Abstract

Observational evidence of the large-scale environmental influence on dwarf galaxy evolution
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We investigate how the cosmic environment affects galaxy evolution in the Universe by studying gas-phase chemical abundances and other galaxy properties as a function of the local and cosmic density of galaxies. Using spectroscopic observations from the Sloan Digital Sky Survey Data Release 7, we estimate the oxygen and nitrogen abundances of 993 star-forming void dwarf galaxies and 759 star-forming dwarf galaxies in denser regions. We use the Direct T_e method for calculating the gas-phase chemical abundances in the dwarf galaxies because it is best suited for low metallicity, low mass galaxies. A substitute for the [O II] λ3727 doublet is developed, permitting oxygen abundance estimates of SDSS dwarf galaxies at all redshifts with the Direct T_e method. We find that star-forming void dwarf galaxies have slightly higher oxygen abundances than star-forming dwarf galaxies in denser environments, but we find that void dwarf galaxies have slightly lower nitrogen abundances and lower N/O ratios than galaxies in denser regions. At smaller scales, 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 within 0.05 h^{-1}Mpc or $0.05r_{vir}$ of another galaxy tend to be bluer, have higher sSFRs, and have higher oxygen and nitrogen abundances than average. In contrast, 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. We also investigate how a galaxy transitions through the color-magnitude diagram, evolving from a blue, star-forming spiral or irregular galaxy in the blue sequence to a red elliptical galaxy in the red cloud through the green valley. We discover that combining a galaxy's color, color gradient, and inverse concentration index defines a galaxy's location on the color-magnitude diagram. The results indicate that there is a higher fraction of dwarf galaxies in denser regions than void dwarf galaxies in the green valley. From these analyses, we surmise that void dwarf galaxies experience delayed star formation as predicted by the ΛCDM cosmology and a dependence of the large-scale environment on cosmic downsizing. We present evidence that void dwarf galaxies have a higher ratio of dark matter halo mass to stellar mass when compared to dwarf galaxies in denser environments.

Chapter 1: Introduction

Large sky surveys (such as the Sloan Digital Sky Survey — SDSS; York et al., 2000) have revealed a non-uniform distribution of galaxies throughout the universe. Taking on a shape similar to that of a sponge or a three-dimensional cosmic web (Bond et al., 1996), galaxies clump together in clusters and along filaments, leaving void regions between these large-scale structures. Evidence of this distribution can be seen in Fig. 1.1 for galaxies in the SDSS Data Release 7 (SDSS DR7; Abazajian et al., 2009). Based on these observations, dark matter simulations have been constructed which successfully reproduce the same large-scale structure. If we start with a mostly uniform distribution of dark matter at the Big Bang, Fig. 1.2 outlines the evolution of that dark matter up through the present. These snapshots from the Millenium Simulation project (Springel et al., 2005) show that small perturbations in the initial distribution of dark matter are amplified as the universe expands. Gravity causes the slightly overdense regions to collapse while simultaneously causing the underdense regions to expand. Due to dark matter's strong gravitational interaction, we believe that the baryonic mattter (matter which interacts electromagnetically) will trace the dark matter distribution, resulting in the galaxy distribution we observe today.

Existing in the cosmological voids, void galaxies are thought to demonstrate the fundamental characteristics of galactic evolution. Cosmic voids are an important environment for studying galaxy formation (see van de Weygaert & Platen, 2011, for a review). Gravitational clustering proceeds as if in a very low density universe, where the amassment of gravitationally bound dark matter halos ends relatively early and there is little subsequent interaction between the galaxies due to the lower density and the faster local Hubble expansion. Therefore, ΛCDM cosmology predicts that galaxies formed in voids should have lower mass and be retarded in their star formation when compared to those in denser regions (e.g., Gottlöber et al., 2003; Goldberg et al., 2005; Cen, 2011). Goldberg & Vogeley (2004) show that a void region that is only 10% of the mean density of the universe with $\Omega_{matter} = 0.3$, $h = 0.7$ dynamically evolves as if $\Omega_{matter} = 0.02$, $\Omega_{\Lambda} = 0.48$, and $h =$

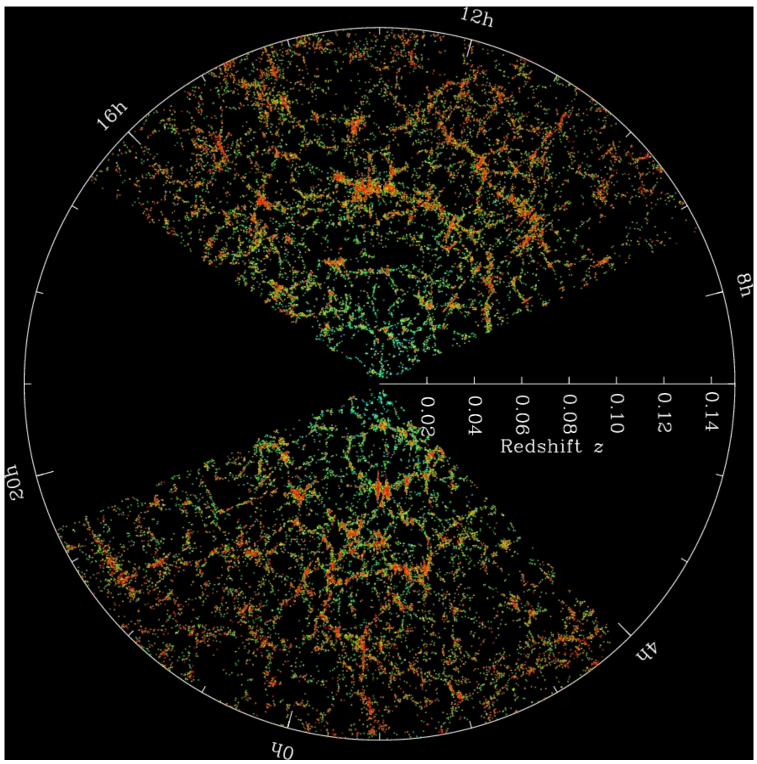

Figure 1.1: A slice through the SDSS galaxy distribution; each point on this plot is a galaxy. Large sky surveys such as SDSS have revealed a non-uniform distribution of galaxies throughout the universe. Dubbed the cosmic web, galaxies clump together in clusters and along filaments, leaving giant gaps between them (similar to a sponge).

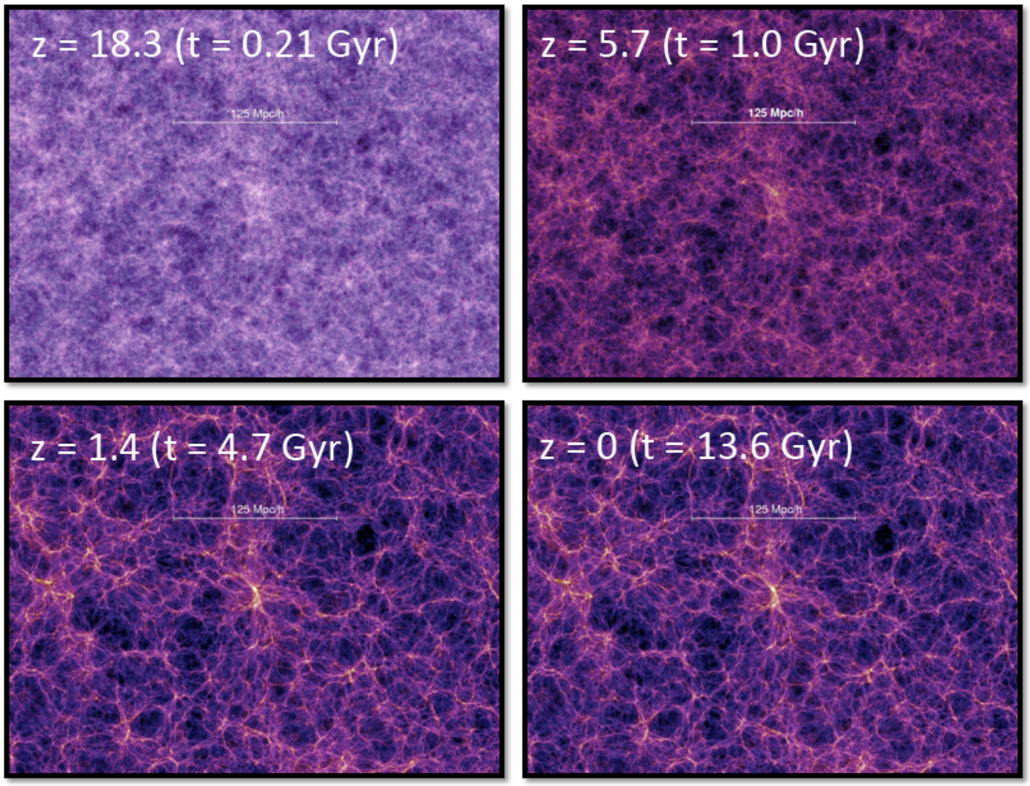

Figure 1.2: Snapshots of a portion of the Millenium Simulation showing the dark matter distribution at different points in time from 0.21 Gyr after the Big Bang to the present. Small perturbations in the initial distribution of dark matter are amplified as the universe expands. Gravity causes the slightly overdense regions to contract while simultaneously causing the underdense regions to expand.

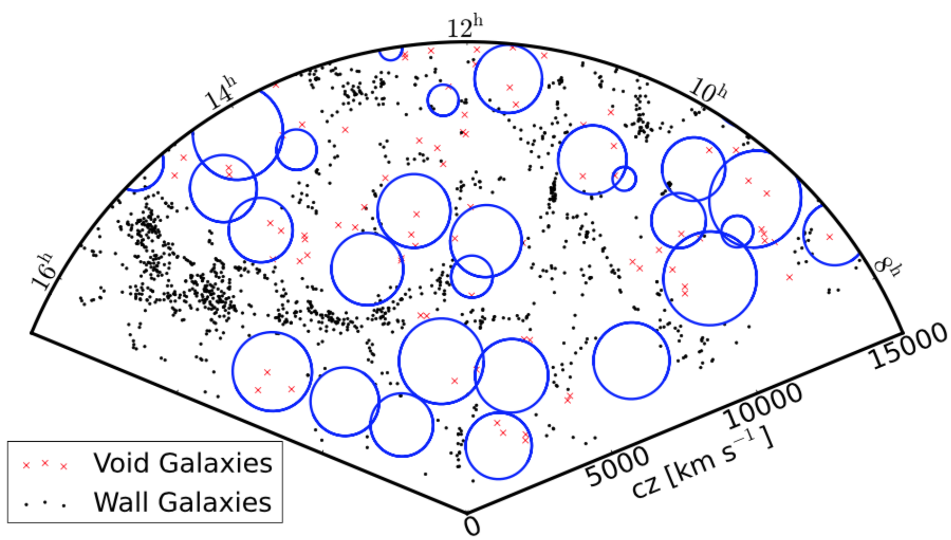

Figure 1.3: A 10 h^{-1}Mpc slice of SDSS DR7 (Moorman et al., 2014, Fig. 1) with void regions highlighted in blue circles. Void galaxies are shown as red points while wall galaxies are black. Existing in the cosmological voids (space between the galactic filaments), void galaxies are though to demonstrate the fundamental characteristics of galactic evolution.

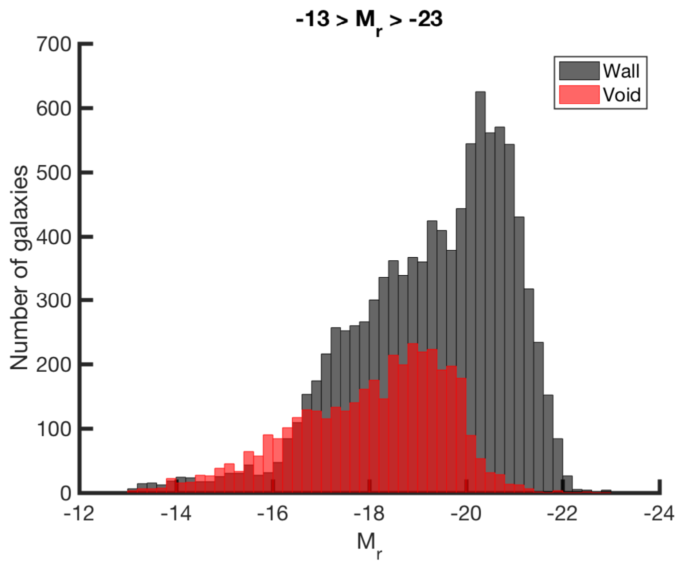

Figure 1.4: Absolute magnitude (M_r) distribution of galaxies in SDSS DR7, separated into void and wall environments. Dwarf galaxies are defined as galaxies with absolute magnitudes fainter than -17 ($M_r > -17$). For reference, the Milky Way has an absolute magnitude $M_r \approx -20$.

0.84. Additionally, hydrodynamical cosmological simulations by Cen (2011) show that void galaxies continue to form stars because the gas in voids remains below the critical entropy threshold. Void galaxies evolve in a relatively pristine environment where interactions are rare and star formation proceeds up to the present epoch because void galaxies are able to retain their gas. This contrasts the denser environments, where the chemical composition and evolution of galaxies are drastically altered due to mergers and tidal and/or ram-pressure stripping.

Observational studies of void galaxies have included investigation of photometric properties such as luminosity (Hoyle et al., 2005; Croton et al., 2005; Moorman et al., 2015), color and morphological 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), star formation rates estimated from optical spectroscopy and UV photometry (Rojas et al., 2005; Moorman et al., 2015; Beygu et al., 2016), and gas content (Kreckel et al., 2012; Moorman et al., 2016; Jones et al., 2016). When compared to galaxies in denser regions, void galaxies are fainter, of late morphological types, bluer, forming stars at higher rates per unit stellar mass, and more gas rich.

In particular, we study the effects of the large-scale environment on the formation and evolution of dwarf galaxies. Fig. 1.4 shows the distribution of galaxies by their absolute magnitudes detected in SDSS DR7. Defined to be galaxies with absolute magnitudes fainter than -17 ($M_r > -17$), the low stellar masses of these systems correspond to more shallow gravitational potential wells. This causes any environmental effects to have a more significant influence on dwarf galaxies than on galaxies with larger stellar masses. In addition, studying void dwarf galaxies will complement previous studies of dwarfs in groups and clusters because the assembly histories of low-mass galaxies are predicted to be very different (e.g., Gao & White, 2007; Lackner et al., 2012). Observations to date also show that the properties of dwarf galaxies vary dramatically with the environment (e.g., Ann et al., 2008; Geha et al., 2012).

The first stars that formed are thought to have been composed of only hydrogen (and possibly some trace amount of helium). As stars burn, nucleosythesis creates heavier elements at the core. When the stars die and expel their content, the heavier elements are distributed between the surrounding interstellar gas and circumgalactic medium. When new stars form from this gas, they include both hydrogen and some of the heavier elements. By measuring the fraction of elements heavier than helium ("metals") relative to the hydrogen content (the metallicity), we measure the integrated star formation history of the galaxy.

We use a galaxy's spectrum to measure various properties of the stellar population and interstellar medium. A galaxy's spectrum is a superposition of light from the stars and emission lines from the gas. Depending on our viewpoint of the galaxy's light, we will see a different type of spectrum. As shown in Fig. 1.5, if we separate a star's light by its wavelength, we will observe a continuous spectrum, since it is a blackbody. If instead we observe the starlight after it has passed through a cloud of cooler gas, we will measure an absorption line spectrum; the elements in the gas cloud have absorbed some of the star's light at specific wavelengths corresponding to the particular ions present. Finally, if we only observe the light emitted from the cool gas cloud, we will measure an emission line spectrum. The method we employ to estimate the metallicity of a galaxy requires particular emission lines. We study the gas-phase chemical abundances of H II regions in a galaxy, where the

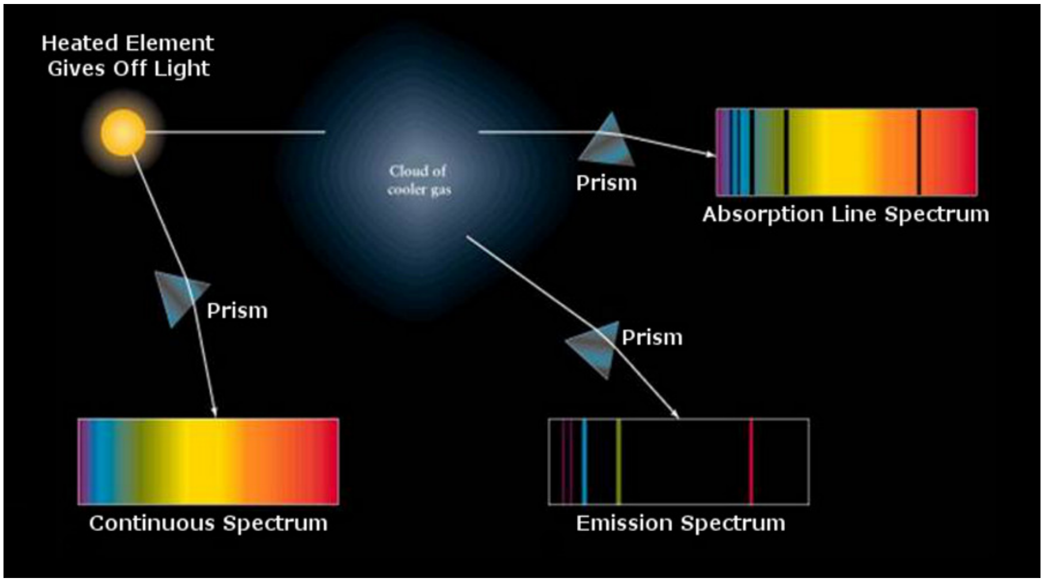

Figure 1.5: Three different viewpoints of the light emitted from a star and/or a cool cloud of gas, representing Kirchoff's laws of spectroscopy. A star emits light across all wavelengths, so the resulting spectrum is known as a continuous spectrum. Star's light that has passed through a cloud of cool gas before being observed is an absorption spectrum, where the elements in the cloud have absorbed some of the light at specific wavelengths (corresponding to the particular elements present in the gas). If observed off the line-of-sight of the star, the light emitted from the cloud of cooler gas results in an emission spectrum, where the gas is re-radiating the light it absorbed from the star.

light is coming from low-density gas partially ionized by UV photons emitted from young, hot stars. Therefore, we are measuring the abundances of the elements produced in previous generations of stars.

The ion transitions observed in the optical part of the spectrum (where SDSS DR7 operates) consist of forbidden transitions. As explained in detail in Section A, forbidden transitions have much longer lifetimes than the allowed electron transitions. These transitions depend strongly on the temperature and density of the electron gas, because the long lifetimes allow the atoms to easily collisionally de-excite. By taking the ratio of the [O III] λ4363 auroral line to the [O III] $\lambda\lambda$4959,5007 doublet, we can get an estimate of the temperature of the gas. These lines are highlighted on the example SDSS DR7 spectrum shown in Fig. 1.6.

Oxygen is used as a proxy to measure the metallicity of an H II region, because oxygen is the most abundant element in the universe after hydrogen and helium. It also has strong emission lines in the

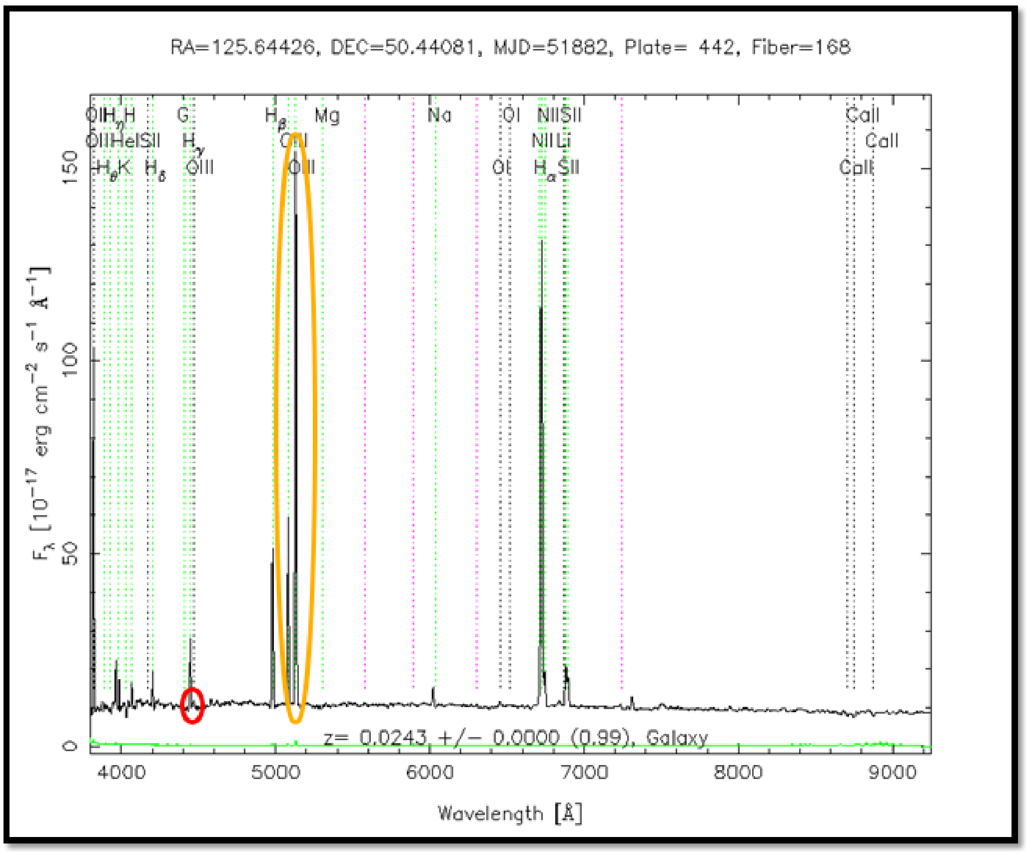

Figure 1.6: Example SDSS DR7 spectrum — this is a void dwarf galaxy whose gas-phase chemical abundances are slightly above average. The [O III] λ4363 auroral line is circled in red, while the [O III] $\lambda\lambda$4959,5007 doublet is circled in yellow.

visible wavelength range, so it is relatively easy to observe. Oxygen emission is the most effective cooling source in an H II region, so lower metallicities correspond to higher temperatures. There are three main factors which determine the strength of an emission line: the temperature, density, and number of ions in the gas. It is possible to calculate the number ratios for any of the heavy elements with respect to hydrogen once the electron temperature and density of the interstellar gas are estimated.

We want to understand how dark matter affects the evolution of a galaxy and what influence it has on a galaxy's star formation. To do this, we compare the properties of galaxies living in voids with galaxies in denser regions in an effort to understand how the properties of the gas and the history of star formation in a galaxy depend on the environment. We then try to infer what these results tell us about the dark matter structure and history of the galaxy. In Chapter 2, we calculate and compare the metallicity of 135 star-forming dwarf galaxies as a function of their large-scale environment. We continue studying this galaxy sample in Chapter 3 by estimating their ratios of nitrogen to oxygen and looking at how that depends on the large-scale environment. To expand our dwarf galaxy sample, we derive an approximation for the amount of singly-ionized oxygen and repeat our analysis of the large-scale environmental influence on the gas-phase chemical abundances of 1920 star-forming dwarf galaxies in Chapter 4. In Chapter 5, we investigate how the dwarf galaxies' properties depend on the galaxies' distances to the nearest neighbors and groups. Finally, in an effort to better understand how galaxies evolve from blue, star-forming systems to "red and dead," we discover a way to classify galaxies into their location on the color-magnitude diagram in Chapter 6.