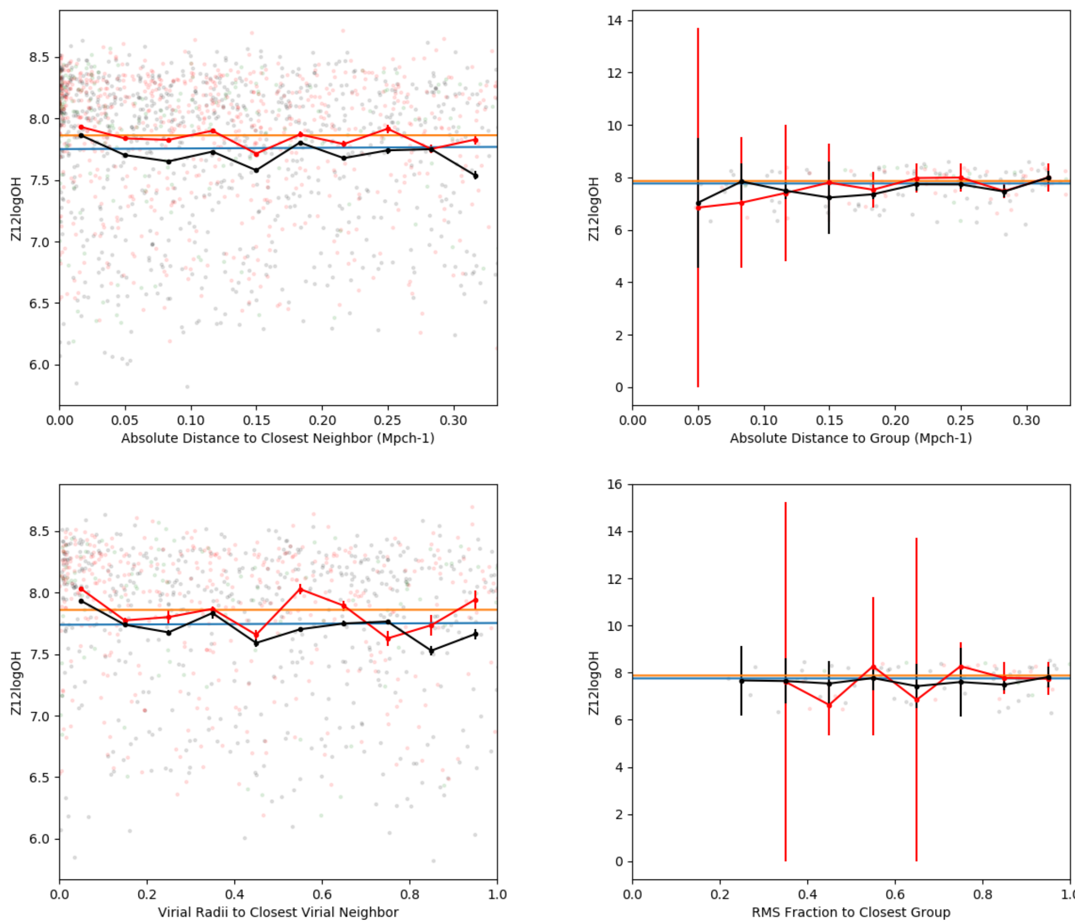

Figure 5.3: Metallicity versus distance to the nearest galaxy (on the left) and nearest group (on the right). The top panel shows the metallicity as a function of the sky separation in h^{-1}Mpc between the target dwarf galaxy and the neighbor, while the bottom panel shows the metallicity as a function of the closest virial neighbor. Void galaxies are shown in red, while wall galaxies are shown in black and unknown in green. We have also included the average metallicity for the galaxies after binning by distance, to discern any finer behavior in the relationships. Linear fits to the void and wall galaxies are shown in orange and blue, respectively. It is clear that the void dwarf galaxies have higher metallicities than the wall dwarf galaxies. Only the neighbor galaxies at separations less than 0.05 h^{-1}Mpc or $0.05r_{vir}$ appear to have some affect on the dwarf galaxies' metallicity. When measuring the distance to the nearest group in h^{-1}Mpc, it appears that the dwarf galaxies have lower metallicities at distances less than 0.1 h^{-1}Mpc from their nearest group.

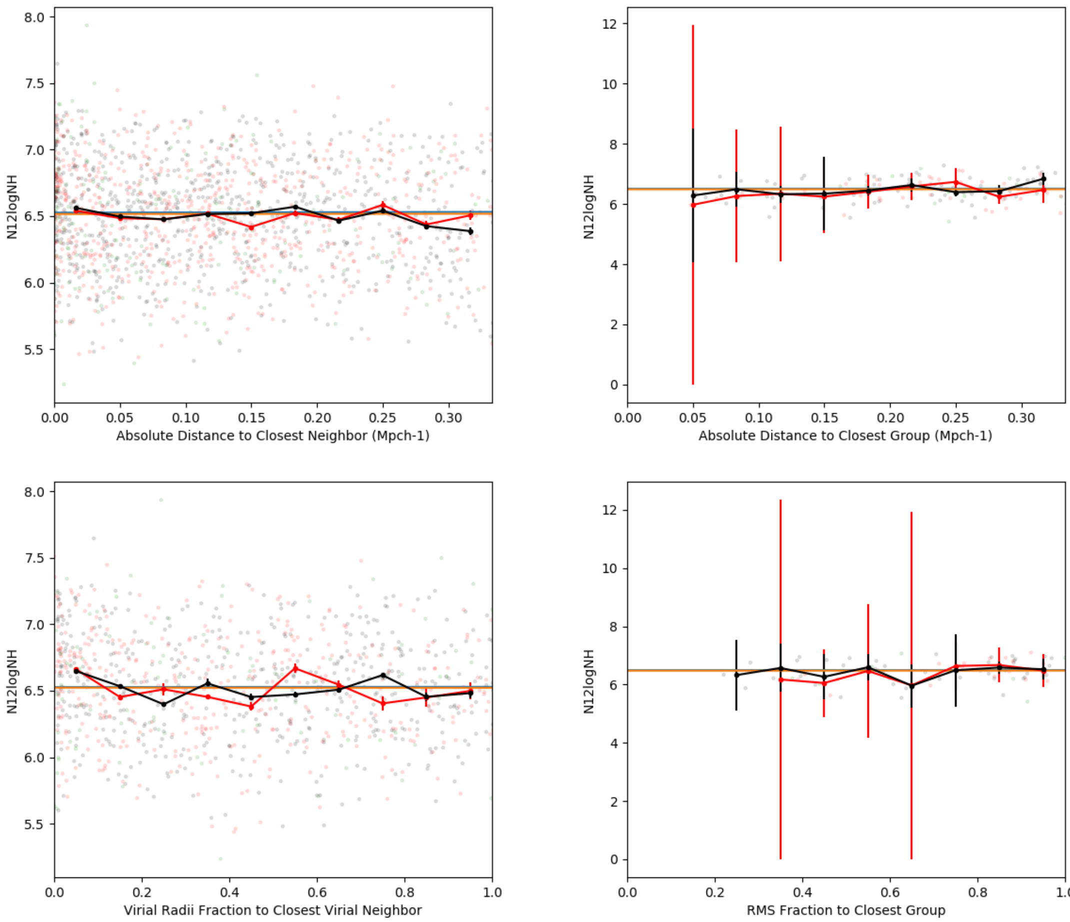

Figure 5.4: Gas-phase nitrogen abundance versus distance to the nearest galaxy (on the left) and nearest group (on the right). The top panel shows N/H as a function of the sky separation in h^{-1}Mpc between the target dwarf galaxy and the neighbor, while the bottom panel shows N/H as a function of the closest virial neighbor. Void galaxies are shown in red, while wall galaxies are shown in black and unknown in green. We have also included the average nitrogen abundance for the galaxies after binning by distance, to discern any finer behavior in the relationships. Linear fits to the void and wall galaxies are shown in orange and blue, respectively. There is very little difference in N/H between the two large-scale environments. Only the neighbor galaxies at separations less than $0.05r_{vir}$ appear to have some affect on the dwarf galaxies' nitrogen abundance. There does not appear to be any relationship between the dwarf galaxies' nitrogen abundance and the distance to their nearest group.

N/O ratio

We do not expect any influence on the relative synthesis of oxygen and nitrogen from the proximity to a nearest neighbor. Unlike the other parameters studied, Fig. 5.5 shows that the N/O ratio does not have any relationship with the distance to a nearest neighbor at any separation. This is reflected in the linear fits to the data — the slopes are on the order of 10^{-2} and smaller. When looking at the relationship between the N/O ratio and the distance to the nearest group, though, the N/O ratio might be higher than average in galaxies within 0.1 h^{-1}Mpc of the group's center. The shift towards lower N/O ratios in star-forming void dwarf galaxies is readily apparent, as Douglass & Vogeley (2017b) and Douglass & Vogeley (2017, in prep) find.

5.4.2 Linear fit parameters

To quantify the results shown in Figs. 5.1–5.5, we calculate the parameters for the best fit linear line. Any slope of significant magnitude shows an overall correlation between a given physical parameter and the galaxy's distance to its nearest neighbor or group. The results of this analysis are listed in Table 5.1. These slopes reflect the observations described in Section 5.4.1: there is no correlation between the distance to the nearest neighbor and a galaxy's color, sSFR, or gas-phase chemical abundances. This analysis does not capture any variations within the range of distances for all dwarf galaxies included in this study.

5.4.3 Selection effects

We test two components of our nearest neighbor criteria to understand how sensitive our results are to any initial conditions. The first parameter we discuss is the sensitivity of our results on the maximum peculiar velocity to define a match. Throughout our analysis, we use 300 km/s as the maximum velocity separation allowed between the target galaxy and its nearest neighbor or group. We look at how this affects our results by repeating the analysis with maximum velocities of 150 km/s and 600 km/s. The results of this comparison on the color of the galaxies can be seen in Fig. 5.6. The nearest neighbors in the left-hand panel are restricted to a maximum peculiar velocity of 150 km/s, while those in the right panel are restricted to 600 km/s. When compared to each other

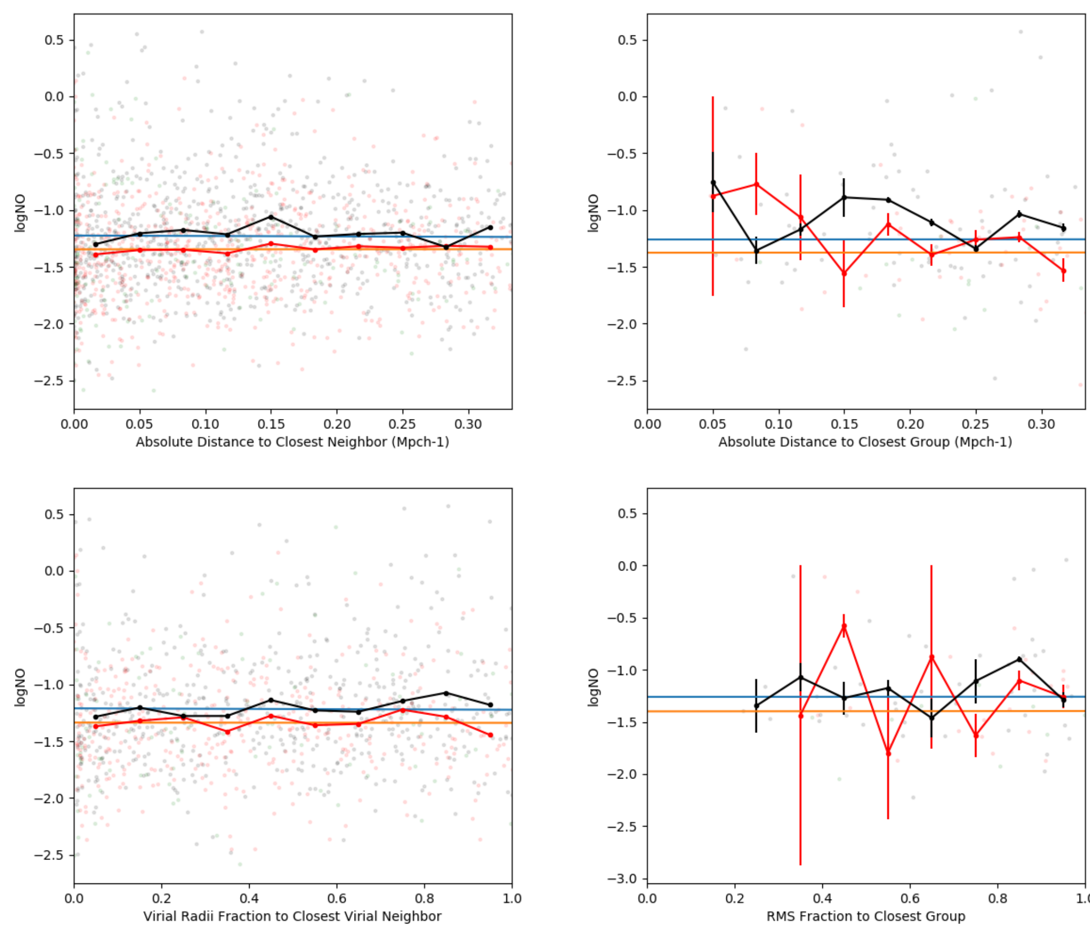

Figure 5.5: N/O ratio versus distance to the nearest galaxy (on the left) and nearest group (on the right). The top panel shows the N/O ratio as a function of the sky separation in h^{-1}Mpc between the target dwarf galaxy and the neighbor, while the bottom panel shows N/O as a function of the closest virial neighbor. Void galaxies are shown in red, while wall galaxies are shown in black and unknown in green. We have also included the average nitrogen abundance for the galaxies after binning by distance, to discern any finer behavior in the relationships. Linear fits to the void and wall galaxies are shown in orange and blue, respectively. The void dwarf galaxies have lower N/O ratios than the wall dwarf galaxies, but there is no distinct relationship between the distance to the nearest neighbor and the N/O ratio. The N/O ratio might be higher in dwarf galaxies within 0.05 h^{-1}Mpc of the center of the closest group.

Table 5.1: Linear fit parameters to various properties of the target dwarf galaxies by their distances to the nearest galaxy in units of h^{-1}Mpc, the nearest galaxy in units of the neighbor's virial radius, the center of the nearest group in units of h^{-1}Mpc, and the nearest group in units of the group's rms radius; all objects must be within 300 km/s of the target galaxy. The slopes are all negligible, quantifying the observations made that the proximity to a galaxy or group has little influence on a dwarf galaxy's evolution.

Property	Slope (wall)	Slope (void)	Intercept (wall)	Intercept (void)
Nearest galaxy by distance				
$u-r$	$1.25 \pm 1.17 \times 10^{-3}$	$-9.14 \pm 0.56 \times 10^{-3}$	1.15 ± 0.00076	1.09 ± 0.00049
sSFR	$2.07 \pm 0.18 \times 10^{-2}$	$-0.16 \pm 0.08 \times 10^{-3}$	-9.45 ± 0.001	-9.34 ± 0.0007
$12 + \log(\text{O/H})$	$5.35 \pm 0.17 \times 10^{-2}$	$0.33 \pm 0.08 \times 10^{-2}$	7.75 ± 0.0011	7.86 ± 0.0007
$12 + \log(\text{N/H})$	$1.64 \pm 0.11 \times 10^{-2}$	$0.62 \pm 0.06 \times 10^{-2}$	6.53 ± 0.0007	6.52 ± 0.0006
$\log(\text{N/O})$	$-3.70 \pm 0.13 \times 10^{-2}$	$0.29 \pm 0.07 \times 10^{-2}$	-1.23 ± 0.0009	-1.35 ± 0.0006
Nearest galaxy by fraction of virial radius				
$u-r$	$-3.81 \pm 0.04 \times 10^{-3}$	$-0.46 \pm 0.01 \times 10^{-3}$	1.16 ± 0.00014	1.09 ± 0.00008
sSFR	$5.96 \pm 0.06 \times 10^{-3}$	$-0.41 \pm 0.02 \times 10^{-3}$	-9.45 ± 0.0002	-9.33 ± 0.0001
$12 + \log(\text{O/H})$	$1.41 \pm 0.005 \times 10^{-2}$	$0.12 \pm 0.08 \times 10^{-2}$	7.74 ± 0.0002	7.86 ± 0.0001
$12 + \log(\text{N/H})$	$1.82 \pm 0.11 \times 10^{-3}$	$-1.14 \pm 0.002 \times 10^{-3}$	6.53 ± 0.0001	6.52 ± 0.0001
$\log(\text{N/O})$	$-1.22 \pm 0.004 \times 10^{-2}$	$-0.41 \pm 0.02 \times 10^{-3}$	-1.21 ± 0.0002	-1.33 ± 0.0001
Nearest group by distance				
$u-r$	$-2.53 \pm 0.01 \times 10^{-3}$	$1.34 \pm 0.01 \times 10^{-3}$	1.16 ± 0.00008	1.08 ± 0.0001
sSFR	$7.77 \pm 0.02 \times 10^{-3}$	$-1.68 \pm 0.02 \times 10^{-3}$	-9.48 ± 0.001	-9.33 ± 0.0001
$12 + \log(\text{O/H})$	$3.65 \pm 0.16 \times 10^{-4}$	$2.06 \pm 0.19 \times 10^{-4}$	7.77 ± 0.0001	7.86 ± 0.0001
$12 + \log(\text{N/H})$	$4.84 \pm 0.01 \times 10^{-3}$	$6.30 \pm 0.01 \times 10^{-3}$	6.51 ± 0.00008	6.49 ± 0.0001
$\log(\text{N/O})$	$4.47 \pm 0.01 \times 10^{-3}$	$6.09 \pm 0.01 \times 10^{-3}$	-1.26 ± 0.0001	-1.38 ± 0.0001
Nearest group by fraction of group radius				
$u-r$	$-1.00 \pm 0.002 \times 10^{-3}$	$0.90 \pm 0.002 \times 10^{-3}$	1.16 ± 0.00003	1.07 ± 0.00003
sSFR	$2.70 \pm 0.002 \times 10^{-3}$	$-1.71 \pm 0.002 \times 10^{-3}$	-9.48 ± 0.00005	-9.31 ± 0.00005
$12 + \log(\text{O/H})$	$8.81 \pm 0.02 \times 10^{-4}$	$-8.74 \pm 0.19 \times 10^{-4}$	7.76 ± 0.00005	7.88 ± 0.00005
$12 + \log(\text{N/H})$	$2.31 \pm 0.001 \times 10^{-3}$	$2.47 \pm 0.001 \times 10^{-3}$	6.49 ± 0.00003	6.47 ± 0.00004
$\log(\text{N/O})$	$1.43 \pm 0.002 \times 10^{-3}$	$3.35 \pm 0.002 \times 10^{-3}$	-1.26 ± 0.00005	-1.40 ± 0.00005

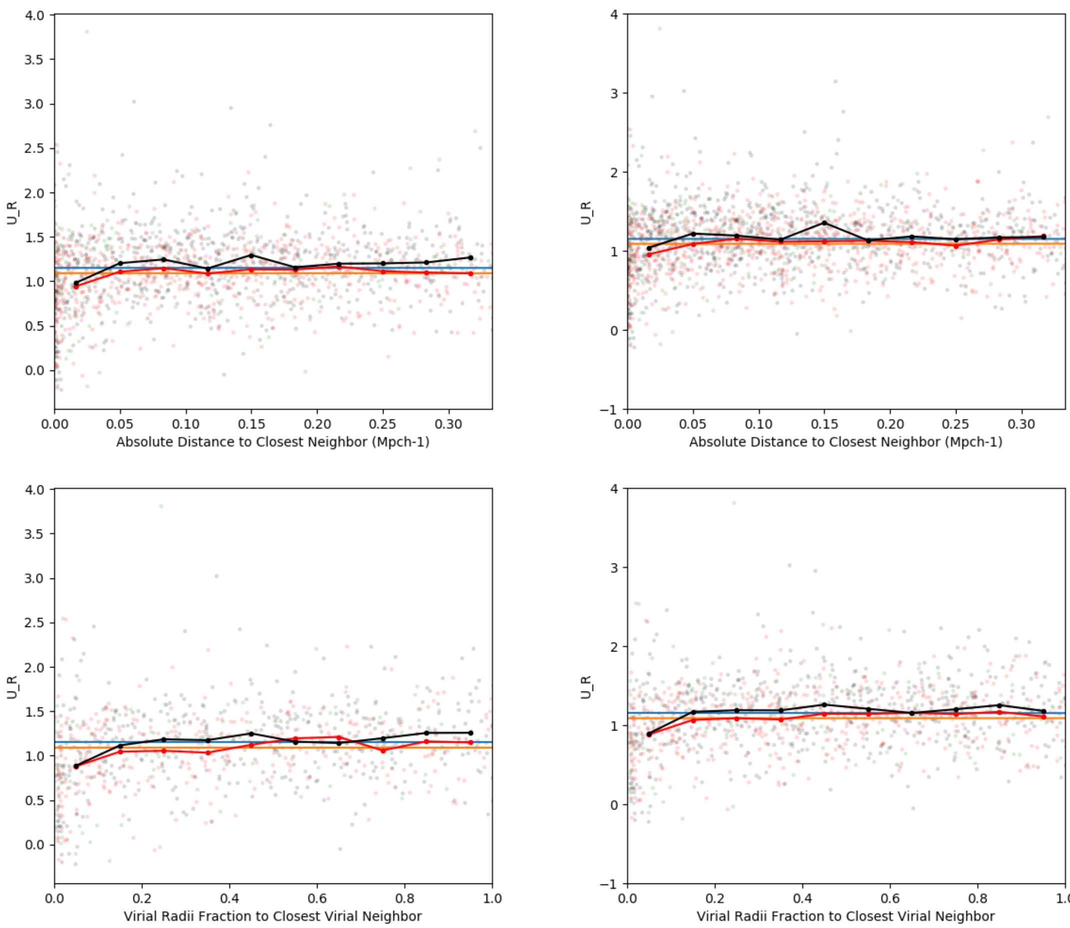

Figure 5.6: Color versus distance to nearest galaxy (in units of h^{-1}Mpc on top and virial radii on bottom), with a maximum allowed peculiar velocity of 150 km/s in the left panel and 600 km/s in the right panel. Void galaxies are shown in red, wall in black, and unknown in green. The galaxies are binned by distance to tease out any trends at smaller distance scales; linear fits to the void and wall galaxies are shown in orange and blue, respectively. When compared with the two plots in the left panel of Fig. 5.1, we see that there is no significant influence on our results from the choice of maximum peculiar velocity allowed.

and to the left-hand panel of Fig. 5.1, it is clear that our choice of maximum peculiar velocity has no affect on the results of the study.

We also test the sensitivity of our results to the population of galaxies being studied. Because we want to look at the relationship between distance and the gas-phase chemical abundances of the dwarf galaxies, our sample is limited to star-forming dwarf galaxies with detected emission lines necessary for estimation of the chemical abundances with the Direct T_e method (see Douglass & Vogeley, 2017a, for more details). We perform the same distance analysis on all dwarf galaxies detected in SDSS DR7 with respect to their color, to understand how our results depend on our sample. When we compare Fig. 5.7 with the left-hand panel of Fig. 5.1, we see that there is no difference in the correlation between color and distance to the nearest neighbor. It is clear that our selection bias to star-forming dwarf galaxies does not influence any trends we observe in our analysis.

For about 41% of our dwarf galaxy sample, the two different metrics by which to define the nearest neighbor (minimum in units of h^{-1}Mpc or virial radius of the nearest neighbor) return different neighboring galaxies. Fig. 5.8 compares the absolute magnitude distributions of these two nearest neighbor populations. The left panel shows the distribution of the absolute magnitudes of the nearest neighbor galaxies, while the right panel shows the distribution in absolute magnitude of the nearest neighbor galaxy relative to its target galaxy. The top row includes those nearest neighbors in units of h^{-1}Mpc, and the bottom row consists of the nearest neighbors in units of the neighbor's virial radius. Comparing the two plots in the right panel, we see that the closest galaxy to the target dwarf galaxy is often of equal or fainter magnitude than the target galaxy. Alternatively, using the virial radius of the neighbor galaxy as a measure of the distance often finds a brighter galaxy than the target galaxy, as the bottom right plot in Fig. 5.8 shows. By using these two different distance metrics, we are able to probe the relationship between a dwarf galaxy and its nearest neighbor and nearest dark matter halo.

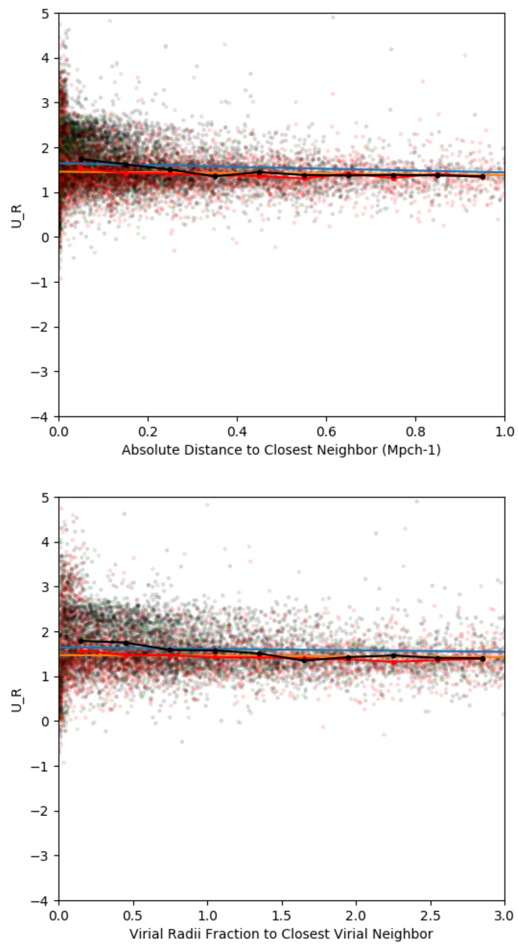

Figure 5.7: Color versus distance to the nearest galaxy (in units of h^{-1}Mpc on top and virial radii on the bottom) for the entire dwarf galaxy population in SDSS DR7. When compared to the left-hand panel of Fig. 5.1, we see that there is no difference in the results of the analysis by studying only star-forming galaxies with sufficient detection of the various emission lines necessary to estimate the gas-phase chemical abundances.

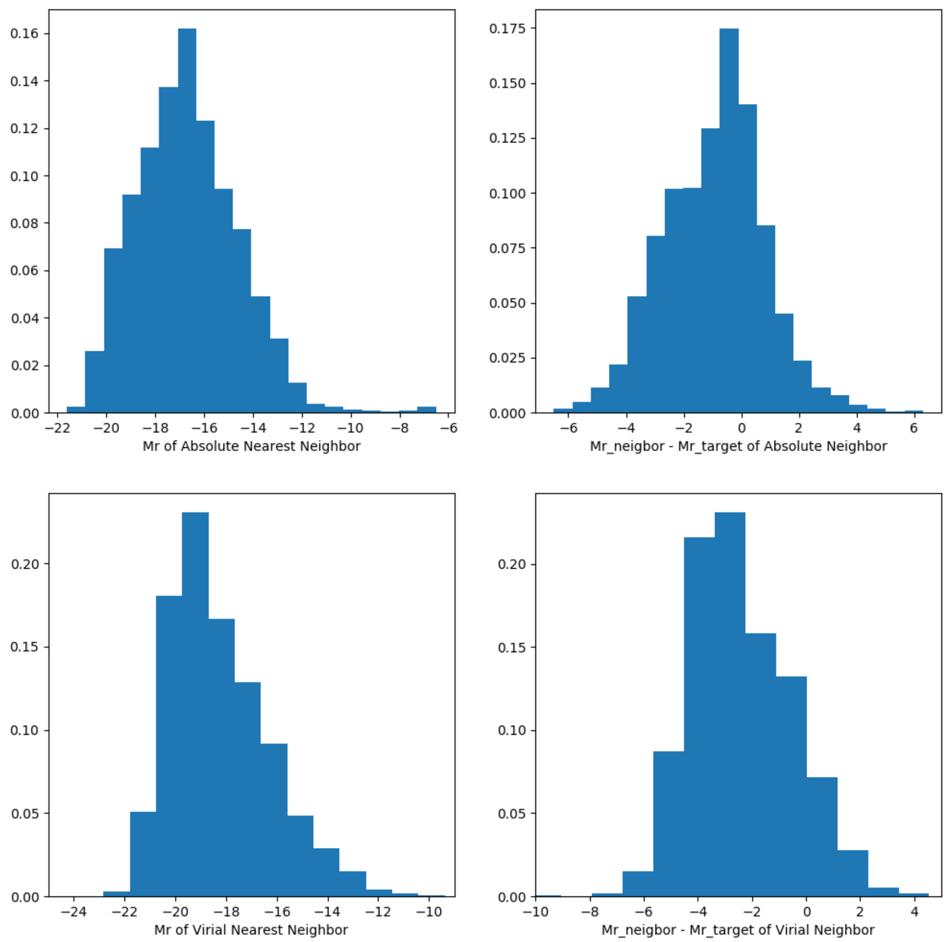

Figure 5.8: The distributions in absolute magnitude (left panel) and absolute magnitude relative to the target galaxy (right panel) of the nearest neighbor galaxies. The top row includes those nearest neighbors in units of h^{-1}Mpc, and the bottom row consists of the nearest neighbors in units of the neighbor's virial radius. Comparing the two plots in the right panel, we see that the closest galaxy to the target dwarf galaxies is often of equal or fainter magnitude than the target galaxy. Alternatively, using the virial radius of the neighbor galaxy as a measure of distance often finds a brighter galaxy than the target galaxy, as the bottom right plot shows.

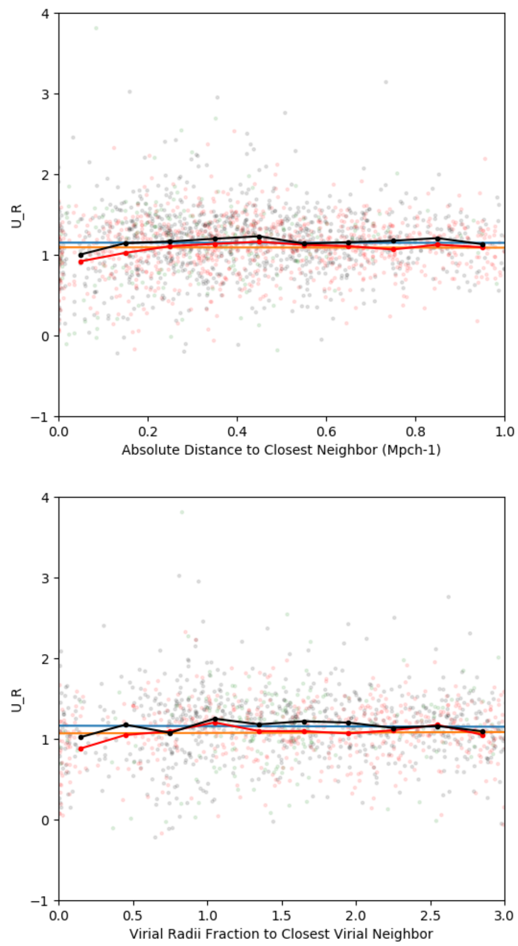

Figure 5.9: Color versus distance to the nearest galaxy (in units of h^{-1}Mpc on top and virial radii on the bottom) for the star-forming dwarf galaxies. The redshift is included when calculating the distance to the nearest neighbor. While there is still no correlation between distance and color, we do note that there is a gap in the distribution of galaxies around a distance of 0.05 h^{-1}Mpc or $0.5r_{vir}$ from the nearest neighbor.

5.4.4 Including redshift in the distance

Realizing that the peculiar velocity, which is included in a galaxy's redshift, is not insignificant at the smaller scales, we have been careful to avoid calculating the distance between objects with the redshift. However, we are interested to see how the inclusion of redshift in the distance calculations affects the results of our analysis. Therefore, we repeat the same analysis on the relationship between color and distance, but this time we include redshift as a third component in the distance calculations. Consequently, we no longer limit our sample by a peculiar velocity separation. Fig. 5.9 shows the relationship between these distances and the color of the star-forming dwarf galaxies. When compared to Fig. 5.1, we see that there is no change in the correlation between distance and color for the galaxies.

We note the existence of a gap in the distribution of galaxies around a distance of 0.05 h^{-1}Mpc or $0.5r_{vir}$ from the nearest neighbor that is not present in Fig. 5.1. When we incorporate the redshift into the distance calculations, the resulting distance between galaxies which have small sky separations but larger redshift separations is much larger than those with larger sky separations and little redshift separation. As a result, galaxies which were originally close to the color axis in Fig. 5.1 will be moved to much larger distances, while the locations of those which were originally further from the color axis will change much less. The dwarf galaxies which remain close to the color axis in Fig. 5.9 must, therefore, have small sky separation and almost no difference in their peculiar velocities. We surmise that these represent merging systems, which future visual inspection will help to confirm.

5.5 Discussion

We see no relationship between a dwarf galaxy's color, sSFR, or gas-phase chemical abundances and its distance to the nearest galaxy or group beyond the target galaxy's immediate vicinity, implying that the small-scale environment does not significantly influence a dwarf galaxy's evolution. This is in contrast to the large-scale environment, which we have seen to influence the formation and evolution of dwarf galaxies.

Only those galaxies within 0.05 h^{-1}Mpc and $0.05r_{vir}$ of a nearest neighbor, or those within 0.1 h^{-1}Mpc of the nearest group appear to deviate from the average galaxy values. The target galaxies within this proximity of their nearest neighbor tend to be bluer, have a higher sSFR, and have higher oxygen and nitrogen abundances. Based on the shift in the distribution of galaxies seen in Fig. 5.9, these galaxies might be merging or strongly interacting with their nearest neighbor. If so, this provides evidence that galaxy interactions result in a burst of star formation that increases the gas-phase chemical abundances of the dwarf galaxies. Because merging galaxies share the same dark matter halo, it appears that the sharing of a dark matter halo has more influence on the evolution of a galaxy than the distance to its nearest neighbor.

In contrast, dwarf galaxies within 0.1 h^{-1}Mpc of the center of the nearest group are redder, have lower oxygen abundances (O/H), and have higher N/O ratios than average. Being so close to the center of a group seems to prevent more recent episodes of star formation. Due to their proximity to the group center, it is also likely that these dwarf galaxies are not able to retain as much of their heavy elements as a more isolated galaxy, thereby reducing their gas-phase oxygen abundance (and increasing their N/O ratio).

5.5.1 Comparison to literature results

The influence on the gas-phase oxygen abundance within 0.05 h^{-1}Mpc and $0.05r_{vir}$ agrees with the results of Shields et al. (1991); Pustilnik et al. (2006); Cooper et al. (2008); Ellison et al. (2009); Pustilnik et al. (2011b); Pustilnik (2014), and Sánchez Almeida et al. (2016), which all find that galaxies with higher metallicities preferentially reside in denser regions. Work by Rupke et al. (2008) finds that interacting galaxies have suppressed metallicities due to interaction- or merger-induced gas flows into the galaxy centers.

A study combining the effects of interactions and the large-scale environment is explained in Park & Choi (2009). They find two characteristic distances within which the behavior of the target galaxy changes: $0.05r_{vir}$ and r_{vir} of the neighboring galaxy. Our results seem to confirm the significance of distances out to $0.05r_{vir}$, while we see no significant change around the virial radius of the neighboring galaxy. While they only look at galaxies with $M_r < -19$ and limit the neighbors to be at least half a magnitude brighter than the target, Park & Choi (2009) find that the morphology and luminosity play a significant role in these relationships. Of particular note is their observation that star formation increases in late type galaxies when their nearest neighbor is also of late type. This is the same behavior we see in our sample of dwarf galaxies at distances less than $0.05 r_{vir}$. With all our target galaxies actively forming stars, and more than half of their nearest neighbors also dwarf galaxies, it is most likely that our galaxy pairs are also of the late-late type. Based on the results of Park & Choi (2009), the deviations we see for those galaxies with nearest neighbors within 0.05 h^{-1}Mpc and $0.05 r_{vir}$ warrant further study.

5.6 Conclusions

Using the star-forming dwarf galaxies in the SDSS DR7 sample with gas-phase chemical abundances from Douglass & Vogeley (2017, in prep), we investigate the influence of the small-scale environment on the evolution of dwarf galaxies. From the ∼2000 galaxies in the sample, there only appears to be an effect from a neighboring galaxy within 0.05 h^{-1}Mpc or $0.05 r_{vir}$. The proximity of a group seems to only affect the target dwarf galaxy if it is within 0.1 h^{-1}Mpc. Thus, the small-scale (∼ 1 h^{-1}Mpc) environment does not appear to strongly influence the evolution of dwarf galaxies.

We examine the relationship between distance to the nearest neighbor or group and the target galaxy's color, sSFR, and gas-phase chemical abundances. We find that, for those galaxies with a neighbor within 0.05 h^{-1}Mpc or $0.05 r_{vir}$, the dwarf galaxies are bluer, have a higher sSFR, and have higher oxygen and nitrogen abundances than average. 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 do not depend on the maximum peculiar velocity difference or on the sample (star-forming versus all galaxies).

When we incorporate the redshift into the distance calculations, we find that those galaxies within $0.05 r_{vir}$ are most likely mergers or strongly interacting with their nearest neighbor. This matches the results of Park & Choi (2009), who find that late-late type galaxy pairs within $0.05 r_{vir}$ are bluer and have higher star formation rates. These merging galaxies likely share the same dark matter halo, indicating that the dark matter halo is more influential on a galaxy's evolution than its distance to the nearest neighbor.

Further analysis of this study should include comparing the properties of the target galaxies with the nearest neighbors' properties as a function of distance ("galactic conformity"). The gas-phase chemical abundances between a galaxy and its nearest neighbor could be strongly correlated.