The Assembly of Massive Galaxy Clusters

Brett Feldman
Brett.Feldman@Colorado.EDU

Follow this and additional works at: http://scholar.colorado.edu/honr_theses
Part of the External Galaxies Commons, Other Astrophysics and Astronomy Commons, and the Physical Processes Commons

Recommended Citation
The Assembly of Massive Galaxy Clusters

Brett A. Feldman
Department of Astrophysical and Planetary Sciences, University of Colorado at Boulder

Defended November 7th, 2014

Thesis Advisor:
Erica Ellingson, Associate Professor- Department of Astrophysical and Planetary Sciences

Defense Committee:
Erica Ellingson, Associate Professor- Department of Astrophysical and Planetary Sciences
Julia Comerford, Assistant Professor- Department of Astrophysical and Planetary Sciences
Bernard Gillett, Senior Instructor- Farrand Residential Academic Program
Abstract

Here we present an investigation into galaxy evolution in the cluster and intercluster filamentary environments, and follow the evolution of the large scale structure of the universe over 4 billion years. After designing and applying a new “filament finding algorithm” to galaxy survey data from the Sloan Digital Sky Survey and the Red Sequence Cluster Survey, we identify galaxies belonging to the intercluster filamentary environment, along with three other cluster populations. By carrying out a detailed photometric and spectroscopic investigation into the star formation rates of galaxies in different environments, we are able to shed light on the processes responsible for the cessation of star formation in cluster galaxies. In particular, we find that the quenching mechanisms of harassment and mergers are quite effective at pre-processing galaxy groups outside of the cluster, contingent upon the local density being large enough. Next, we find that the filamentary environment at low redshift does have a considerable effect on the evolution of a galaxy. Specifically, we see evidence that the intrafilamentary medium has the potential to ram pressure strip the gaseous halos of infalling galaxies, and that infalling galaxies are subject to significant filament tidal forces at a few virial radii, enough to dismantle infalling groups within filaments. We see evidence for the filamentary environment inducing starbursts in infalling dwarf galaxies within groups, which we attribute to the exponentiation of the harassment mechanism by filament tidal forces. However, we conclude that this starburst population is relatively small, and thus starbursts are not a main contributor to the population of passive galaxies within clusters. Lastly, we compare the cluster composition between the two data sets, which provides insight into the assembly of galaxy clusters and the evolution of large scale structure over 4 billion years. From this comparison study, we see direct observational evidence for hierarchical clustering, and find that the dominant mechanism responsible for the population of “red and dead” galaxies in cluster cores is ram pressure stripping in the intracluster medium.
# Table of Contents

I. Introduction 4

II. Techniques
   II.1: Cosmological Context 8
      II.1.a: Redshift as a Distance Measurement 8
      II.1.b: Angular Diameter Distance 9
   II.2: Luminosity Functions 10
   II.3: The Red Sequence 11
      II.3.a: Definition and Characteristics 11
      II.3.b: Evolution towards the Red Sequence 12
   II.4: Measuring Star Formation and other Galaxy Properties 14
   II.5: Virial Radii of Clusters through Velocity Densities 15

III. Data
   III.1: The Red Sequence Cluster Survey 18
   III.2: The Sloan Digital Sky Survey 22

IV. RCS Analysis
   IV.1: Galaxy Group Finding 23
   IV.2: Filament Finding 25
      IV.2.a: Three-Dimensional Filament Finding 27
      IV.2.b: Two-Dimensional Radial Spokes Filament Finding Algorithm 29
   IV.3: Photometric Groups and Filaments 34
   IV.4: Photometric Background Subtraction 35
   IV.5: Photometric Magnitude Limits 37
   IV.6: Calculation of Uncertainties 40
   IV.7: Definitions and Locations of Cluster Populations 42

V. SDSS Analysis
   V.1: Differences between SDSS and RCS Analyses 45
   V.2: Relationships between Photometrically and Spectroscopically Derived Quantities 46
   V.3: Cluster-Centric Distance Gradients in Galaxy Properties 49

VI. Results
   VI.1: RCS Results 51
   VI.2: SDSS Results 57
   VI.3: Evolution with Redshift: Comparison of RCS and SDSS 64

VII. Discussion
   VII.1: Galaxy Quenching in the High Redshift Universe 67
   VII.2: Galaxy Quenching in the Low Redshift Universe 69
      VII.2.a: Interpretation of SDSS Photometric Analysis 69
      VII.2.b: Interpretation of SDSS Spectroscopic Analysis 71
   VII.3: Evolution of Large Scale Structure in Time 74
   VII.4: Illuminating the Origin of Red and Dead Galaxies in Cluster Cores 76

VIII. Conclusions and Future Direction
   VIII.1: Summary of Results 78
   VIII.2: Future Direction 80

IX. References 82
I. Introduction

In the realm of extragalactic astronomy, galaxies are often considered to be the fundamental, discrete “units” of matter, serving as the building blocks of the large-scale structure of the universe. Our present understanding of the organization of galaxies on these cosmic scales is that they are arranged in a network of clusters, voids and filamentary configurations (Peebles, 1980; Pimbblet et al. 2004; Gott et al. 2005; Zhang et al. 2009; Tully et al. 2014). Galaxy clusters are the largest gravitationally bound structures in the universe, comprised of hundreds, if not thousands of constituent galaxies held together by their mutual gravitational attraction in a roughly spherical shape (see Figure 1) (Voit et al. 2005). Key features that distinguish clusters are their over-densities, high masses (ranging from $10^{14}$ to $10^{16}$ solar masses), and abundance of large, elliptical galaxies inhabiting their cores (Dressler 1980; Butcher & Oemler 1984; Poggianti et al. 2006). Galaxy clusters form at the intersection of filaments (Springel et al. 2005; Dietrich et al. 2012) which are long, threadlike configurations of galaxies that connect neighboring clusters (see Figure 2). Together with the sparsely populated “voids” outside of the denser filaments and clusters, these three main components of the large scale structure of the universe are collectively referred to as the “cosmic web”.

![Figure 1:](image-url) Optical image of nearby galaxy cluster Abell 1689, obtained with the Hubble Telescope. In this image, nearly every point of light is an entire galaxy. The massive, red elliptical galaxy population in the cluster core is clearly evident at the center of the image (NASA/ESA, Hubble Heritage).
Figure 2: Simulation depicting the large scale structure of the universe that collectively forms the cosmic web. Here, the bright yellow/red spherical objects represent galaxy clusters that form at the intersections of filaments. The intercluster filaments are the long tendrils that connect nearby clusters. Lastly, the massive intercluster voids are represented by the dark cavities surrounded by filaments (Springel et al. 2005).

Our current understanding of the formation of the cosmic web is that structure grows hierarchically through gravitational instability; larger structures are built up via the merging of smaller structures (Springel et al. 2005; Berrier et al. 2009; Vogelsberger et al. 2014). Due to the strong gravitational field associated with the enormous mass of a galaxy cluster, galaxies will inevitably be pulled into the inner regions of clusters, or “infall” if given enough time. These galaxy clusters thus grow by accreting individual or small groups of galaxies from the general “field population” outside of clusters, or along higher density intercluster filaments (Ebeling et al. 2004; Braglia et al. 2007; Fadda et al. 2008; Porter & Raychaudhury 2008; Berrier et al. 2009; Coppin et al. 2012).

The existence of galaxy clusters is well documented; (eg. Dressler et al. 1980; Hao et al. 2010) many different imaging surveys have found and catalogued a multitude of galaxy clusters, such as the Sloan Digital Sky Survey, or the Red Sequence Cluster Survey. On the other hand, intercluster filaments of galaxies are not well documented or as well understood as galaxy clusters (Pimbblet et al. 2005; Zhang et al. 2009). Despite the relatively sparse observational data, evidence of the existence of these filaments is well established theoretically (Springel et al. 2005; Berrier et al. 2009).
A ubiquitous feature of galaxy clusters throughout the universe is a distinct population of large, red-colored elliptical galaxies found in the cluster core (see Figure 1) (Dressler et al. 1980; Butcher & Oemler 1984; Moore et al. 1996). The red color of these core galaxies signifies a lack of the relatively blue H II regions (clouds of ionized hydrogen gas) found in many of the “field population” galaxies outside of clusters (Oemler 1974; Ellingson et al. 2001; Balogh et al. 2004). H II regions are a signature of recent star formation activity in a galaxy, so, we can conclude that these large, red galaxies in cluster cores do not have active star formation occurring, hence their designation as “red and dead.”

Since galaxies start out in the field as blue and star-forming, then eventually fall into a cluster core rendering them red and dead, there must be some specific physical process which acts on an infalling galaxy that quenches it of its ability to form new stars. By determining where this transformation from blue to red occurs, we can hope to shed some light on the processes responsible for this galactic evolution in the cluster environment, and the origin of the “quenched” red and dead galaxies in cluster cores. As the evolution of galaxies is one of, if not the most important topic in extragalactic astronomy, the answer to this question is essential to the further development of this field of study.

Two of the main factors that influence the evolution of a galaxy are its stellar mass and environment (Baldry et al 2006; Gilbank et al. 2008; Peng et al. 2010). Some of the environment-specific mechanisms that could be responsible for this cessation of star formation in infalling cluster galaxies are “ram pressure stripping”, “harassment” or galaxy mergers. Galaxy clusters are pervaded by hot, X-ray emitting gas, denoted as the intra-cluster medium (ICM). When an infalling galaxy encounters this intra-cluster medium, it exerts a pressure on the galaxy, and if great enough, can potentially overcome the galaxies own gravitational attractive force holding onto its gas reserves, stripping the galaxy of its “fuel” for star-formation. This process is known as ram pressure stripping (Gunn & Gott 1972; Moran et al. 2007; Porter & Raychaudhury 2008; Dressler et al. 2013). Galaxy harassment occurs during a “fly-by” between two galaxies as they move through a cluster, during which they interact gravitationally. This gravitational interaction from a neighboring galaxy can sometimes perturb the interstellar gas clouds within a galaxy, causing them to gravitationally collapse, and thus form new stars (Moore et al. 1996). These “harassments” are often strong enough to collapse the majority of a galaxy’s interstellar clouds at once, causing a sudden burst of star formation which consumes the “fuel” for new star formation, leaving a galaxy red and dead. The harassment quenching mechanism can sometimes be less violent, and rather disrupt a galaxy’s diffuse gaseous halo leading to the removal of gas from the galaxy, which contributes to the quenching of star formation (Dressler et al. 2013). Lastly, a merger event occurs when two galaxies
directly collide with one another. This violent event can lead to massive starbursts followed by quenching, or the direct loss of gas from a galaxy as it becomes gravitationally unbound during the chaotic episode (Baldry et al. 2004; Balogh et al. 2009). We suspect ram pressure stripping to be an effective means to quench an infalling galaxy, but only in the inner regions of a cluster where the intracluster medium is dense enough. We suspect infalling groups of galaxies to be subject more to harassment and mergers, due to their close encounters with neighboring galaxies, and the lack of a dense, intracluster medium in those environments.

The first question that remains concerns the origin of the population of red and dead galaxies in cluster cores. Are extra-cluster quenching mechanisms like harassment and mergers effective enough to quench infalling group galaxies, or is the red and dead core population mainly a result of ram pressure exerted by the ICM within the cluster? Previous work on this subject has provided evidence that some degree of “pre-processing” does occur in groups outside of the inner-cluster environment (Ellingson et al. 2001; Balogh et al. 2009; Moran et al. 2007; Berrier et al. 2009). The second remaining question concerns the nature of the filamentary environment, and how this environment affects the evolution of galaxies. Is there pre-processing occurring in filaments before the infalling galaxies encounter the cluster environment? If so, what physical mechanism is acting on these filament galaxies, and where in the filament are they being quenched? Recently, evidence has been emerging that the filamentary environment does have a considerable effect on the evolution of galaxies (Braglia et al. 2007); specifically, dwarf galaxies of low mass might undergo starbursts while infalling along a filament (Fadda et al. 2008; Porter & Raychaudhury 2008; Coppin et al. 2012). Lastly, the details remain unclear as to how large scale structure evolves in time as the universe ages, and related, how the different populations of infalling galaxies (groups, filaments, etc.) contribute to the growth and assembly of massive galaxy clusters.

In this study, we attempt to answer the questions set forth by quantifying the star formation rates and various other properties of galaxies in different cluster environments, and at different periods of time in the universe’s evolution. This study is a three-fold process. We first find the various populations of galaxies in the different cluster environments. Since this step requires locating intercluster filaments, we devise a “filament finding algorithm” to locate these structures and the member galaxies within. Next, we quantify the star formation rates and numbers of red and dead galaxies in each of the different cluster environments. Lastly, we apply our methodology to two different data sets that probe different epochs of the universe. By comparing the efficacy of quenching mechanisms in each environment, along with the
cluster composition at these different periods of time, we will gain insight into how large scale structure evolves in time, and the main drivers for the assembly of galaxy clusters.

II. Techniques

II.1: Cosmological Context

II.1.a: Redshift as a Distance Measurement

While determining the distance of an astronomical object is not the most rudimentary of things, there are a number of different techniques that astronomers employ in order to determine how far away an object is. In the extragalactic realm, as is the case in this study, methods such as parallax or radar-ranging cannot be applied, as our objects of interest, namely galaxies, are simply too far away. In this scenario, we must measure the redshift of a distant object in order to determine its distance from us.

Qualitatively, when an object at cosmological distances emits light at a certain wavelength, the emitted light takes a substantial amount of time to reach us, due to the finite speed of light. As the universe is expanding on these cosmological scales, the electromagnetic waves of the emitted light in transit are also stretched by this universal expansion, increasing their characteristic wavelengths. Thus, the light that reaches us is always more red than what was actually emitted, and the degree of the redshift is related to how long the light was in transit, and hence, how far away the object is from the observer. One also needs to take into consideration the rate of expansion of the universe during the light-transit interval, which will be discussed further in the next section. To quantitatively determine the redshift of emitted light, we obtain a spectrum, and measure the wavelength-offset of well-known emission lines that we can identify.

In this study, we are most interested in whether objects that appear to be close together in the observed plane of the sky (right-ascension and declination) are actually correlated in the dimension parallel to the observer’s line of sight, the “distance-dimension, or z-dimension.” Thus, we use the following interpretation of redshift in the extragalactic, galaxy cluster regime: the cosmological redshift of a galaxy clusters’ core tells us the “distance” to all objects associated with the cluster, while individual cluster members’ differences in redshift from the cluster core (Doppler redshift) tell us their z-dimension velocities within the cluster, relative to the stationary reference frame of the cluster core. This interpretation is necessary because the cosmological
redshift of an object due to the expansion of the universe is not necessarily equivalent to its Doppler redshift due to its relative motion within a stationary reference frame (see section IV.2.a for further explanation). The criteria we use to determine whether a galaxy is associated with the cluster is whether its line of sight velocity relative to the core’s redshift is no greater than +/- 3000 km/s. Any object moving faster than this relative to a core is considered unlikely to be in or near the cluster. To determine the possible range of redshifts around a cluster that would constitute a spatial velocity of +/- 3000 km/s, we use the following:

\[ Z_{\text{range}} = (1 + Z_{\text{cluster}}) \frac{3000 \text{ km/s}}{c} \]

where \( Z_{\text{range}} \) is the range of possible cluster-member redshifts, \( Z_{\text{cluster}} \) is the redshift of the cluster in question, and \( c \) is the speed of light.

II.1.b: Angular Diameter Distance

In this study, we also like to know how far away, physically, a cluster member is from the cluster core, or from other cluster galaxies. To convert our measured values of the right ascension (RA) and declination (Dec) of objects to a physical, two dimensional distances in the plane perpendicular to the observers’ line of sight, we use the angular diameter distance, defined as:

\[ d_A(z) = \frac{d_m(z)}{1 + z} \]

where \( d_A(z) \) is the angular diameter distance at the clusters’ redshift \( z \), and \( d_m(z) \) is the transverse comoving distance at the clusters’ redshift. The transverse comoving distance is defined as:

\[ d_m(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{E(z')} \]

where \( H_0 \) is the Hubble Constant, \( c \) is the speed of light, and \( E(z) \) is the simplified Friedmann Equation for a universe containing matter and a cosmological constant. \( E(z) \) is derived from the Friedmann-Robertson-Walker metric for a Euclidian, expanding universe, and is expressed in the following way:

\[ E(z) = \sqrt{\Omega_m (1 + z)^3 + \Omega_A} \]
where $\Omega_m$ is the matter density parameter, and $\Omega_A$ is the dark energy density parameter of the universe. This term contains the effects of the expansion history of the universe, a requirement noted above. The matter density parameter is defined to be the ratio of the density of matter in the universe to the critical density of the universe, where the critical density is the spatial density of energy and matter that would make the universe Euclidian (flat). At the current epoch, this is defined as:

$$\Omega_m = \frac{\rho_m}{\rho_{\text{crit}}} = \frac{\rho_m}{\frac{8\pi G}{3H_0^2}}$$

$\Omega_m$ and $\Omega_A$ denote the effects of dark matter and dark energy, and $H_0$ represents the current expansion rate of the universe (at $z = 0$). In this study, we adopt a value of 70 km/s/Mpc for the Hubble Constant, 0.3 for the matter-density parameter, and 0.7 for the dark energy density parameter.

To give a sense of the massive scales involved in this study and to illustrate an application of the cosmological physics described above, we can determine the lookback time to a distant object. As mentioned previously, it takes a substantial amount of time for photons emitted from a distant object to reach us, due to the finite speed of light. The largest redshift of one of the galaxy clusters that we examined in this study (see data section) is ~0.8. Thus, the light that we are receiving today from a cluster at this redshift was emitted almost 7 billion years ago, when the universe was roughly half of its current age.

II.2: Luminosity Functions

In order to classify individual galaxy luminosities, and compare those luminosities or magnitudes to other cluster members to determine if a specific galaxy is relatively bright or faint, we study the luminosity function, or the distribution of galaxy luminosities. The differential luminosity function for a cluster gives the number of galaxies per cubic mega parsec, that we would expect to find in the luminosity interval between $L$ and $L + dL$. Integrated over all luminosities, its shape is usually described analytically by a “Schechter Function” of the form:

$$\phi(L) = C \left( \frac{L}{L^*} \right)^{\alpha} e^{-L/L^*}$$
where $C$, $\alpha$ and $L^*$ are parameters that are adjusted to fit the analytic Schechter Function to the actual distribution of galaxy luminosities (Schechter et al. 1976). The parameter $L^*$ is known as the characteristic luminosity of the cluster, representing the dividing line between bright and faint galaxies (the Milky Way galaxy is roughly an $L^*$ galaxy). In this study, we also make use of the Schechter function in terms of galaxy magnitudes, which takes the form:

$$\phi(M) = C \left[10^{-0.4(M-M^*)}\right]^{\alpha-1} \left[e^{-10^{-0.4(M-M^*)}}\right]$$

Where $C$, $\alpha$, and $M^*$ are free, adjustable parameters. In terms of the measured apparent magnitudes of galaxies, $M^*$ takes the role of $L^*$, and represents the division between relatively bright and relatively faint galaxies (or the “knee” of the Schechter Function, as it is sometimes called). Since brightness and magnitude are inversely related, a larger magnitude corresponds to a fainter galaxy.

II.3: The Red Sequence

II.3.a: Definition and Characteristics

Nearly every galaxy cluster possesses a certain population of galaxies that exhibit a tight relationship between their color and magnitude. In “color-magnitude space”, a cluster’s relatively red, elliptical and lenticular galaxies all inhabit a well-defined area, known as the red sequence (Ellingson et al. 2001; Gilbank et al. 2008; Loh et al. 2008; Hao et al. 2010). Since this tight relationship exists, an elliptical galaxy in a given cluster will have a specific color, determined by its overall magnitude and the redshift of the cluster.

![Color-Magnitude Diagram](image)

**Figure 3:** Color-Magnitude diagram of a low-redshift cluster, with the red sequence highlighted. “R” indicates the magnitude of a galaxy in the red filter during observations, while “B” indicates the magnitude in the blue filter.
Magnitudes scale as -2.5 log(brightness), so a larger magnitude indicates a fainter galaxy. B-R magnitude is a measure of color, with larger values corresponding to redder galaxy. (astro.utoronto.ca/~gilbank/RCS2/redseq.html)

The color of the red sequence matches expectations for the color of a galaxy that stopped forming stars a few billion years before the current epoch (Loh et al. 2008). An important feature to notice in the above color-magnitude diagram is the density of the red sequence in comparison to other regions in color-magnitude space. As mentioned before, the red sequence is populated by many red, elliptical galaxies, and since clusters, especially at lower redshifts contain a significant portion of “red and dead” galaxies in their core, we would expect this region in color-magnitude space to be highly populated. Another feature to note is that since a cluster’s reddest, core galaxies inhabit the red sequence, this area on a color-magnitude diagram effectively marks the reddest galaxies that can exist in the cluster; anything more red than the red sequence (above the upper line in the plot) is not part of the cluster, and is most likely a higher redshift galaxy that appears along our line of sight. Lastly, since we believe that all “red and dead” galaxies at varying redshifts share an intrinsic degree of redness, the color of a specific clusters’ red sequence can be used to estimate the redshift of that cluster (Yee et al. 2007).

II.3.b: Evolution Towards the Red Sequence

A color-magnitude diagram of field population galaxies that have not yet been quenched by the cluster environment, and hence blue and star-forming, would not have a prominent red sequence. These blue galaxies would inhabit what is known as the “blue cloud” in color-magnitude space, the region below the red sequence for those galaxies’ specific redshift. As field galaxies fall into the cluster, and quenching mechanisms begin to act on them, their star-formation rates decrease, and they start to become redder in color, evolving upwards towards the red sequence (Balogh et al. 1998; Ellingson et al. 2001; Webb et al. 2013). A fundamental assertion of galaxy evolution is that larger galaxies (and hence, more luminous) evolve earlier in cosmic time than their smaller, fainter companions (Juneau et al. 2005; Seymour et al. 2008; Gilbank et al. 2008). As a result of this “cosmic downsizing”, a population of galaxies that has been recently quenched, or is still in the process of being quenched, will only have had time for its largest and most luminous galaxies to have evolved onto the red sequence. The faint end of the red sequence (higher-magnitudes on the color-mag diagrams) will be much less populated than the more luminous region on the left-side of the color-magnitude diagrams. By the same token, an older
population of galaxies that has been quenched long ago will have a red sequence containing many faint galaxies.

![Cluster Galaxy Evolution Towards Red Sequence](image)

**Figure 4:** Schematic representation of cluster galaxies’ evolution towards the red sequence in color-magnitude space. The more luminous, giant blue galaxies are first to be quenched, and populate the left-end of the red sequence first (1), while the smaller, less luminous blue galaxies take longer to be quenched and populate the right-end at a later time (2). In general, the red sequence is populated from left-to-right.

As a result of the evolutionary behavior in color-magnitude space described above, color-magnitude diagrams for specific cluster populations will thus tell us two very important quantities of interest, one of which is the main point of focus in this study. The first is the red fraction, which is simply the ratio of the number of red galaxies (on the red sequence) to the total number of galaxies in both the red sequence and the blue cloud. The red fraction of a given galaxy population (such as core galaxies, group galaxies, field galaxies, etc.) will allow us to quantify the degree of quenching that has taken place in that cluster population. The second quantity of interest is the red sequence dwarf fraction. We will consider a dwarf galaxy to be one whose color is on the red sequence, and whose magnitude is greater than $M_* + 0.5$, and a giant galaxy to be one whose color is on the red sequence, and whose magnitude is less than $M_* + 0.5$. By calculating the dwarf fraction for various galaxy populations in the cluster environment, we will be able to quantify how recently that population has been quenched, or if the quenching mechanisms are still in effect.
II.4: Measuring Star Formation and Other Galaxy Properties

As mentioned in the previous section, the red fraction of a certain population of galaxies is a good tracer of the overall star formation rate in a specific region. Galaxies that are actively forming new stars have an abundance of blue colored H II regions (H II being atomic hydrogen ionized from the high energy UV radiation emitted from massive, young stars) in their interstellar mediums, and related, a higher proportion of younger, blue colored O and B type stars. Thus, a galaxy that is actively forming new stars appears bluer in color (Bernardi et al. 2010). Conversely, galaxies that are quenched and have ceased their star formation do not contain these blue colored regions. They instead are comprised of mostly older, red colored K and M type stars, giving quenched galaxies a characteristic red hue (Roberts et al. 1994). We can exploit this general property to quantify the degree of star formation in a population of galaxies, by calculating the red fraction of that population, as described in the previous section. A higher red fraction indicates low levels of star formation, while a low red fraction is indicative of higher rates and more recent star formation. This number ranges from roughly 0.2 for field galaxy populations outside of clusters, to 0.8 for the most quenched, cluster core populations (Loh et al. 2008).

Although the red fraction is a good tracer of star formation, it is subject to ambiguities. For example, a star forming galaxy that has a large amount of interstellar dust can be mistaken as a “red and dead” galaxy, due to dust reddening placing it on the red sequence in color-magnitude space (Balogh et al. 2009). These dust clouds, or congregations of molecules in their solid states have the irritating property of absorbing light and re-radiating it at longer, redder wavelengths. Although galaxy color is a good tracer, and easy to determine for large numbers of galaxies with only photometric data (see next section for explanation of photometry), the red fraction can only be determined for a collection of galaxies, and is sometimes misleading. Therefore, when available, we desire more direct measures of star formation rates of individual galaxies, derived through a methodology known as stellar population synthesis.

Stellar population synthesis requires detailed spectra of individual galaxies, and attempts to recreate the observed spectrum by combining theoretical spectral energy distributions. The method takes advantage of the notion that stellar populations with various star formation histories can be expanded in a series of instantaneous starbursts, or simple stellar populations
(SSPs) with their individual star formation rates, masses and ages well known from spectral libraries. By tuning these various parameters, and combining multiple SSPs until the observed spectrum of a galaxy is reproduced, one can deduce surprisingly accurate information about the stellar populations that comprise a specific galaxy, and hence, general galaxy properties like star formation rates and stellar masses (Charlot et al. 2001; Bruzual et al. 2003).

In this study, we make use of the stellar masses and specific star formation rates (SSFR) of galaxies calculated in this way, whenever available. The specific star formation rate is the rate at which a galaxy is forming new stars, divided by the overall stellar mass of the galaxy, taking on the units of $\frac{M_{\text{sun}}/\text{year}}{M_{\text{sun}}}$ where $M_{\text{sun}}$ is a solar mass unit (the mass of our sun). Specific star formation rate, as opposed to simply the star formation rate (SFR), provides a quantification of star formation activity normalized by the size of the galaxy in which it occurs. A tiny dwarf galaxy that is undergoing a starburst and converting the majority of its gas into new stars might still have a smaller SFR than a massive galaxy that, relative to its size, is only forming a small amount of stars. The SSFR provides us with a measure of the significance of a galaxy’s star formation activity, relative to its overall size. This will allow us to pick out dwarf galaxy starbursts, which will prove to be useful in this study (see Results and Discussion sections).

II.5: Virial Radii of Clusters through Velocity Dispersions

In this study, it will be of importance to be able to define an “edge” to a cluster, so we can determine whether a galaxy is inside or outside, and hence, a cluster member or simply an associated galaxy. Although this is a somewhat vague concept, as the density of gas that “belongs” to a cluster, known as the intra-cluster medium (ICM) does not simply drop off at a discrete point, the virial radius is often cited as the boundary of influence of a cluster. This is the radius of a sphere, centered on the cluster, within which virial equilibrium should hold. The virial radius is correlated with the mass of the galaxy cluster, and can be related to observables, such as the distribution of galaxy velocities within the cluster.

The virial theorem is a result of statistical mechanics, which states that when a self-gravitating system is stable, there is a balance between the tendency of objects in the system to collapse (due to an excess of gravitational potential energy) and the tendency of the objects to expand (due to
an excess of thermal or kinetic energy). In the context of the virial theorem, this stable system is considered to be in virial equilibrium, in which the time-average of the total kinetic energy of the particles is equal to negative one half of the time averaged, total potential energy:

\[ \langle T \rangle = -\frac{1}{2} \langle W \rangle \]

In practice, it is often quite difficult and tedious to determine the radius at which galaxies obey the virial theorem, and hence, the magnitude of the actual virial radius. However, the virial radius can be approximated by comparing the over-density of cluster regions within a certain radius, to the critical density of the universe. From simple spherical collapse, it is expected that regions with a density of approximately 200 times the critical density of the universe will be dynamically relaxed, and hence, virialized. So in practice, the radius at which the interior density is roughly 200 times the critical density of the universe, serves as the virial radius, and is appropriately named \( R_{200} \):

\[ R_{\text{virial}} \approx R_{200} \]

As mentioned previously, the virial radius, and hence, \( R_{200} \) can be related to easily observable properties of galaxy clusters, such as the velocity dispersion of galaxies contained within the cluster (the velocity dispersion, \( \sigma \), is measured by the standard deviation of galaxy velocities, which are determined by their individual redshifts). From our definition of the critical density of the universe cited previously, we can define \( \rho_{200} \), the density within \( R_{200} \):

\[ \rho_{200} = 200 \ast \rho_{\text{crit}} = 200 \ast \frac{3H(z)^2}{8\pi G} \quad (1) \]

We can also relate this density and radius to \( M_{200} \), the mass contained within \( R_{200} \):

\[ \rho_{200} = \frac{M_{200}}{4\pi R_{200}^3} \quad (2) \]

From the virial theorem, we can now relate \( M_{200} \) to the measured, one-dimensional velocity dispersion:

\[ 2\langle T \rangle + \langle W \rangle = 0 \]

By noting that our potential energy is simply gravitational potential energy, this simplifies to:
\[ \langle \nu^2 \rangle = \frac{GM}{R} \]

The measured observable, namely, the one dimensional velocity dispersion can now be implemented into the derivation by noting that the time average of the square of the three-dimensional velocities \( \langle \nu^2 \rangle \) is equivalent to the three times the square of the one-dimensional velocity dispersion \( 3\sigma^2 \), when the statistics of large numbers is applicable, as in this case. Now, we can express \( M_{200} \) in terms of our observed velocity dispersion:

\[ M_{200} = \frac{3\sigma^2 R_{200}}{g} \quad (3) \]

By combining equations (1), (2) and (3) above, we can now express \( R_{200} \) in terms of the measured one-dimensional velocity dispersion of cluster galaxies:

\[ R_{200} = \frac{\sqrt{3}\sigma}{10 \, H(z)} \]

where \( H(z) \) is the Hubble-constant at the specific redshift of the cluster under consideration. From this result, we can now determine the virial radius of a galaxy cluster from simple observable quantities, and define a boundary of influence in the cluster vicinity. The application of the virial theorem to galaxy clusters is justified, as most low to moderate redshift clusters are dynamically relaxed in their inner, core regions, and virialized as the dynamical relaxation time of a cluster is much less than the age of the universe (Xu et al. 1999).

Another method of determining the virial radius of a galaxy cluster that is used in this study relies on a simple observable quantity; the richness of a cluster. The richness of a galaxy cluster, and hence the virial radius as a function of richness, is often defined differently by different groups. The definition we will make use of in this study is:

\[ R_{200} = 1.77 \times \left( \frac{\text{richness}}{20} \right)^{0.52} \]

Where the richness of the cluster is the number of red sequence galaxies contained within 1 Mpc of the core and within a z-band magnitude of \( M^* + 1 \) (Ellingson et al., in preparation). In this study, we will analyze regions where \( < R_{200} \), where galaxies are likely to have been influenced by the inner-cluster environment, along with regions where \( R > R_{200} \), where galaxies are likely infalling fragments of the cosmic web.
III. Data

III.1: Red Sequence Cluster Survey

Our initial data sample consists of 101 galaxy clusters from the Red-Sequence Cluster Survey I (RCS-1; Yee et al., 2007). The photometric database for these clusters includes measurements of R and $z'$ band magnitudes from the Canada-France Hawaii 3.6m Telescope and the CTIO Blanco 4m telescope over the entire 90 square degrees survey area. Previous analyses of cluster core properties from stacked data were carried out by Loh et al. (2008) and Gilbank et al. (2008), including luminosity functions, the properties of the cluster red sequence (including the evolution of $M^*$ and the red sequence with redshift, which is utilized in this study) and the evolution of the overall cluster red galaxy fractions. The study presented here will add to the previous studies, by focusing on identifying individual infalling groups and filaments at large cluster-centric radii, to identify and characterize the different components of cluster-building and identify the regions where the quenching of star formation is most likely taking place.

These clusters were later targeted for spectroscopic observations during the period from 2008-2011 using the IMACS multi-object spectrograph at the Magellan 6.5m telescope at Las Campanas in northern Chile. Altogether, 50 clusters were targeted using a highly multiplexed observation technique. The clusters were chosen to span both the range of redshift and also a range of richness (≈cluster mass). As such, they are neither mass- nor volume- limited, but do span a range of cluster masses. For each 27 arcminute field, galaxies were chosen for observation based on their position and magnitude. In general, galaxies were not chosen to be on the red sequence, though a few fields, which had multi-color observations available, were screened for galaxies whose photometric colors placed them well outside of the cluster. Multi-object spectroscopic masks were fabricated for each cluster, using a 5-10 arcsecond long slit for each galaxy. A medium-band filter was also inserted into the beam, limiting the length of each spectrum and essentially allowing a triple-tiering of targets and observations of up to 700 galaxies simultaneously. Several different filters were used, depending on the redshift of the cluster, so that rest wavelengths of about 3500-6000 Angstroms were covered using the R=300 gratings. Two or three spectroscopic masks were made for each cluster.

The entire database of 42,000 spectra was analyzed at the University of Colorado yielding more than 230,000 redshifts to an R-band magnitude of 23.5, using a spectral cross-correlation
algorithm, confirmed by eye. Only a fraction of these redshifts in a particular field are associated with the cluster, due to the wide field of view. In general, the cluster cores are very undersampled, whereas the outer regions are uniformly sampled with a relatively high completeness. Previous work by this group has not found a significant bias in the ability to measure redshifts for blue versus red galaxies. The spectral range chosen includes both bright emission lines and the distinctive break at 4000 Å for red populations.

Although 50 clusters were targeted for observation, the wide field of view also overlapped other RCS-1 clusters for a total of 101 potential clusters. Many of these are very poor and were barely detected spectroscopically, but others yielded significant numbers of redshifts. On the other hand, weather and other observing constraints limited the amount or quality of data in some fields. From the resulting dataset, we chose 38 clusters with more than 15 cluster members in the core (along with large numbers outside). These clusters also have no obvious signs of superposition or major merging in the core which would make mass estimation from the galaxy dynamics difficult. From these, we adopt the velocity dispersion measurements for each cluster determined by Ellingson et al. (2014), and calculate virial mass and radius (R200) for each cluster. Overall, our subsample of 38 clusters (see table 1) from RCS-1 spans a redshift range of 0.2 < z < 0.8, with a mean redshift of 0.5. This provides us with photometric R and z’ magnitudes for 830,000 associated cluster galaxies, and spectroscopic redshift information for 42,000 associated cluster galaxies.

<table>
<thead>
<tr>
<th>Cluster Name</th>
<th>RA</th>
<th>Dec</th>
<th>z</th>
<th>Nspec</th>
<th>( \sigma_{vel} ) (km/s)</th>
<th>( R_{200} ) (Mpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCS022145.5-03455</td>
<td>35.4397697</td>
<td>3.7647445</td>
<td>0.4306900</td>
<td>180</td>
<td>874</td>
<td>1.7210958</td>
</tr>
<tr>
<td>RCS022441.9+01220</td>
<td>36.1746521</td>
<td>1.3685996</td>
<td>0.2425700</td>
<td>121</td>
<td>676</td>
<td>1.4810053</td>
</tr>
<tr>
<td>RCS022419.7+01232</td>
<td>36.0820999</td>
<td>1.3913970</td>
<td>0.5018200</td>
<td>123</td>
<td>1659</td>
<td>3.1334517</td>
</tr>
<tr>
<td>RCS022456.4-034840</td>
<td>36.2351990</td>
<td>3.811775</td>
<td>0.6140000</td>
<td>170</td>
<td>902</td>
<td>1.5935270</td>
</tr>
<tr>
<td>RCS022620.7++00164</td>
<td>36.5863152</td>
<td>0.2786476</td>
<td>0.6150000</td>
<td>139</td>
<td>1165</td>
<td>2.0569289</td>
</tr>
<tr>
<td>RCS033354.9-283823</td>
<td>53.4789619</td>
<td>-28.6399422</td>
<td>0.6650500</td>
<td>127</td>
<td>724</td>
<td>1.2460451</td>
</tr>
<tr>
<td>RCS033538.3-270233</td>
<td>53.0998892</td>
<td>-27.0426363</td>
<td>0.3424000</td>
<td>130</td>
<td>565</td>
<td>1.1707300</td>
</tr>
<tr>
<td>RCS035144.4-104150</td>
<td>57.9351006</td>
<td>-10.6974068</td>
<td>0.3482400</td>
<td>57</td>
<td>568</td>
<td>1.1731564</td>
</tr>
<tr>
<td>RCS044124.8-281317</td>
<td>70.3536224</td>
<td>-28.2214661</td>
<td>0.6429200</td>
<td>79</td>
<td>580</td>
<td>1.0072528</td>
</tr>
<tr>
<td>RCS044143.7-284222</td>
<td>70.4323578</td>
<td>-28.7063274</td>
<td>0.6080000</td>
<td>126</td>
<td>540</td>
<td>0.9581845</td>
</tr>
<tr>
<td>RCS044405.2-282027</td>
<td>71.0202490</td>
<td>-28.3409271</td>
<td>0.3382800</td>
<td>101</td>
<td>509</td>
<td>1.0572931</td>
</tr>
<tr>
<td>RCS051815.4-431933</td>
<td>79.5644150</td>
<td>-43.3260345</td>
<td>0.3962600</td>
<td>140</td>
<td>272</td>
<td>0.5465222</td>
</tr>
<tr>
<td>RCS051935.5-440200</td>
<td>79.8979416</td>
<td>-44.0335732</td>
<td>0.8303600</td>
<td>59</td>
<td>580</td>
<td>0.9005286</td>
</tr>
<tr>
<td>RCS110101.5-035133</td>
<td>165.2565497</td>
<td>-3.8592443</td>
<td>0.6083000</td>
<td>126</td>
<td>600</td>
<td>1.0684711</td>
</tr>
<tr>
<td>RCS110235.3-033952</td>
<td>165.6473999</td>
<td>-3.6646283</td>
<td>0.3881700</td>
<td>328</td>
<td>840</td>
<td>1.6956061</td>
</tr>
<tr>
<td>RCS110258.3-052219</td>
<td>165.7431946</td>
<td>-5.3720107</td>
<td>0.3196400</td>
<td>89</td>
<td>267</td>
<td>0.5605001</td>
</tr>
<tr>
<td>RCS110312.8-034622</td>
<td>165.8035889</td>
<td>-3.7728415</td>
<td>0.4747200</td>
<td>110</td>
<td>477</td>
<td>0.9154037</td>
</tr>
</tbody>
</table>
Table 1: Properties of the 38 clusters that comprise our subsample of RCS-1 used in this study. Columns: (1) cluster name, (2-3) coordinates of the cluster center, (4) mean cluster redshift, (5) number of spectroscopic cluster members within 3000 km/s of the core, (6) cluster velocity dispersion, (7) cluster $R_{200}$. (Gladders et al. 2007; Ellingson et al. 2014)

This data sample from RCS-1 is unprecedented, as it probes out to regions well beyond the cluster virial radius (out to $\sim 5R_{200}$). For a comparison, most other spectroscopic surveys at these higher-redshifts cover only the virialized, inner-regions of clusters, missing the cluster outskirts where some of the quenching is most likely starting to occur. As a result, we possess the unique ability in this study to compare the effectiveness of quenching mechanisms in cluster cores with the relatively unknown effectiveness of mechanisms in the cluster outskirts (see Figure 5 below).
Figure 5: Cluster map of RCS022456.4-034840 at z=0.58, showing the coverage of our sample (dots represent photometric galaxy data, squares represent spectroscopically confirmed cluster galaxies, and the circle around cluster core indicates the virial radius). As can be seen in the above figure, the RCS-1 data extends well beyond the virial radius and can identify infalling groups and filaments.

Figure 6: Plots showing the velocity dispersion (upper panel) and local surface density (lower panel) of spectroscopic cluster galaxies in RCS022456.4-034840_z0.58 vs cluster-centric radius. The infalling dense substructures at about 2 R200 and again about 3.5 R200 in the lower panel can clearly be seen on the map in Figure 5 above.
III.2: Sloan Digital Sky Survey

Our second data sample makes use of photometric and spectroscopic galaxy measurements in the local universe probed by the 7th data release (DR7) of the Sloan Digital Sky Survey (SDSS) (Abazajian et al. 2009). Specifically, our photometric subsample of DR7 (details of the subsample are as follows) provides us with R and z’ band magnitudes for 6,645,000 galaxies up to the 95% completeness level of R=22.2 and z’=20.5. The criterion for selection of our subsample from the overall DR7 sample was that the galaxy was within 15 Mpc of one of our targeted GMBCG galaxy clusters. The GMBCG galaxy cluster catalog (Hao et al. 2010) provides positions, redshifts and richness measurements of clusters in DR7. We chose only the most robust clusters from the GMBCG catalog, restricting our study to those that had a richness of at least 12, a redshift of less than 0.2, and at least 150 spectroscopically targeted associated cluster galaxies within 15 Mpc and 3000 km/s in line-of-sight velocity from the cluster core. We make use of the MPA-JHU DR7 value-added catalogs to obtain measurements of specific star formation rates, stellar masses and redshifts of the galaxies around GMBCG clusters in our sample (Brinchmann et al. 2004; Kauffmann et al. 2003; Salim et al. 2007). With the aforementioned cuts on the original data sample, our study utilizes an initial subsample of DR7 consisting of 64,000 associated cluster galaxies with spectroscopic redshift, specific star formation rate (SSFR) and stellar mass measurements around 208 GMBCG clusters, spanning a redshift range of 0.05 < z < 0.2, with a mean redshift of 0.12.
**Figure 7**: Cluster map of a typical cluster in our subsample; GMBCG J200.35602-00.69340 at z=0.108, showing the data coverage of SDSS DR7. The dots represent photometric galaxies in the field within the specified magnitude limits, while the squares represent spectroscopic galaxies within 3000 km/s of the cluster core. The circle around the cluster core marks R200 (the virial radius). As can be seen in the above figure, the coverage of SDSS extends well beyond the virial radius, allowing us to investigate quenching mechanisms that occur outside of the cluster.

**IV. RCS Analysis**

**IV.1: Galaxy Group Finding**

In order to identify infalling galaxy groups in and around clusters in our data, we search for significant spatial overdensities of galaxy positions outside of the cluster core \(r > 0.5 \text{Mpc}\). There are a number of different methods to identify spatial overdensities of a roughly spherical shape present in a data set. In this study, we employ two common overdensity finding methods.

The name we give to the first finding method is the “friend density finding method.” This is a simple non-adaptive algorithm, in which we count the number of galaxies that lie within 0.3 Mpc of each galaxy associated with a specific cluster. We then use this number of “friends” that each galaxy has to determine the friend density (in galaxies/Mpc\(^2\)) of each associated cluster galaxy:
The second group finding method we employ in this study is the “surface density finding method.” This is an adaptive algorithm, where we determine the distance to a certain galaxy’s fifth-closest neighbor, and using that distance (denoted $R_5$), we determine the surface density (denoted $\Sigma_5$, in units of $\text{galaxies}/\text{Mpc}^2$) of each associated cluster galaxy:

$$\Sigma_5 = \frac{5}{\pi (R_5)^2}$$

The appeal of the adaptive, surface density method over the friend density method is that it allows a smaller radius to be used in the calculation of a compact group’s density. To expound upon this, consider for example a group of ten isolated galaxies that are all nearly touching, and all contained within a circle of 0.2 Mpc. The friend density method would not differentiate between this spatial distribution, and one in which ten galaxies were not as tightly grouped, but still were contained within the limiting group radius of 0.3 Mpc. The surface density method, on the other hand would differentiate between these two spatial distributions, and assign a higher density to the more tightly grouped galaxies, as would be appropriate.

Since our redshift measurements ($z$) in the spectroscopic data set allows us to constrain a galaxy’s position in three dimensions (RA, DEC and $z$), as opposed to only two dimensions with the photometric data (RA and DEC), we employ another criterion for a spectroscopic galaxy to be considered as a group member. This criterion is that a galaxy must not only be within the specified, two dimensional group radius in the plane of the sky (0.3 Mpc), but it must also be within 1000 km/s of the other galaxies within the group, about three times the likely velocity dispersion. As a result, we effectively undertake in two dimensional group finding with the photometric data set, and three dimensional group finding with the spectroscopic data set.

From these measures of the friend density and surface density of each associated cluster galaxy, we are now able to find significantly high overdensities of galaxies, and hence, the positions of galaxy groups around clusters. We only consider a galaxy group to be one in which the surface density or friend density of the densest member is greater than or equal to the ninetieth percentile for galaxies outside of the core ($R > 0.5 \text{ Mpc}$), and, the group must contain at least four
members. We define the position of the actual group to be the RA and DEC (and $z$ if it is a spectroscopically found group) of the member with the highest density.

![Spectroscopic and Photometric Galaxy Groups in 022456](image)

**Figure 8:** Cluster map of 022456, showing the galaxy groups found with the different finding algorithms. All of the photometric data again appears as dots with the squares representing the spectroscopic data. Thick circles indicate that the group was found with spectroscopic data, while a thin circle indicates that the group was found with photometric data. A red circle indicates that the group was found with the surface density finding method, while a blue circle indicates that the group was found with the friend density finding method. A green circle means that the group was found with both finding methods.

**IV.2: Filament Finding**

As mentioned previously, inter-cluster filaments of galaxies, or simply filaments, are a major component of the large scale structure of the universe and many galaxies find themselves embedded in these elusive “strands of the cosmic web”. The finding of galaxy groups in our data set, described above, was fairly straightforward. Galaxy groups are roughly spherical in shape and have high central surface densities. There exist a number of different ways to identify spherical overdensities, such as the surface density method previously described. Inter-cluster filaments, on the other hand, are not spherical in shape, and, are not significantly denser than the general cluster infall regions. While galaxy groups have been analyzed extensively in other
studies, little work has been done to classify and study filaments, so there is no commonly used algorithm or methodology to pick filaments out of an observational data set.

Other groups have relied on less sophisticated methods, such as visually identifying, or “eyeballing” a dense string of galaxies connecting two clusters (Pimbblet et al. 2004). The drawback to this manual technique is that it is labor intensive for large data sets and perhaps less sound due to the qualitative nature of identifying structure by eye. Another proposed method that is more sophisticated relies on the observed correlation between cluster galaxy orientations and outlying substructure. More specifically, there is evidence that the major axis of a galaxy cluster is usually aligned parallel to its first-ranked galaxy, as well as other cluster galaxies, and that the cluster orientation is oftentimes aligned with the filament orientation (Binggeli et al. 1982; Struble et al. 1990; West, Jones & Forman 1995; Plionis & Basilakos 2002). Using this assumption, the algorithm attempts to identify anisotropy in the orientations of a large number of cluster galaxies, potentially indicating the direction of an outlying intercluster filament (Pimbblet et al. 2005). The drawback of the “Pimbblet Algorithm” is that it requires morphology and orientation measurements of a large number of associated cluster galaxies, which can be complex and relatively difficult to acquire. Furthermore, Pimbblet et al. (2005) notes that the method is unlikely to work on very isolated, dynamically “cold” clusters, as the high degree of relaxation is expected to smooth out any primordial anisotropies in galaxy alignments.

So, in this study, we devise a new filament finding algorithm that relies only on galaxy positional measurements, which we use to identify filamentary structures around galaxy clusters and collect the locations of the galaxies contained within these filaments for further analysis. After trial and error, we came upon our favored filament finding method, which we designate as the “Radial Spoke Filament Finding Algorithm.” Before this algorithm is described, we will briefly discuss our other attempted algorithm, and possible explanations for its failure.

From studying large, N-body simulations of the large scale structure of the universe, such as that found in (Springel et al. 2005), we felt comfortable making a few assumptions about common properties of filaments (see Figure 2) that could be of use for devising a filament finding algorithm to be used on an observational data set. The first was that inter-cluster filaments are regions of the universe that have a slightly higher density in comparison to the voids and general cluster infall regions, but are not quite as dense as groups or cluster cores. The second was that
since matter streams into cluster cores along filaments, and filaments thus connect these “nodes” in the cosmic web, a filament around a galaxy cluster could be found by looking radially outwards from a cluster core.

IV.2.a: Three Dimensional Filament Finding

Using these two underlying assumptions about filament properties, we set out to devise an algorithm to find stream-like overdensities emanating from cluster cores. Our first attempt was to locate filaments in three dimensional space, using the RA, DEC and redshift of galaxies around a cluster to find radially oriented spatial overdensities. By using a galaxy’s RA as our “x-coordinate”, its DEC as our “y-coordinate” and its redshift as our “z-coordinate”, we thought it would be possible to create a three-dimensional map of a cluster, from which we could see the filaments streaming into cluster cores. In practice, the two dimensional filaments that our eyes picked out around clusters seemed to fade as we attempted to view them in three dimensional space. While we did see several obvious filaments in multiple clusters using the broad “cluster member criterion” of \( \Delta v \leq 3000 \, km/s \) (see Figure 10 below), the more detailed velocity information added little insight, and seemed to blur these structures.

The explanation for this behavior stems from our interpretation of redshift in the cluster environment, and the fundamental ambiguity that is present in that interpretation: the redshift of a cluster core tells us the cosmological distance to all objects in the cluster, while an individual cluster galaxy’s difference in redshift from the core tells us it’s line-of-sight velocity within the cluster, relative to the core. As galaxy clusters are inherently dynamical places in the universe due to their massive gravitational potentials, we cannot assume that a specific galaxy’s Doppler-shifted spectrum is a good indication of its z-dimensional position within the cluster. Rather, two galaxies that may in fact be tightly correlated in three dimensional space may not exhibit a tight correlation in their redshifts in the bustling cluster environment, as one of the galaxies’ instantaneous velocities could be oriented towards the observer, while the others’ could be oriented away from the observer, effectively uncoupling the two in the line-of-sight dimension constructed through redshift. These redshift-space distortions can be evidenced in the “finger of god” structures present in all-sky maps from large galaxy surveys, where an intrinsically spherical object (a galaxy cluster) appears as an extended object, smeared out along the “redshift dimension” (see Figure 9 below).
We did search specifically for “chains” of galaxies in radius-velocity space to try to detect the signature of infall along a filament (see Figure 10 below). Unfortunately we only found one or two candidates, which we were not able to confirm via our other methods, leading us to conclude that there exists no clear velocity dispersion correlation between filament galaxies.

**Figure 9:** The lower plot shows galaxy positions in distance(constructed through cosmological redshift)-declination space from a large scale galaxy survey. The red points are galaxies contained in a specific cluster, illustrating how redshift-space distortions blur the apparent distance to objects, creating the “finger of god” structures (AAO Newsletter, Aug. 1996). The upper plot shows a cartoon of how an intrinsically spherical object will appear to be elongated in the line-of-sight dimension constructed through redshift. (Arp, Halton. “Seeing Red”, 1998)
**Figure 10:** Illustration of the lack of correlation between filament galaxy velocity dispersion. The left plot shows a cluster map of RCS022456, with the obvious filaments highlighted in blue. The right plot shows a radius-velocity space diagram for RCS022456. It can be seen that the obvious filament galaxies (blue) have no clear correlation in radius-velocity space on the right-plot. The naive assumption that the outlying structure, or “chain” on the velocity dispersion plot on the right (red) is a filament, is clearly incorrect when one attempts to find a correlation in physical space between these (red) galaxies in the cluster map.

**IV.2.b: Two Dimensional Radial Spoke Filament Finding Algorithm**

Abandoning the attempt to locate filaments in three dimensional space, we removed the z-dimension redshift coordinate from our detection algorithms, and instead only used a galaxy’s redshift to confirm whether or not it was associated with the cluster. In this two dimensional “Radial Spoke” algorithm, we begin by starting at a cluster core, and look at the number of galaxies that lie along a radially oriented slice in the plane of the sky.

In the first iteration, we consider a galaxy to lie along a certain radial spoke if it is within 0.15 Mpc of the outward-oriented line (giving the filament an overall width of 0.3 Mpc, motivated by the typical size of a galaxy group), a first-run “filament search width”. The algorithm spins around the cluster core in one-degree increments, collecting the number of galaxies with $R > 0.5$ (to exclude core galaxies) that lie along each of these 360 radial spokes. First iteration “potential filaments” are selected to lie along a radial spoke orientation that contains a significantly greater number of galaxies than the rest of the radial spoke orientations; the specific criterion for selecting these first iteration filaments is that they contain at least three times the median number of galaxies in all 360 radial spokes.
Figure 11: Depiction of the Radial Spokes Filament Finding Algorithm’s first iteration. The upper plot shows the number of galaxies contained in each radial spoke around the specific cluster. The median number of galaxies in a spoke is shown as the horizontal dashed line, and the dot-dashed line represents $3 \times \text{median}$, the lower limit cutoff for a first iteration potential filament. The vertical dotted lines show the three potential filaments that the algorithm found around 022456. The lower plot is a cluster map of 022456, highlighting the potential filament galaxies found through the first iteration.

The next feature of the Radial Spokes algorithm is called the “adaptive filament width technique”, which assigns each filament its own specific width. To accomplish this, the full width at half max (in units of degrees) is found for each potential filament peak on the degree increment plots. Then, the length of the first iteration filament that contains 85% of its member
galaxies is found, and denoted as the “eighty-fifth length”, or $L_{85}$. Finally, the actual width of each filament, calculated through this adaptive filament width technique is defined as:

$$\text{Width} = \frac{L_{85} \times 2\pi \times FWHM}{360}$$

This adaptive filament width technique allows “skinny” filaments to be kept skinny, and “fatter” filaments to be kept fatter. We set hard limits on the algorithm’s calculated filament width at 0.3 Mpc and 1 Mpc, and did not count any galaxies as being part of a filament if they were within 0.5 Mpc of the cluster core, as these would be largely affected by the dense ICM and not representative of typical filament galaxies.

The next step in finding these elusive structures around clusters was to sift through our large list of potential filaments found through the first iteration of the Radial Spokes Algorithm, and pull out the bona fide filamentary structures. This entailed assigning each filament a score to quantify how significant or insignificant it was. This “filament score” was based on the following parameters, which were chosen for their ability to retain the most obvious filaments found visually, while excluding less pronounced structures.

1. The total number of galaxies contained in the filament ($N_{total}$). After a comparison of all the potential filaments, we determined that a filament with 40 or more member galaxies would receive an “A” grade in this parameter category, and one with 15 or less members would receive an “F”.

2. The $\chi^2$ rms width of the filament about the line of best fit through the filament galaxies, which we defined to be: $RMSwidth = 1/\chi^2$. We determined, again by a comparison of this parameter for the potential filaments, that a filament with an rms width of 2 or more would receive an “A” grade, while one with an rms width of 0.25 or less would receive an “F” grade in this parameter category.

3. The length-wise uniformity of the filament. This was determined by looking radially outwards and dividing up the filament into 1 Mpc length bins, and collecting the number of member galaxies in each of these bins. The uniformity of each filament was defined to be: $niformity = \frac{\sqrt{N_{total}}}{\sigma}$, where $N_{total}$ is the total number of galaxies contained in the filament, and $\sigma$ is the standard deviation of the number of galaxies in
each bin. A filament with a uniformity score of 3.5 or greater would receive an “A”, while one with a uniformity score of 1 or less would receive an “F” for this parameter.

4. Prominence of the filament peak on the radial slices degree increment plots (see Figure 11). This was defined as: peak prominence = \( \frac{N_{total}}{3 \times \text{median}} \), where \( N_{total} \) is again the total number of galaxies contained in the filament, and “median” refers to the median of the number of galaxies contained in all of the 360 radial spokes for the specific cluster. A filament with a peak-prominence score of 4 or more would receive an “A” while one with a score of 1.5 or less in this category would receive an “F”.

For this filament rating system, an “A” grade would receive a numerical score of 10, a “B” would receive a numerical score of 9, and so on, with the lowest numerical score of 5 corresponding to a grade of “F”. After trial and error, and attempting to have our algorithm’s filament score reflect that which our eyes would rate any given filament, we weighted each of these filament score parameters as follows. Parameter 1, the total number of galaxies contained in the filament (\( N_{total} \)) would constitute 42% of the score. Parameter 2, the \( \chi^2 \) rms width of the filament would constitute 10% of the score. Parameter 3, the uniformity of the filament would constitute 18% of the total score. And parameter 4, the filament peak prominence would represent 30% of the overall score. From these various weights, we defined the overall score of each potential filament to be:

\[
F_{\text{score}} = (0.42 \times S_1) + (0.1 \times S_2) + (0.18 \times S_3) + (0.3 \times S_4),
\]

where \( S_i \) represents the numerical score for parameter “i”. Under this rating system, a certain filament could receive a score between five and ten. We determined that the most robust filaments had scores of six or greater, and they all had at least ten members. These were the criteria that were used to sift the bona fide filaments out of the large list of potential filaments that the first iteration of the algorithm found. We initially found five robust filaments visually, but after the implementation of the Radial Spoke Algorithm, we increased that number, giving us a total of 14 prominent filaments in our sample of 38 clusters. Of the 38 clusters encompassing our subsample of RCS, 25 had zero substantial filaments, 13 had one filament, and one cluster had two prominent filaments emanating from the core.
Figure 12: Two examples of filaments found by the Radial Spokes Algorithm for different clusters, and the filament score that it assigned to each. As can be seen, the algorithm assigns lower scores to more tenuous filaments. Filaments were only considered to be “real” if they had a score of 6 or greater, and had at least ten member galaxies.
IV.3: Photometric Groups and Filaments

In this study, there is a tradeoff between the use of the photometric data and the spectroscopic data. With the spectroscopic data, we can be sure that a galaxy is contained within its host cluster by the use of its redshift measurement, allowing us to rule out superpositions of different infall structures. However, spectroscopic samples include strong sampling biases, as high density regions are relatively under-sampled due to constraints on placing spectroscopic slits during the observation process. Photometric data has the downfall of only allowing us to constrain a galaxy’s membership in two dimensions with its RA and DEC measurements, so any seemingly dense region in a cluster could simply be a superposition of foreground and background galaxies. To negate these superposition effects, a statistical background correction is necessary (see section IV.4). Photometric samples have the advantage of being unbiased with respect to magnitude and color within our defined fields, as this imaging data captures nearly all of the associated cluster galaxies down to a specified magnitude limit. For each cluster we possess anywhere between 10 and 20 times more photometric data than spectroscopic, so any derived quantity (such as a red fraction for a specific galaxy population) with the spectroscopic data will have a much larger intrinsic uncertainty in comparison to one derived with the photometric data.

To reconcile this “uncertainty in position” with the photometric data, we find filaments and groups (as described in the previous sections) with the spectroscopic data, so we can be sure that a certain structure is actually associated with a cluster in the line of sight dimension. Then, to reconcile the “uncertainty in sampling bias” with the spectroscopic data, we define a photometric group or filament to consist of all the photometrically obtained galaxies that lie along the line of sight of the spectroscopic group or filament (using the filament width from the spectroscopic, radial spokes algorithm). To reiterate this point, we only use spectroscopic data to identify structure around a cluster. We then use photometric data coinciding with the spectroscopic structure positions to derive our quantities of interest. This allows us to use a large number of galaxies in deriving our results and to get around the spectroscopic sampling bias, while being sure that our physical structures are associated with a certain cluster.
IV.4: Photometric Background Subtraction

Although we possess a large number of photometric galaxies for each cluster, a large fraction of those are inevitably foreground and background galaxies not associated with the cluster, since we cannot constrain each photometric galaxy’s line of sight position without a redshift. The effect that this has on our main quantity of interest, namely, the red fraction of a certain population of galaxies, is to decrease this quantity below its true value. This is because the foreground and background galaxies around a cluster mainly consist of “field galaxies” which, as discussed previously, are mostly blue in color and star forming. In order to account for this projection effect, we must subtract-off the expected number of red and blue background galaxies from the number of red and blue galaxies we count in a certain population of interest (such as core, group or filament galaxies).

To determine the background subtraction, we first construct a large sample of these galaxies from our entire data set (assuming that the background and foreground overlaid on each clusters’ signal is uniform). To do this, we collect the photometric galaxies for each cluster that are at a cluster-centric distance greater than 3 Mpc, under the assumption that the majority of these are background galaxies who have not been influenced by the cluster environment. We also collect the area of each of these background regions (in arcminutes) that we use for the subtraction.

Figure 13: Demonstration of the photometric background region for a cluster. The inner circle represents a cluster-centric radius of 3 Mpc, outside of which the bold points represent background-selected galaxies.
The entirety of these background galaxies are represented in color-magnitude space, from which we can extract the expected numbers of red and blue background galaxies that are contaminating our signal of a specific galaxy populations’ color-mag distributions. More specifically, we lay the red sequence of each cluster (which is a function of redshift, as described previously) over this distribution of background galaxies in color-magnitude space. We then determine the number of red background galaxies that we expect to be in our cluster signal by counting the number of background galaxies that lie on the red sequence of our specific cluster (and similarly for the blue background galaxies).

![RS of 022456 overlaid on Fish Head](image)

**Figure 14:** Composite color-magnitude space representation of the background present in the photometric data, constructed from every cluster in our data set. In this specific image, the red sequence (horizontal, bounded region) has been overlaid on the background (sometimes called the fish head, due to its overall appearance) for RCS cluster 022456. The background galaxies expected to be present on the red sequence and blue cloud of 022456 are highlighted, as red and blue points respectively. As one can see, when the vertical position of the red sequence changes with differing cluster redshift (a redder red sequence for higher redshift clusters) very different numbers of red and blue background galaxies will be contaminating the cluster signal, so the background subtraction needs to be done for each cluster separately.

To actually carry out this background subtraction for each cluster and each specific galaxy population, we find the numbers of these red and blue background galaxies per square arcminute
that are present in the data by dividing the total numbers counted, say, on the red sequence by the total area of our background that was constructed from all clusters in the data set:

\[ \rho_{\text{red,back}} = \frac{N_{\text{tot,red}}}{\text{Area}_{\text{back}}} \]

where \( \rho_{\text{red,back}} \) is the spatial density of red background galaxies expected for a specific cluster, (in units of galaxies/arcmin\(^2\)), \( N_{\text{tot,red}} \) is the total number of red galaxies counted on the background, fish head, and \( \text{Area}_{\text{back}} \) is the total area of the background regions (the sum of the area of the background regions for each cluster). To subtract the background contamination out of our red fraction numbers for a specific galaxy population, we subtract the numbers of red and blue background galaxies we would expect to be present in the two dimensional area of our specific population (such as the area of a group, core or filament):

\[ N_{\text{red,core}} = N_{\text{red,counted}} - \rho_{\text{red,back}} \times \text{Area}_{\text{core}} \]

where \( N_{\text{red,core}} \) is the true number of red core galaxies present in a specific cluster, \( N_{\text{red,counted}} \) is the number of red galaxies seen in the core (including the background contamination), \( \rho_{\text{red,back}} \) is again, the density of red background galaxies at the specific cluster redshift, and \( \text{Area}_{\text{core}} \) is the area of the region of interest (in this case, the core of a cluster) in units of arcmin\(^2\).

This background subtraction can be carried out on the other populations in a similar way, by using the area of the group or filament within which numbers of red and blue galaxies are being counted. This technique of background subtraction will assure that we are isolating our cluster signal from the projected foreground and background galaxies that may appear to be correlated with our cluster, when in fact they are not.

**IV.5: Photometric Magnitude Limits**

Even in the highest redshift clusters used in this subsample of RCS, the photometry is complete up to \( M^* + 2.5 \). This means that we can be fairly sure that we have data for all galaxies brighter than 2.5 z-magnitudes past the characteristic magnitude of the cluster. With this in mind, we make a hard cut in our data at a z-magnitude of \( M^* + 2.5 \), rejecting any galaxy fainter than this limit (this cut needs to be made individually for each cluster, as \( M^* \) is a function of redshift) (see Figure 15 below).
In an attempt to reduce sampling biases as much as possible with our photometric data, we impose one last cut on the photometry; the aim of which is to get as close to a mass-limited sample as possible. It is commonly known that red and dead galaxies have much larger mass to light ratios than bluer, star forming galaxies (Roberts et al. 1994; Bernardi et al. 2010). As a result, if we impose the same magnitude limit on red sequence galaxies that we do on blue galaxies, we are preferentially including more low-mass blue galaxies in our sample (since a blue galaxy with the same brightness as a red galaxy will have a smaller mass than the red one). To help negate this bias, we impose color-specific magnitude limits for our photometric data, accepting more faint (higher magnitude) red galaxies than blue, in an attempt to arrive at similar mass limits for galaxies at the faint end of our sample.

As we cannot directly measure galaxy mass from photometry, we must do the best we can with the data at hand, so these color-specific magnitude limits are not exactly creating mass-limited samples (although they get us closer to mass-limited samples than a straight cut in z-band magnitude would). The problem with counting more low-mass blue galaxies than red galaxies changes with redshift, and is a minimum at a redshift of zero. Considering this, our qualitative methodology is as follows: we create an oblique, color-specific magnitude limit across our photometric data set for our high-redshift clusters in order to arrive at a constant z-magnitude cut across all colors if the galaxies were in the rest frame (at a redshift of zero). So, this constant z-magnitude cut at a redshift of zero, imposed on our higher-redshift galaxies partially negates the bias of including more low mass blue galaxies, as discussed previously. This also allows us to better compare the high redshift RCS results to the low redshift SDSS results, as it gives us closer mass-limits in photometry between the two different data sets (see section VI. Results for the comparison of RCS and SDSS results).

In practice, this process of creating color-specific magnitude limits uses the empirical red sequence R-z color evolution and galaxy spectral type R-z color evolution from template spectra as a function of redshift, as described in Loh et al. (2008). The results of that study show that for a certain galaxy spectral type, say, an Sab spiral galaxy, the difference between its R-z color and the color of the red sequence, change with redshift. Specifically, the difference between the color of the Sab galaxy and the color of the red sequence increases with increasing redshift. Since an Sab galaxy’s deviation in color from the red sequence should be constant at different redshifts, we can conclude that the use of a straight cut in z-band apparent magnitude is including a
disproportionate amount of Sab galaxies with large z-magnitudes, as redshift increases. To counter this bias, we impose a new z-band magnitude limit for Sab galaxies, as to limit the maximum deviation in R-z color between the Sab galaxy and the red sequence to the maximum physically realistic deviation we see at redshift zero. So, if an Sab galaxy should only deviate at most from the red sequence color by 0.1 magnitudes (as dictated by the deviation at redshift zero), but at redshift 0.8 the model deviation in color is 0.4 magnitudes, we reduce the z-band magnitude limit at the color of an Sab galaxy at redshift 0.8, by $0.4 - 0.1 = 0.3$, from the usual limit of $M^* + 2.5$. We repeat this process for the different galaxy spectral types so they each get their own color-specific magnitude limit in the z-band, and linearly interpolate an oblique cut in color-magnitude space, effectively limiting the maximum deviation in color between a galaxy type and the red sequence to that which is physically realistic. This process is graphically depicted below, and helps us to get closer to a mass limited sample in photometry, across a wide redshift range.

**Figure 15:** Color-magnitude diagrams for two different RCS clusters at different redshifts. The left panel shows a cluster at a redshift of 0.2, while the cluster in the right panel is at redshift 0.8. In both images, the upper and lower limits of the red sequence is overlaid (horizontal red lines), along with the initial, constant z-magnitude cuts of $M^* - 2$ and $M^* + 2.5$ (vertical dotted lines). We notice that the position of the red sequence changes with increasing redshift, as well as its slope (the greater number of galaxies in the higher redshift cluster because these have not been background subtracted). The oblique line in the bottom-right corner of each panel is the linearly interpolated color-specific magnitude limit, and the highlighted galaxies below this line are the low-mass blue galaxies that have been excluded, allowing us to create a more mass-limited sample.
IV.6: Calculation of Uncertainties

To determine the uncertainties associated with our main quantities of interest such as the red fraction of a specific population of galaxies, we add in quadrature the binomial statistical uncertainty associated with the total number of galaxies used to calculate a red fraction, with the variance associated with our derived red fraction from a statistical resampling method known as bootstrapping.

The binomial statistical uncertainty results simply from the number of data points (or lack thereof) used to determine our derived quantity. In the case of this study, if we find 100 red galaxies in say, a cluster core, along with 50 blue galaxies, we can be fairly sure that the red fraction of the core is around 66%. On the other hand, if we find only two red galaxies in a core, and only one blue galaxy, our derived red fraction of 66% will be much less certain than the former case, due to the small sample in the latter. Assuming a parent binomial distribution of the red fraction of a specific population of galaxies (due to the discrete, “yes/no” nature of a galaxy being red or blue), the statistical error associated with this derived quantity is:

\[ \sigma_{\text{binomial}} = \sqrt{\frac{RF(1 - RF)}{N}} \]

where RF is the derived red fraction, and N is the total number of galaxies used to calculate that red fraction.

The bootstrapping method is similar to a Monte Carlo random resampling technique, where multiple virtual samples are built up by randomly selecting data from the real data sample to be of the same size. The quantity of interest is then determined from each of the virtual samples, and the variance of that distribution of results from the virtual samples is used as an error on the derived quantity from the real sample. This approach is more effective than standard Gaussian estimates, as the bimodal distribution of galaxy colors is not a single-peaked Gaussian. To put this into perspective with our study, we would begin by measuring the 100 red galaxies and 50 blue galaxies that were cited in the previous example with the binomial statistical uncertainty. We would then randomly select galaxy colors out of our sample of 150 (allowing a galaxy to be drawn multiple times), slowly building up a virtual sample until it matches the size of the original sample, namely, until it has 150 randomly selected galaxy colors in it. Finally, the red
fraction of this virtual sample would be calculated from the randomly selected galaxy colors. This process of random selection to build up a virtual sample is then repeated (in the case of our study, we use 1000 bootstrap iterations), and the variance in the distribution of the derived quantity (the red fraction values from each bootstrap) is cited as the uncertainty in our red fraction determination from the real data sample. More specifically, this uncertainty from the bootstrap method is the standard deviation of the distribution of bootstrapped red fractions.

**Figure 16:** An example of a bootstrapped distribution of red fraction values for group galaxies with the spectroscopic data. The dotted line represents the true red fraction value derived from the original sample. The dot-dashed lines represent the $1\sigma$ deviations from the median of the bootstrapped distribution, represented by the dashed line. The error associated with the true red fraction value is the width of the $1\sigma$ deviation markers.

After finding both the binomial statistical uncertainty and the uncertainty derived from the bootstrap technique, we add the two uncertainties in quadrature to determine the overall uncertainty in the red fraction value:

$$
\sigma_{\text{tot}} = \sqrt{(\sigma_{\text{binomial}})^2 + (\sigma_{\text{bootstrap}})^2}
$$

The motivation for adding these two sources of uncertainty in quadrature is as follows. When the numbers of galaxies in a sample are small, the binomial uncertainty dominates, and the
IV.7: Definitions and Locations of Cluster Populations

As indicated previously, the aim of this study is to study the star formation rates of galaxies in various regions around clusters. In this section, we will define or summarize these various regions and the conditions for membership of a galaxy to a certain population.

The first population of galaxies that we will analyze is the core. For membership as a core galaxy, the one in question must be within 0.5 Mpc of the core centroid position (and within 3000 km/s of the redshift of the core, if we are dealing with spectroscopic data). The second population is that of galaxies in groups.

As discussed in section IV.1 and IV.3, a galaxy group centroid position is the location of a groups’ member with the largest surface density. That is, this central group galaxy must have a surface density (Σₖ) greater than the 90th percentile of surface densities of galaxies outside of the cluster core. Surface densities are determined with the spectroscopic data, and only galaxies within 1000 km/s of the galaxy in question are used in the surface density calculation. If a certain galaxy has a surface density above the 90th percentile, and has at least four spectroscopically confirmed “friend galaxies” within 0.3 Mpc and 1000 km/s, its position is cited as the group centroid position. The population of group galaxies on which we perform our analysis is then constructed from all photometric galaxies within 0.3 Mpc of the spectroscopic group centroid positions.

As discussed in sections IV.2 and IV.3, we find filaments in the spectroscopic data set, with each having its own specific filament width. The population of filament galaxies on which we perform our analysis of red fractions is then built from all photometric galaxies within a distance of ½ of the filament width from the radially outward line defining the center of the filament (again, the filament location is originally found with the spectroscopic data set). These photometric filament galaxies are also restricted to a cluster-centric radius greater than 0.5 Mpc, as to not include core galaxies in filaments. The galaxy population that we call “groups in filaments” is constructed from every photometric galaxy that happens to be part of a group that is embedded in a filament.
The last population of galaxies around clusters that we will refer to in this study is what we call “infalling singleton galaxies”, or simply “singletons”. These are infalling, isolated galaxies around a cluster not contained in a filament, within a group, or in the core region. This population is constructed of all photometric galaxies with a cluster-centric radius greater than 0.5 (to exclude core galaxies), and less than 3 Mpc. The choice of 3 Mpc was chosen because we define our field population from which we determine the necessary background subtraction as any photometric galaxy with a radius greater than 3 Mpc. Any singleton galaxy past this radius would be, by definition, statistically subtracted away from the cluster signal. An illustration of these populations is presented in Figure 17 below.
Figure 17: A cluster map of a typical field in our RCS subsample. Every point represents a photometric galaxy in the field, within the specified magnitude limits. Every square represents a spectroscopically confirmed cluster galaxy. The central circle of radius 0.5 Mpc marks the boundary of the core population; any photometric galaxy within this region is considered to be part of the core population. The galaxy group positions have 0.3 Mpc circles marking their boundaries, with the photometric group galaxy populations inside these boundaries marked in red. In this image, there are three group positions, the one indicated, close to the core, and the two in the lower-right corner of the map, below the filament. The filament center-line is the solid black line emanating from the core, found with the spectroscopic data in the filament finding algorithm. The photometric filament population galaxies are marked in blue, and are all the photometric galaxies within a half-filament-width of the filament center-line. The group in the filament is indicated in the image, and all photometric “group in filament” population galaxies from this cluster are those within the indicated group boundary. The singleton population from this cluster are represented by the larger black dots, with a cluster-centric radius of $0.5 < R < 3$. The singleton population does not include any found within the filament or group in this region. Lastly, the background galaxies are the remaining tiny black dots, with a cluster-centric radius greater than 3 Mpc, excluding any galaxies within the filament or groups in this region.
V. SDSS Analysis

V.1: Differences between SDSS and RCS Analysis

Overall, the analysis carried out on the SDSS data set and GMBCG clusters is for the most part, identical to that carried out on the RCS data set and clusters. In this section, I will describe the minor differences between the SDSS and RCS analysis. If a method or parameter is not explicitly mentioned here as being dissimilar, the reader should assume it was done in the exact same way as in the RCS analysis, and refer to section IV for those details.

The main differences between the two analyses arise due to the difference in data coverage of RCS versus SDSS. RCS cluster fields contain a larger amount of spectroscopic data within 5 Mpc, but past 5 or 6 Mpc, spectroscopic and photometric data in RCS dwindle. In contrast, SDSS spectroscopic data, although less dense close to the cluster extends much further, out to 15 Mpc for the GMBCG clusters chosen in this study. As a result of this difference in spectroscopic coverage, if we restrict our SDSS/GMBCG cluster field analysis to the roughly 6 Mpc used in RCS, we would preferentially find more groups around RCS clusters, and potentially more robust filaments. To counter this bias, we use the entirety of the SDSS/GMBCG fields out to 15 Mpc for our group and filament finding with the spectroscopic data. We again, find the photometric group galaxy population by collecting all photometric galaxies within the line of sight of the spectroscopic positions. A dense collection of gravitationally bound galaxies like a group is unlikely to evolve differently at different cluster-centric radii, until the group gets close to the virial radius and the intracluster medium (see sections VI. Results and VII. Discussion), so this difference in radial sampling for groups is unlikely to detrimentally affect the results of this study.

For filament finding, we apply our algorithm to all spectroscopic data out to 15 Mpc, in order to most accurately find the locations of these structures, which are likely to extend even further than this radius (Springel et al. 2005). Then, in defining our filament population of photometric galaxies in SDSS, we collect the photometric galaxies within one half of the filament width of the filament center-line, out to a limiting cluster-centric radius of 6 Mpc, to match the radial limit of RCS. The singleton photometric population in SDSS extends from 0.5 Mpc to 3 Mpc, as in the RCS analysis.
As mentioned previously, we only use the photometric data in RCS to quantify star formation in various populations. In the study of SDSS clusters, we perform a photometric analysis, and a spectroscopic analysis to quantify star formation, as the direct measures of specific star formation we have for SDSS spectroscopic galaxies allows a more detailed look at the radial dependence of star formation rates for various populations (see section VI. Results). Since we do not perform a similar analysis in RCS due to the lack of direct measures of star formation, we extend the spectroscopic analysis of SDSS to 10 Mpc, in order to collect more data and have better number statistics.

The last difference between the studies of the two data sets is the choice of a constant red sequence (independent of redshift) across the redshift range of our GMBCG clusters in Sloan. Our chosen subsample of these clusters (see section VI. Results) span a redshift range of 0.08 < z < 0.12, over which the position of the red sequence in color-magnitude space does not vary significantly. We adopt the red sequence parameters from the models of Gilbank et al. (2008), at a redshift of 0.1 for use in the analysis of SDSS cluster populations. However, the z-magnitude value of $M^*$ does vary over this redshift range, so we determine each clusters’ characteristic magnitude via the following:

$$M^*(z) = 16.31 + 5 \cdot \log \left[ \frac{z}{0.1} \right]$$

Where 16.31 is the model characteristic cluster magnitude at a redshift of 0.1 (Gilbank et al. 2008).

V.2: Relationships between Photometrically and Spectroscopically Derived Quantities

As discussed in section II.4, our two methods of quantifying star formation are the red fraction and the specific star formation rate. The specific star formation rate distribution for the entire SDSS data set is shown below, as well as the relation between SSFR and R-z color.
Figure 18: Specific star formation rate distribution for SDSS data set. It can be seen that the distribution reflects the well-known bimodality in galaxy color (Loh et al. 2008), with the peak at log(SSFR) = −10 corresponding to the population of blue, star forming galaxies, and the peak at log(SSFR) = −12.3 corresponding to the population of red and dead galaxies. The vertical dotted line represents the “green valley” cutoff between star forming and non-star forming galaxies at log(SSFR) = −11.1.

Figure 19: R-z galaxy color versus log(SSFR). It can be seen that the R-z color does not differentiate between star forming and non-star forming until about log(SSFR) = −10.3, past the obvious cut of -11.1 in Figure 18. In addition, the relation has a significant blur, illustrating that while the red fraction is a good tracer of star formation, an actively star forming galaxy could mistakenly be placed on the red sequence, and considered red and dead.
The above figure serves as our motivation for using the more accurate SSFR measurements in the SDSS data set wherever possible, as it is better at differentiating between star forming and quenched galaxies.

As discussed in section II.3, we use a galaxy’s z-magnitude relative to the cluster characteristic magnitude $M^*$ to distinguish between dwarf and giant galaxies, with the former having a z-magnitude less than $M^* + 0.5$ and the latter having a z-magnitude greater than this limit. It is necessary to normalize a galaxy’s z-magnitude with respect to its host clusters’ characteristic magnitude, as apparent z-magnitude varies with redshift (so a lower redshift dwarf galaxy could have a similar z-mag to a higher redshift giant). The stellar mass measurements we possess from the SDSS spectroscopic data set allow us to assess the accuracy of this measure of $zmag - M^*$ as a tracer for mass. The following figures depict the relationship between the two quantities, and illustrate the distribution of stellar masses in the SDSS data set:

**Figure 20:** Relationship between galaxy z-magnitude, normalized by the cluster characteristic magnitude and the log(stellarMass). It is quite apparent from the figure that the photometric tracer of galaxy mass, $zmag - M^*$ is a good indication of the actual galaxy stellar mass.
Figure 21: Distribution of stellar masses for the spectroscopic data set in SDSS. The vertical line shows the chosen cut between dwarf and giant galaxies at log(stellarMass) = 10.3 used in the spectroscopic analysis of the SDSS data set (see sections V.3 and VI).

V.3: Cluster-Centric Distance Gradients in Galaxy Properties

As was mentioned in the previous section, the larger amount of data and the direct measures of specific star formation rate in our SDSS spectroscopy allow us to further investigate the environmental dependence on a galaxy’s ability to form new stars. In addition to the photometric analysis of SDSS/GMBCG cluster galaxy properties like red fraction, we also investigate galaxies SSFR as a function of cluster-centric radius, for various cluster populations (see section VI.Results). In the following section, we average the specific star formation rate for dwarf and giant galaxies separately (the cutoff between dwarfs in giants in stellar mass being log(SSFR)=10.3, as discussed in the previous section), in multiple cluster-centric radius bins. To compare clusters of different masses and sizes, which may act on galaxies at different distances away from their core, we use the mass-normalized measurement of cluster-centric distance, /R_{200}, where R_{200} is the cluster virial radius (see section II.6). It is expected that once an infalling galaxy reaches the cluster virial radius, the dense intracluster medium (ICM) can quickly quench it via ram pressure stripping. Since the extent of the ICM is related to the mass of the cluster, and
hence, the virial radius, normalizing a galaxy’s cluster-centric distance by $R_{200}$ allows us to compare radial gradients in SSFR for different size clusters more effectively and accurately.

The uncertainties on the average SSFR in each radial bin are quantified in two separate ways, and added in quadrature. The first measure of uncertainty on these average SSFRs is determined by the bootstrap method (see section IV.6). The second measure of uncertainty is in this case determined by the standard deviation of the mean (SDOM) of the array of individual galaxy SSFR measurements in a certain radial bin. In this case, the SDOM is warranted, as the distribution of galaxy SSFRs around their average follows a parent Gaussian distribution. The SDOM is determined in the following manner:

$$
\sigma_{SDOM} = \frac{\sigma}{\sqrt{N}}
$$

Where $\sigma$ is the usual standard deviation of the array of SSFR values, and $N$ is the number of galaxy SSFR values in the specific radial bin. To determine the overall uncertainty on the average SSFR in each radial bin, we add in quadrature the uncertainty obtained from the bootstrap method, and the uncertainty obtained from the SDOM:

$$
\sigma_{SSFR} = \sqrt{\left(\sigma_{bootstrap}\right)^2 + (\sigma_{SDOM})^2}
$$

The last measure of star formation that we will analyze as a function of cluster-centric radius (again in $R/R_{200}$) is the starburst fraction. We define a galaxy as starbursting if it has a very high SSFR value, namely, $\log(\text{SSFR}) > -9.5$. As can be seen in Figure 18 above, this cutoff between non-starbursting galaxies and starbursting only includes a very small portion of the data set in the starburst fraction, so the uncertainties on these measurements will be relatively large due to dwindling numbers. We define the starburst fraction in a certain radial bin to be the number of starburst galaxies (with $\log(\text{SSFR}) > -9.5$) divided by the total number of galaxies in the bin. Due to the statistical similarities between the starburst fraction and the red fraction, we will determine the uncertainties on each starburst fraction as we did for the red fraction, assuming a parent binomial distribution (see section IV.6).
VI. Results

VI.1: RCS Results

After imposing the previously discussed criteria on filament selection in the Radial Spoke algorithm, we found 13 significant filaments from our RCS subsample of 38 of the most massive clusters. For the analysis of core, group, and singleton galaxy populations, we utilized the entire subsample of 38 clusters. The following table summarizes the derived properties of each of the investigated cluster galaxy populations in the RCS subsample:

<table>
<thead>
<tr>
<th>Population</th>
<th>Photometric Red Fraction</th>
<th>Spectroscopic Red Fraction</th>
<th>Average Redshift</th>
<th>z-weighted Core Comparison Red Fraction</th>
<th>Average Surface Density [galaxies/Mpc^2]</th>
<th>Total Number of Galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cores</td>
<td>0.69 +/- 0.04</td>
<td>0.72 +/- 0.03</td>
<td>0.51</td>
<td>N/A</td>
<td>90.7</td>
<td>1,045</td>
</tr>
<tr>
<td>Filaments</td>
<td>0.35 +/- 0.04</td>
<td>0.38 +/- 0.04</td>
<td>0.56</td>
<td>0.65</td>
<td>46.3</td>
<td>4,248</td>
</tr>
<tr>
<td>Groups in Filaments</td>
<td>0.45 +/- 0.08</td>
<td>0.64 +/- 0.06</td>
<td>0.54</td>
<td>0.67</td>
<td>58.9</td>
<td>331</td>
</tr>
<tr>
<td>Groups</td>
<td>0.66 +/- 0.02</td>
<td>0.63 +/- 0.04</td>
<td>0.52</td>
<td>0.68</td>
<td>74.7</td>
<td>615</td>
</tr>
<tr>
<td>Singletons</td>
<td>0.32 +/- 0.04</td>
<td>0.36 +/- 0.03</td>
<td>0.57</td>
<td>0.64</td>
<td>37.6</td>
<td>5,860</td>
</tr>
</tbody>
</table>

Table 2: Derived properties of various galaxy populations across the cluster environments in the RCS subsample.

The overall photometric red fraction for each population was determined by first counting the number of photometric red and blue galaxies and performing the necessary background subtraction for each individual cluster. Then, we divided the total number of red, background subtracted galaxies by the total number of (background subtracted) galaxies from all clusters combined, for the population in question.

The spectroscopic red fraction was performed in the same way as the photometric red fraction, excluding the background subtraction (as our spectroscopic galaxies are confirmed cluster members due to redshift measurements). Even though the spectroscopic red fraction numbers cited in table 2 agree with the photometric red fraction numbers for the most part, it should be noted that these values are not as reliable as the former, due to a sampling bias present in the spectroscopy of RCS. In general, we find that the spectroscopic red fractions for each population are slightly larger than their photometric counterparts. We attribute this to a bias in the choice of spectroscopic target galaxies in a given field, related to the use of multi-object spectroscopic
masks used during the observation process. Due to the limitations of placing two spectroscopic slits in close proximity on the mask, it is expected that more luminous galaxies were preferentially chosen to have their spectra measured, especially in dense environments like groups. We were able to confirm this bias in high density, group environments by measuring the average magnitude \((Zmag - M^*)\) for photometric group galaxies, and spectroscopic group galaxies separately. We found that the average magnitude of spectroscopic group galaxies was smaller (more luminous) than the average magnitude of photometric group galaxies, indicating that the RCS spectroscopic sample preferentially chooses more luminous and hence, redder galaxies in high density environments. This explains why the spectroscopic red fractions are larger than the photometric red fractions for RCS groups (see table 2).

The “z-weighted core comparison red fraction” was also done as a comparison, in order to compare the red fraction of a certain population to the core red fraction, \textit{at that population’s average redshift}. Although it is evident from the table that the average redshifts of each population are fairly similar, this was done in case we were preferentially finding more filaments at low redshift, which would have resulted in an unfair comparison between filament red fraction and core red fraction, as these measures may be redshift dependent. The redshift dependence of the core red fraction was determined for this purpose, which we deem the “fiducial Butcher-Oemler Effect”, depicted in Figure 22 below. The average surface density of each population was determined by averaging all \(\Sigma_5\) measurements for every photometric galaxy in the population, then statistically subtracting the background density. This background subtraction was also performed on the total number of galaxies in the last column.
In our analysis of the RCS cluster populations, we determine the luminosity functions for each cluster population. The statistical background subtraction was applied to each luminosity (magnitude) bin, for each individual cluster, by subtracting the total number of background galaxies expected to be in the magnitude bin from the raw counts. As mentioned previously, the background subtraction has to be done for each cluster individually, since the expected amount of foreground and background contamination is redshift dependent (see section IV.4). For each galaxy population, we sum the counts in every magnitude bin for all clusters in the sample. Finally, we normalize the luminosity function to a maximum value of 1, and overlay the best fit (by a $\chi^2$ minimization) Schecter Function with free parameter $\alpha = -1$. The red sequence and blue cloud galaxy luminosity functions are also overlaid, indicated by the dotted red and blue curves, respectively.
Figure 23: Luminosity function for RCS core galaxies (photometric).

Figure 24: Luminosity Function for RCS filament galaxies (photometric).
Figure 25: Luminosity function for RCS group galaxies in a filament (photometric).

Figure 26: Luminosity Function for RCS isolated group galaxies (photometric).
Lastly, we present the main results of this study of RCS cluster galaxy populations, namely, the red fraction of each population as a function of that population’s average surface density:
**Figure 28:** Average red fraction versus average galaxy surface density, for the various cluster galaxy populations in the RCS study. Specifically, these are the derived photometric red fraction, and photometric average $\Sigma_5$ values for each cluster population (see table 1).

VI.2: SDSS Results

After imposing the aforementioned criteria on filament selection from the Radial Spoke algorithm, we found a total of 46 significant filaments around the most massive GMBCG clusters in our subsample of SDSS. For the analysis of core, group and singleton galaxy populations, we restricted our search to only the 46 clusters around which we identified significant filamentary structures (see section VII. Discussion). The following table summarizes the derived properties of each of the investigated cluster galaxy populations in the SDSS photometric subsample:

<table>
<thead>
<tr>
<th></th>
<th>Photometric Red Fraction</th>
<th>Average Surface Density [galaxies/Mpc$^2$]</th>
<th>Total Number of Galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cores</td>
<td>0.82 +/- 0.02</td>
<td>96.6</td>
<td>1,624</td>
</tr>
<tr>
<td>Filaments</td>
<td>0.45 +/- 0.01</td>
<td>47.4</td>
<td>6,979</td>
</tr>
<tr>
<td>Groups in Filaments</td>
<td>0.64 +/- 0.03</td>
<td>49.7</td>
<td>419</td>
</tr>
<tr>
<td>Groups</td>
<td>0.65 +/- 0.01</td>
<td>71.7</td>
<td>3,016</td>
</tr>
<tr>
<td>Singletons</td>
<td>0.34 +/- 0.01</td>
<td>27.5</td>
<td>2,571</td>
</tr>
</tbody>
</table>

**Table 3:** Derived properties of various galaxy populations across the cluster environments in the SDSS photometric subsample.

As in the RCS tabulated results, the overall red fractions were found by summing the background subtracted counts of red and blue galaxies across all clusters first. The average surface density and total number of galaxies for each population were determined in the same way as in the RCS results. These SDSS results do not include three of the columns of derived quantities that were present in table 2 (the average redshift, the $z$-weighted core comparison red fraction, and the spectroscopic red fraction). The average redshift and $z$-weighted core comparison redshift were not determined for the SDSS cluster galaxy populations, because of the limited redshift range of the GMBCG clusters we analyzed in SDSS. The spectroscopic red fraction was not determined for the SDSS populations either, as a more detailed analysis of the spectroscopic SSFR gradients will be presented later in this section.
The following figure illustrates the main result of the photometric study of the SDSS cluster populations; namely, the red fraction of each cluster galaxy population as a function of the average surface density of that population.

![Figure 29: Average red fraction versus average galaxy surface density for SDSS Cluster Populations](image)

**Figure 29:** Average red fraction versus average galaxy surface density, for the various cluster galaxy populations in the SDSS study. Specifically, these are the derived photometric red fraction, and photometric average $\Sigma_g$ values for each cluster population (see table 3).

Next, we present the first result of the spectroscopic study of the SDSS cluster galaxy populations. Specifically, Figure 30 below shows the bimodal specific star formation rate distributions for three of the largest populations (by number) in the SDSS subsample. Each distribution was normalized in order to compare populations with different total numbers of galaxies, by requiring that the sum of the number of galaxies in each SSFR bin equal one. The figure reflects the well-known relationship between local galaxy surface density and star formation rate. Specifically, it is clear that the dense, core galaxy population has a larger, more pronounced “red and dead” region of the distribution around $\log(SSFR) = -12.5$ in comparison to the less dense singleton galaxy population. Similarly, the singleton galaxy population has a larger “blue cloud” around $\log(SSFR) = -10$ in comparison to the core galaxy population, illustrating that cluster cores mainly contain “red and dead” galaxies, while the lower density...
Singletons have larger numbers of actively star-forming galaxies. The previously unknown result present in the figure is that the filament galaxy population resides somewhere between singletons and cores. Filament galaxies initially appear to be more quenched than infalling singletons, but less quenched than core galaxies (see section VII.Discussion).

Figure 30: Specific star formation rate distributions for the three largest cluster populations in the SDSS spectroscopic study. The figure illustrates that core galaxies have a diminished blue cloud (at $\log(SSFR) = -10$), and a pronounced red sequence (at $\log(SSFR) = -12.2$), indicative of significant galaxy quenching in this environment. Singleton galaxies have the largest amount of blue, star-forming galaxies, while filament galaxies are more quenched than singletons, but less than cores. In general, this figure demonstrates the well-supported idea that environment can significantly affect a galaxy’s evolution.

Next, we present the main results of the spectroscopic study of SDSS cluster galaxy populations, namely, the average SSFR versus cluster-centric radius ($R/R_{200}$) for various cluster populations. Specifically, we determine the average SSFR in radial bins for dwarf and giant galaxies separately, with the cutoff between dwarfs and giants occurring at $\log(stellarMass) = 10.3$. This star formation rate gradient analysis has been carried out for infalling, isolated singleton galaxies, infalling groups, isolated filament galaxies, and galaxy groups within filaments.
Figure 31: Average specific star formation rate versus $R/R_{200}$ for dwarf and giant galaxies in different cluster populations. The horizontal dotted line at $\log(SSFR) = -11.1$ marks the divide between star-forming and non-star-forming galaxies (see Figure 18). The upper-left panel shows the SSFR gradients for isolated, infalling singleton galaxies. The upper-right panel corresponds to infalling galaxy groups. The lower-left panel corresponds to isolated, filament galaxies, and the lower-right panel corresponds to galaxy groups within filaments.

As a comparison, we also determine the average SSFR as a function of cluster-centric radius, without further separating dwarf galaxies from giants. This analysis is presented in Figure 32 below, and helps to reconcile the results of the photometric analysis with these spectroscopic results (see section VII.2).
Figure 32: Average specific star formation rate vs $R/R_{200}$, consolidated for both dwarf and giant galaxies. The upper left panel corresponds to the population of infalling singleton galaxies; the upper right panel depicts the SSFR gradient of isolated group galaxies; the lower left panel corresponds to isolated filament galaxies, and the lower right panel depicts the SSFR gradient of groups within filaments.

Next, we present the starburst fraction versus cluster-centric radius for the same galaxy populations as in figures 31 and 32 above, for dwarf and giant galaxies individually.
Figure 33: Starburst fraction versus $R/R_{200}$ for dwarf and giant galaxies of the various infalling cluster galaxy populations. Similar to figures 31 and 32 above, the upper-left panel corresponds to isolated, infalling singleton galaxies and the upper-right panel corresponds to infalling galaxy groups. The lower-left panel corresponds to isolated filament galaxies, and the lower-right panel corresponds to galaxy groups within filaments.

Finally, we present the galaxy surface density (measured by $\Sigma_5$) as a function of cluster-centric radius for photometric filament and group galaxies in SDSS. We measure the (background subtracted) surface density of galaxies with the photometric data set in order to avoid the sampling biases present in the spectroscopic sample. The uncertainties on each average $\Sigma_5$ are determined by the standard deviation of the mean (SDOM, see section IV.6). Figure 34 below shows the surface density gradients for all photometric filament galaxies, including both isolated filament galaxies and group galaxies within filaments. This was done in order to increase the number of galaxies in each radial bin, and thus decrease the statistical uncertainty. It should be noted that this choice does not affect the general relationship seen, as the surface density versus cluster-centric radius dependence for isolated filament galaxies is similar to that of groups in filaments.
Figure 34: Average galaxy surface density versus $R/R_{200}$ for photometric filament galaxies in SDSS. These measures of surface density include the statistical background subtraction, and are averaged for both isolated filament galaxies, and galaxy groups within filaments. It can be seen that the average surface density of filament galaxies shows a considerable decrease between two and four times the virial radius (see section VII.Discussion).

Figure 35 below depicts the surface density gradients for all photometric group galaxies, not contained within filaments. Due to the relatively large sample of isolated groups (not within filaments) found in our SDSS subsample, singleton galaxies were not included, as the number statistics with groups alone was sufficient.
Figure 35: Average galaxy surface density versus $R/R_{200}$ for isolated (not within a filament) photometric group galaxies in SDSS. These measures of surface density have again, been background subtracted. It can be seen that the average surface density of group galaxies outside of filaments shows an increase between two and four times the virial radius (see section VII.Discussion).

VI.3: Evolution with Redshift; Comparison of RCS and SDSS

The last of the results of this study include a comparison of the cluster galaxy populations and their star formation rates between the RCS and SDSS subsamples. Due to the different redshift ranges, and hence, ages of the universe that RCS and SDSS probe, a comparison between the two studies provides insight into how these various cluster galaxy populations evolve in time. Since we do not possess spectroscopic measures of SSFR and stellar mass for the RCS sample, this comparison between the two studies is done with just the photometric data. As was discussed previously (see section V.1), we attempted to define the different galaxy populations between RCS and SDSS as similarly as possible in order to make a robust comparison.

The first of these comparisons can be seen in Figure 36 below, where we plot the red fraction of each cluster galaxy population as a function of that population’s average surface density, for both
the RCS and SDSS studies. These measures were carried out exactly as they were described in sections VI.1 and VI.2.

![Red Fraction vs Galaxy Surface Density for RCS and SDSS](image)

**Figure 36:** Red fraction versus galaxy surface density for each cluster galaxy population, for both the RCS and SDSS subsamples. The dotted lines between like points visually connect two similar populations between both data samples. For example, the lower-left most points consisting of gold and red diamonds show the red fraction vs surface density for the singleton galaxy populations, for SDSS and RCS, respectively. One can get a sense of the evolution in time between these parameters by following the dotted line from RCS (red) to SDSS (gold) for a specific population of galaxies.

The final comparison between the RCS and SDSS cluster populations is shown in Figure 37 below. Here, we present each cluster population’s contribution to the overall cluster composition in galaxy number. By carrying out this “comparison census” of the numbers of galaxies in each cluster environment in SDSS and RCS, we can gain some insight into how the structure of galaxy clusters evolves with time. Due to the fragility of this counting census on the exact definitions of each cluster population, here we limit the radial extent of galaxy groups in SDSS to the 6 Mpc used in RCS. With this included, the sizes and radial extents defining each population in SDSS are identical to that used in RCS. To determine a certain population’s contribution to the overall number of galaxies in the cluster environment, we count galaxies with the photometric data to avoid sampling biases, and include the relevant statistical background subtraction. For each data
sample, we sum the number of galaxies in each environment, for all clusters to determine the total number of galaxies in the cluster population. To determine each population’s percentage in galaxy number of the cluster composition, we divide the total number of galaxies in that population by the sum described above.

**Figure 37:** Bar-plot showing the significance of each cluster population by number, for both the RCS and SDSS samples. The x-axis shows each cluster galaxy population, with the y-axis depicting that populations’ percentage of the overall cluster composition. It can be seen that almost 50% of cluster galaxies at the higher redshifts of RCS are part of the singleton population, roughly 35% are contained within filaments, and a very small number live in higher density environments like groups and cores. In contrast, the majority of cluster galaxies at the lower redshifts of SDSS live in filaments (almost 50%), while less than 20% are part of the singleton population. It is also evident that the higher-density environments make up roughly 35% of the cluster composition in low redshift clusters.
VII. Discussion

VII.1: Galaxy Quenching in the Higher Redshift Universe

Since the mean redshift of the clusters studied in our subsample of RCS is $z \approx 0.5$, our analysis of these environments provides insight into quenching mechanisms and galaxy cluster composition when the universe was roughly 60% of its current age. Referring to Figure 28, we see a general trend of increasing red fraction with increasing galaxy surface density, across each of the specific cluster galaxy populations analyzed in this study. This well-known behavior has been studied extensively (Dressler et al. 1980; Webb et al. 2013), and is due to the increasing effectiveness of quenching mechanisms in higher-density environments. However, subtleties do exist to this seemingly simple correlation, as different quenching mechanisms act in different environments, and hence, on the different cluster populations targeted in this study.

Starting with the singleton population (isolated infalling galaxies between 0.5 and 3 Mpc of the cluster core), we find that these galaxies have the lowest surface density and the lowest red fraction of all the cluster populations. By definition, we expect this population of cluster galaxies to have the lowest surface density. The low red fraction (and hence, relatively large star formation rates) of 0.32 of this population fits in well with our current understanding of galaxy quenching mechanisms outside of the inner-cluster environment. Outside of the cluster core and the dense intracluster medium (ICM), the main physical quenching mechanisms at work are due to interactions with nearby galaxies. These interactions with nearby galaxies include mergers, galaxy-galaxy harassment and galaxy strangulation, all of which will be expounded upon later in this section. With this in mind, these isolated singletons are not subject to any of the higher-density quenching mechanisms that act in other environments, and thus, should have the lowest red fractions and largest star formation rates of any cluster population. As a comparison, field galaxies unassociated with the cluster environment have an average red fraction of 0.2 (Loh et al. 2008), corroborating our derived red fraction for singletons, since singletons are slightly denser and redder than the general field population outside of clusters.

Referring again to Figure 28, we find that filament galaxies at the redshifts of RCS have statistically similar red fractions to singleton galaxies, but with slightly higher surface densities. The larger surface densities are to be expected, as our definition of intercluster filaments ensures that they are slightly denser than the general cluster infall region. The similar red fraction to
singletons indicates that the filamentary environment at these higher redshifts is not that different than the general cluster infall region. This notion is plausible with the ideas of hierarchical clustering and the growth of large scale structure in mind (Springel et al. 2005), as dense pieces of the cosmic web (like filaments) are underdeveloped at large redshifts, and grow to become more substantial as the universe ages towards lower redshifts.

We find that galaxies contained in groups, with the groups themselves embedded in large scale filaments (groups in filaments) are denser and redder than isolated filament galaxies. This behavior fits in well with our understanding of high density quenching mechanisms, as these groups in filaments are more subject to mergers, harassment and strangulation than isolated filament galaxies are, leading to a larger fraction of red and dead galaxies. However, we find that groups in filaments are considerably less dense and bluer than isolated groups in the general cluster infall region outside of filaments. This behavior is also seen in the GMBCG clusters of Sloan, and will be expounded upon in section VII.2 where a discussion and interpretation of the SDSS results is presented.

Isolated groups outside of filaments in the general cluster infall region have the second largest surface density (second only to galaxies in cluster cores), and have an average red fraction statistically similar to that of core galaxies. This finding indicates that galaxies within groups are quite similar to galaxies found within the cores of massive clusters, even at the higher redshifts of RCS. Furthermore, the similar red fractions of these two populations of galaxies indicates that extra-cluster quenching mechanisms (mergers, harassment and strangulation) are just as effective as the favored intra-cluster quenching mechanism of ram pressure stripping, as long as the local galaxy surface density is large enough. This leads us to the conclusion that a substantial degree of pre-processing does occur in higher density regions outside of clusters.

Lastly, we observe the expected behavior in density and red fraction for galaxies within cluster cores. Specifically, the population of core galaxies has the largest surface density and the largest red fraction of any population. Ram pressure stripping is the dominant physical quenching mechanism at work in the inner regions of cluster cores; when the disc of an infalling galaxy encounters the hot, dense ICM in the cluster core, its reserves of gas in the disc and halo are stripped away, extinguishing any hope of new star formation. Even if an infalling galaxy is able to survive the extra-cluster quenching processes at work, ram pressure stripping will continue to
quench some of these infalling survivors in the inner cluster region, giving the population of core galaxies the largest red fraction.

VII.2: Galaxy Quenching in the Low Redshift Universe

VII.2.a: Interpretation of SDSS Photometric Analysis

Considering the mean redshift of $z \approx 0.1$ for our subsample of GMBCG clusters, the results of our SDSS study provide insight into quenching mechanisms and cluster composition ~4 billion years after the mean redshift of RCS at $z \approx 0.5$. Referring first to the main result of the photometric analysis of our SDSS dataset, namely, Figure 29, we again see the general trend of increasing red fraction with increasing galaxy surface density, as in the RCS study.

The population of isolated, infalling singleton galaxies has the lowest red fraction and the lowest surface density, similar to the behavior of this population in the RCS sample. However, in contrast to the results of the RCS study, we see that isolated filament galaxies have begun to deviate from the singleton population at the lower redshifts of Sloan. In particular, we find that isolated filament galaxies in Sloan have a considerably larger surface density and red fraction in comparison to singleton galaxies. This finding is again in line with the concept of hierarchical clustering; at the low redshifts probed by Sloan, filaments and other dense components of the cosmic web are more substantial and developed. Simulations of the growth of large scale structure (Springel et al. 2005) support this, and show that as the universe evolves to lower redshifts, intercluster filaments become more dense and massive, corroborating our finding of the increased density and differentiation between isolated filament galaxies and singleton galaxies. The larger red fraction of isolated filament galaxies in comparison to the singleton population can be attributed to this increase in surface density; a larger surface density increases the effectiveness of extra-cluster high density quenching mechanisms like harassment.

We find that the population of cluster core galaxies has the largest surface density, and the largest red fraction, an expected result in line with the results of the RCS study, and the ideas of hierarchical clustering. Specifically, we determine the average photometric red fraction of all cluster core galaxies in SDSS to be 0.82, in agreement with the results of other studies (Ellingson et al. 2001; Loh et al. 2008).
The most unexpected result of the photometric analysis of our SDSS subsample of associated cluster galaxies is the relative locations of isolated group galaxies, and groups in filaments in red fraction-surface density space. We find that groups in filaments and isolated groups have statistically similar red fractions, but considerably dissimilar surface densities; the average surface density of isolated groups is roughly 44% larger than the surface density of groups within filaments. We attribute the similarity in red fraction between these two populations to the efficiency of quenching mechanisms that act on group galaxies. Specifically, if a group of galaxies at any point in time crosses a certain “density threshold”, quenching mechanisms such as harassment, strangulation and mergers are able to switch on, and quickly and effectively exterminate star formation. We postulate that groups within filaments form at large cluster-centric radii, and reach a high surface density similar to that of isolated groups, which quickly quenches most of the group member galaxies. Then, as the group falls towards the cluster along the filament and approaches within a few virial radii, it begins to feel significant gravitational tidal forces from the cluster potential, the group center’s potential, and from the gravitational potential of the filament within which it is embedded. This gravitational shear increases as the groups approach the cluster virial radius within the filament, effectively diminishing the group central potential and thus pulling groups within filaments apart, after they have been quenched in the filament far away from the cluster. Isolated groups, on the other hand, are not embedded within a large scale filamentary environment with a significant gravitational potential, and thus mainly feel their own groups’ central potential, allowing them to become denser and more compact. Thus, the low surface density of groups within filaments is due to the contribution of groups that have been dismantled due to gravitational tidal forces felt within a few virial radii.

This conjecture is supported by the results depicted in figures 34 and 35, showing the average surface density as a function of $R/R_{200}$ for isolated groups, and for filament galaxies separately. We find that the average surface density of filament galaxies shows a considerable decrease between $2 < \frac{R}{R_{200}} < 4$, supporting the idea that groups within filaments at these cluster-centric radii are being dispersed due to tidal forces felt by the filament (the large increase in surface density between $0 < \frac{R}{R_{200}} < 2$ is a result of the filament galaxies beginning to be incorporated into the very dense, inner cluster environment). In contrast, we find that the average surface density of isolated group galaxies increases between $2 < \frac{R}{R_{200}} < 4$, again, supporting the idea that these isolated groups tend to become more dense, as they are not subject to gravitational tidal forces.
from a filament. Within the virial radius, we see a sharp decline in the surface density of isolated group galaxies, perhaps as a result of this population first feeling the group-dispersing effects of gravitational tidal forces imposed by the cluster.

**VII.2.b: Interpretation of SDSS Spectroscopic Analysis**

The results of the spectroscopic analysis of our SDSS subsample are in agreement with these findings from the photometric analysis, and provide additional insight into galaxy quenching mechanisms. Referring to Figure 31, we first notice that the average specific star formation rate of dwarfs is considerably larger than that of giants in all environments and at all cluster-centric distances. This effect has been observed in numerous other studies (eg. Moran et al. 2005; Seymour et al. 2008; Juneau et al. 2005) and can be attributed to our witnessing of the tail end of cosmic downsizing at these low redshift clusters probed by Sloan. Specifically, at these low redshifts the majority of giant galaxies have already been quenched long ago, leaving only the dwarfs with the means to form new stars.

We also notice a general decline in the specific star formation rate (SSFR) as a galaxy, with any morphology approaches the cluster virial radius (see Figure 32). This expected behavior is indicative of a quenching mechanism specific to the cluster environment, and has been seen in a number of other works (eg. Ellingson et al. 2001; Dressler et al. 2013; Balogh et al. 1998). Specifically, as an infalling galaxy approaches the cluster virial radius, the hot intracluster medium (ICM) begins to ram pressure strip the galaxy’s interstellar medium away, effectively removing its fuel for star formation. This observation is in agreement with the very large red fractions of core galaxies found in the photometric analyses of both SDSS and RCS clusters.

For the populations of isolated singletons (upper left panel of figures 31 and 32) and isolated filament galaxies (lower left panel of the same figures), we see for the most part constant SSFRs as these galaxies approach the cluster virial radius. This indicates that isolated galaxies evolve similarly within their specific environments as they near the cluster. However, an interesting observation is that isolated galaxies (dwarf or giant; see Figure 32) within filaments have slightly smaller SSFRs at all cluster-centric radii, relative to their singleton counterparts. The larger red fractions found for isolated filament galaxies relative to singletons is in agreement with this finding in the spectroscopic analysis. As alluded to previously, this behavior is most likely due to the slightly larger surface density of isolated filament galaxies compared to singletons. Even
though the density is not on the order of a group density, it may be enough to disturb a galaxy’s gaseous halo, resulting in gas loss. However, additional filament-specific quenching mechanisms could contribute to this decrease in SSFR for filament galaxies in comparison to singletons. The tidal forces imposed by the filamentary environment could result in partial stripping of an isolated galaxy’s gaseous halo, after which a drop in the SSFR would be expected. Lastly, recent evidence has been emerging that the intrafilamentary medium (IFM) at low redshifts may have the ability to exert significant ram pressure (~2 orders of magnitude less than the ram pressure exerted by the ICM) on filament galaxies well outside of the cluster virial radius (Dolag et al. 2006; Werner et al. 2008; Edwards et al. 2010). While not expected to be strong enough to remove gas directly from the disc of a galaxy, this IFM ram pressure may be sufficient to strip a filament galaxy’s gaseous halo.

Comparing isolated groups (upper right panel) with singletons, we see that in general, the SSFRs are lower for group galaxies than for singletons. Again, this is in line with the previous discussion of the larger red fraction for groups relative to singletons; group galaxies with higher surface densities are more subject to the quenching mechanisms of harassment, strangulation and mergers. This behavior is also seen when comparing group galaxies in filaments (lower right panel of figures 31 and 32) to isolated filament galaxies (lower left panel), warranting the same conclusion; that group galaxies in filaments should have lower SSFRs than isolated filament galaxies, as they are more subject to density specific quenching mechanisms. The photometric analysis result, that groups in filaments have larger red fractions than isolated filament galaxies is again in agreement with this result of the spectroscopic analysis.

Lastly, we compare the SSFR gradients of isolated groups to those of groups within filaments (figures 31 and 32). We see a relatively constant SSFR for dwarfs and giants in the isolated group population, with a slight decrease within 5 $R/R_{200}$, likely due to the increasing surface densities in this cluster-centric radius (see Figure 35). Within 6 $R/R_{200}$, dwarfs in filament groups have fairly similar SSFRs to dwarfs in the other populations, and the combined SSFR gradient for dwarfs and giants in filament groups is relatively constant at all cluster-centric radii. However, we find that dwarf galaxies within filament groups have very low SSFRs past 6 $R/R_{200}$, much lower than the dwarf galaxies in isolated groups at these cluster-centric radii. We posit that isolated group galaxies at these large radii are only subject to the quenching mechanisms of their group members, while groups in filaments are subject to group specific quenching mechanisms.
as well as the general, large scale filament quenching mechanisms of IFM ram pressure and filament tidal forces. Supporting this supposition is the observation that galaxies of any morphology in filament groups have lower SSFRs at all cluster-centric radii than their isolated group counterparts.

Within \(2 < \frac{R}{R_{200}} < 4\), we notice an increase in the average SSFR of dwarf, group galaxies within filaments. As discussed previously, we suggest that filament galaxies in this range of cluster-centric radii begin to feel significant gravitational tidal forces, which are large enough in magnitude to pull groups apart within filaments. If this is the case, individual group members would begin to feel drastic changes in their neighbors’ gravitational fields as they are pulled away from the group by the filament tidal forces. These changes in the gravitational force felt by neighbors are the same mechanism by which normal galaxy-galaxy harassment works; these gravitational perturbations cause a collapse of ISM gas in a galaxy, resulting in renewed star formation (potentially in the form of a starburst), after which a galaxy is rendered red and dead.

With these ideas in mind, we suggest that the increase in SSFR of dwarf, group filament galaxies is due to the exponentiation of the harassment quenching mechanism as groups are torn apart by the filament tidal forces, effectively “reviving” previously passive dwarf galaxies with one last episode of star formation. Figure 33 supports this proposition, as the starburst fraction of dwarfs and giants in every environment is relatively constant at all cluster-centric radii, except for the population of dwarf, group filament galaxies (lower right panel). This population shows relatively no starburst activity past \(6 R_{/R_{200}}\), but a drastic increase in starburst fraction around \(4 R_{/R_{200}}\), the same region where the SSFR peaks for this population in Figure 31. In general we point out that these starbursting dwarfs within filament groups do not encompass a large number of galaxies, as the overall SSFR gradients for dwarfs and giants combined (Figure 32) in this population is relatively constant at low values, and the photometric red fraction for groups in filaments is consistent with mostly passive galaxies. Accordingly, we find that starbursts are not a significant contribution to the population of passive, quenched galaxies.

Finally, we note that giant galaxies across all environments, at all cluster-centric radii show very constant SSFR gradients and starburst fraction gradients. The explanation for this behavior is that giant galaxies are mostly devoid of any significant reserves of gas in their ISMs due to cosmic downsizing quenching them at earlier epochs, rather than mechanisms which operate
during or after infall into the cluster. Without the gaseous fuel for star formation, giant galaxies are not able to undergo starbursts, or become any more quenched than they already are.

To summarize our evolutionary interpretation of the peculiar population of group galaxies within filaments, we suggest that groups within filaments form at large cluster-centric radii with similar densities to isolated groups. Due to the combined effects of group quenching mechanisms and large-scale filament quenching mechanisms, groups within filaments have slightly less star formation than isolated groups. As these quenched groups within filaments fall towards the cluster and approach within a few virial radii, filament tidal forces disperse the groups, effectively reducing their average surface densities relative to the more dense isolated groups. As these tidal forces pull groups apart within filaments, some dwarf galaxies that were previously quenched could be temporarily “revived” by starbursts, before finally meeting their ultimate demise to ram pressure in the cluster. However, the numbers of starbursting dwarfs within filament groups are relatively small, as the measures of star formation for the combined population of dwarfs and giants are constant, and consistent with mostly red and dead galaxies.

**VII.3: Evolution of Large Scale Structure in Time**

The comparisons of the photometric analyses of the RCS and SDSS cluster populations presented in section VI.3 provide insight into how the large scale structure of the universe has evolved in time. The mean redshift of the RCS sample at $z \approx 0.5$ probes the structure of galaxy clusters and intercluster filaments when the universe was 8.6 billion years old, while the mean redshift of the SDSS sample at $z \approx 0.1$ corresponds to an age of 12.4 billion years. Thus, this comparison study provides us with the unique ability of quantifying how large scale structure has evolved over roughly 4 billion years, almost a third of the lifespan of the universe.

Referring first to Figure 36 in section VI.3, we find that the red fraction of the population of infalling singleton galaxies has remained constant over this period of evolution between the RCS and SDSS samples. However, we find that the surface density of this singleton population has decreased as the universe ages from the redshifts of RCS to the redshifts of Sloan. This observation fits in well with our understanding of the growth of large scale structure and hierarchical clustering from various simulations (eg, Springel et al. 2005). At higher redshifts
When the universe was younger, matter was distributed more uniformly and as a result, the cosmic web was less dense and intercluster voids were more populated. As the universe evolves to lower redshifts, the dominant structures of the cosmic web work to vacate these voids by incorporating the galaxies within them into denser structures like filaments and clusters. Thus, we expect the surface density of singletons (which by definition live in our closest analog to intercluster voids) to decrease as the universe evolves to lower redshifts.

Next, we find that the population of core galaxies increases in surface density and red fraction as the universe evolves from $z = 0.5$ to $z = 0.1$. The observed increase in red fraction is consistent with the findings of various other studies (e.g. Ellingson et al. 2001), and in general is a manifestation of the Butcher-Oemler Effect: as the universe evolves, the overall star formation rate decreases as galaxies use up their reserves of gas or are quenched by various mechanisms. The increase in surface density is also in line with hierarchical clustering, since clusters at lower redshifts have had more time to incorporate infalling galaxies into their cores.

The population of isolated group galaxies remains nearly constant in red fraction-surface density space over the 4 billion years probed by this comparison study. This indicates that isolated group galaxies are mainly affected by the group in which they live. Since they are not embedded in any large scale structures, they evolve independent of the relaxed evolution of the cosmic web.

Isolated filament galaxies remain nearly constant in surface density over this period of time, but do increase in average red fraction from $z = 0.5$ to $z = 0.1$. This increase in red fraction of isolated filament galaxies can be attributed to the Butcher-Oemler Effect, and the increase in size and mass of the filaments themselves. In relation to our previous discussion of a potential general filament quenching mechanism, such as the filamentary environment disrupting a galaxy’s gaseous halo by its movement through the intrafilamentary medium or filament tidal forces, we would expect the effectiveness of this mechanism to grow as the filaments become more robust. Simulations indicate that more massive filaments at low redshift would naturally have denser IFMs than the filaments at high redshift in RCS (Springel et al. 2005). The force exerted on a galaxy’s gas by ram pressure is directly proportional to the density of the ambient medium (Gunn & Gott 1972), so the IFM in the SDSS filaments should exert a greater ram pressure on those galaxies, and hence, be more effective at quenching. Thus, the increase in red fraction of isolated filament galaxies as the universe ages is reasonable.
An interesting result of this comparison study is the change in surface density of groups within filaments. As the universe evolves from $z = 0.5$ to $z = 0.1$, the average surface density of groups within filaments decreases. Considering the previous discussion and evidence of filament tidal forces working to dismantle groups within filaments, we attribute this decrease in surface density to the increasing filament tidal forces as the universe ages. Since filamentary structures become more massive and well defined over time (Springel et al. 2005), we would expect their gravitational potential to increase accordingly, which in turn would also increase the gravitational tidal forces that work to pull groups apart. This effect would result in a decrease of the densities of groups within filaments as the universe evolves, explaining the observed behavior in Figure 36. We also observe an increase in the red fraction of groups within filaments over the 4 billion years of evolution between RCS and SDSS. We attribute this to two consequences of hierarchical clustering. First, the larger filament tidal forces in the more massive filaments at low redshifts work to exponentiate the group quenching mechanism of harassment as these groups are torn apart, and are more effective at stripping gas from a galaxy’s gaseous halo than filaments at higher redshift. Second, we again expect the IFM of filaments at low redshift to be denser, and hence exert more ram pressure on filament groups (similarly to isolated filament galaxies, as discussed above), leading to a larger red fraction than the filament groups at higher redshifts.

The proposition that filament tidal forces are stronger at lower redshifts in more massive filaments is supported by comparing the difference in surface density between isolated groups, and filament groups between RCS and SDSS. In particular, we see that the difference in surface density between isolated groups and groups in filaments in SDSS is greater than the difference in surface density of these two populations in RCS. Again, this observation is in agreement with the suggestion that filament tidal forces are stronger in SDSS at low redshift, since the stronger tidal forces are more effective at dismantling and dispersing groups within filaments.

### VII.4: Illuminating the Origin of Red and Dead Galaxies in Cluster Cores

The “population census” of the numbers of galaxies in each cluster environment presented in Figure 37 provides a visual depiction of the hierarchical clustering phenomenon that fuels the assembly of massive galaxy clusters. We see that at the higher redshifts of RCS, almost 50% of associated cluster galaxies were part of the infalling singleton population, while at the lower
redshifts of Sloan, these galaxies only comprise 18% of the cluster population. In comparison, isolated filament galaxies only contribute 35% to the total number of galaxies in the cluster population at $z = 0.5$, while roughly 50% of the cluster population lives in filaments at $z = 0.1$. These findings are explained well by the notion of hierarchical clustering; as the universe ages from the redshifts of RCS to those of Sloan, gravity has more time to pull galaxies from the void-like singleton environment and incorporate them into denser components of the cosmic web, like filaments, groups and cores. The change in the contribution of the group and core environments to the overall number of galaxies in the cluster between the RCS and SDSS samples is also in agreement with the model of hierarchical clustering. The percentage of galaxies living in groups increases from 5% to 21%, while the percentage of galaxies in cluster cores increases from 8% to 11% over the 4 billion years of evolution probed in this study. Overall, we see that as the universe evolves from the higher redshifts of RCS to the lower redshifts of Sloan, less and less galaxies populate the void-like singleton environment, while an increasing number of galaxies are incorporated into the denser environments of filaments, groups and cluster cores.

Combining the quantifications of the numbers of galaxies that infall in each of the different environments with the quenching efficacy of those environments permits a qualitative conclusion about the assembly of galaxy clusters and the origin of the ubiquitous population of red and dead ellipticals in cluster cores. Considering the relatively short infall timescale of 500 million years in comparison to the 4 billion years of evolution between RCS and SDSS, we can assume that the infall population at the redshifts of RCS is fully integrated into cluster cores by the redshifts of SDSS.

From the results and subsequent discussions of the photometric and spectroscopic analyses presented in this study, it is clear that galaxy groups, whether isolated or embedded in filaments, are quite effective at quenching galaxies through pre-processing mechanisms such as harassment or mergers. Specifically, the similarity in the red fractions between these galaxy groups and the cluster core population shows that mergers and harassment can quench galaxies to a degree comparable with the mechanism of ram pressure in the ICM. However, only $\sim 10\%$ of galaxies infall as groups at the redshifts of RCS. Thus, in order to explain the large numbers of quenched galaxies in SDSS cluster cores, the other $\sim 90\%$ of galaxies around RCS clusters must be quenched by another mechanism or in another environment. We found that the majority of the infall population is accreted along filaments or from the singleton population. But, these environments
are not nearly as effective at quenching, and hence, cannot be fully responsible for the construction of the population of red and dead galaxies in cluster cores. This leads one to the conclusion that although group and filament environments do make a small contribution to the population of passive galaxies in cluster cores, the majority of these red and dead galaxies are quenched in the cluster core, likely by the mechanism of ram pressure stripping.

VIII. Conclusions and Future Direction

VIII.1: Summary of Results

Our spectroscopic and photometric study of associated cluster galaxies from the RCS survey has enabled us to produce a detailed investigation into \( \sim 12,000 \) galaxies in 38 rich clusters spanning a redshift range of \( 0.2 < z < 0.8 \). From this subsample of RCS, we have identified galaxy groups and intercluster filamentary structures with the application of a new filament finding algorithm. From the initial 38 clusters comprising our subsample of RCS, we were able to find 14 significant intercluster filaments. By delineating each cluster into the specific galaxy environments of core galaxies, infalling singleton galaxies, group galaxies, isolated filament galaxies, and group galaxies within filaments, we have been able to quantify the local densities and star formation rates (through the tracer of red fraction) of each of the specific cluster populations. The analysis of the red fractions and galaxy surface densities of each cluster population has provided insight into the specific physical quenching mechanisms in each environment responsible for the transformation of blue, star-forming galaxies into red and dead, passive galaxies.

We find a general trend of increasing surface density corresponding to increasing red fraction. In particular, we find that isolated filament galaxies at the mean redshift of RCS \( (z \approx 0.5) \) have a relatively low average red fraction \( (0.35) \), similar to that of isolated, infalling singleton galaxies, indicating that the filamentary environment at these higher redshifts is still underdeveloped and not too different than the general cluster infall region. Isolated, infalling galaxy groups have statistically similar red fractions to cluster cores, indicating that pre-processing does occur outside of the inner-cluster environment. Thus, quenching mechanisms like harassment, mergers and tidal stripping are just as effective as ram pressure at quenching galaxies, contingent upon a large enough local surface density.
The second data set employed in this study is one obtained from the seventh data release of the Sloan Digital Sky Survey (SDSS), in conjunction with the GMBCG galaxy cluster catalog. A detailed spectroscopic and photometric study of associated cluster galaxies from the SDSS sample has enabled us to produce a comprehensive investigation into ~14,000 galaxies around 46 rich clusters spanning a redshift range of $0.08 < z < 0.12$. Following the same procedure as with the RCS study, we found 46 significant intercluster filaments around the GMBCG clusters of Sloan, and investigated the red fractions and surface densities of the aforementioned cluster populations.

In contrast to the photometric results of the RCS study, we found that isolated filament galaxies in the SDSS subsample were significantly redder and denser than singleton galaxies, indicating that the filamentary environment at the low redshifts of Sloan is more developed, and influences the evolution of galaxies differently than the general cluster infall region. Group galaxies within filaments exhibited the most striking behavior of any population of cluster galaxies. Specifically, we found that galaxy groups within filaments had similar red fractions to isolated groups, but much lower surface densities. We attribute this diminished surface density of groups within filaments to a significant filament tidal force that works to tear groups apart in this environment, after they have been mostly quenched by pre-processing, group mechanisms.

The larger amount of data and detailed spectroscopic measurements of galaxy stellar mass and specific star formation rate with our subsample of SDSS galaxies allowed a more in-depth spectroscopic investigation than was possible with the RCS sample. Specifically, we were able to quantify the average specific star formation rates (SSFR) of dwarf and giant galaxies separately, as a function of cluster-centric radius for each of the infalling cluster populations. We found that giant galaxies at all cluster-centric radii and in any environment had smaller SSFRs than their dwarf counterparts, consistent with the notion of cosmic downsizing. We again witnessed the general trend of increasing local galaxy surface density corresponding to decreasing star formation rates. The SSFRs of isolated filament galaxies, at all cluster-centric radii was found to be less than the SSFRs of isolated singleton galaxies, hinting at the possibility of a large-scale filament specific quenching mechanism. The identity of this filament specific quenching mechanism could potentially be ram pressure stripping of a galaxy’s gaseous halo due to an interaction with the intrafilamentary medium, or filament tidal forces disrupting the halo. Lastly, we observed a significant increase in the SSFRs of dwarf, group galaxies within filaments in the
radial range of $2 < \frac{R}{R_{200}} < 4$. We attribute this increase to harassment-induced starbursts, with the harassment mechanism being exponentiated by the strong filament tidal forces exerted on the group. However, the number of starbursting dwarfs in filaments is relatively small, leading us to conclude that starbursts are not a significant contribution to the population of passive galaxies.

A comparison of the photometric studies of the SDSS and RCS samples provided insight into the evolution of large scale structure over roughly 4 billion years; the mean redshift of RCS at $z \approx 0.5$ probes a younger universe, while the mean redshift of SDSS at $z \approx 0.1$ probes an older, more evolved universe. We observed direct observational evidence for hierarchical clustering feeding the assembly of galaxy clusters; as the universe ages to lower redshifts, denser environments like cluster cores, filaments and groups become more developed and massive as they pull galaxies from the void-like singleton environment. This comparison study provided evidence that the aforementioned filament tidal forces are more significant at lower redshifts, as the filamentary structures become more massive and developed over time. Lastly, we were able to qualitatively attribute a specific physical quenching mechanism as being responsible for the population of red and dead galaxies in cluster cores; although pre-processing in group environments is effective at killing star formation, too few galaxies infall in group environments, so the majority of the passive core population is quenched by ram pressure in the ICM.

VIII.2: Future Direction

Although our photometric measure of star formation, namely the red fraction, is a good tracer of the star formation rate of a group of galaxies, ambiguities are still present in the placement of a galaxy on the red sequence or the blue cloud. Specifically, the r-z color does not take into account any dust reddening, which could potentially place a star-forming galaxy on the red sequence. In addition, the red fraction is not very sensitive to picking up starbursting galaxies. With this in mind, direct measures of star formation rates for galaxies in the RCS sample via infrared data or stellar population synthesis would be a natural extension of this project. These more detailed measures would allow a similar analysis to that done with the SDSS sample, which would permit a quantification of the star formation rates of galaxies as a function of cluster-centric radius. A comparison of the star formation rate gradients as a function of cluster-centric radius between the RCS and SDSS samples would provide further insight into the quenching mechanisms present within filaments, and how the filamentary environment evolves in time.
A larger sample of clusters spanning a wider redshift range would allow a more detailed quantification of how large scale structure evolves in time; the limited amount of clusters spanning the large redshift range of RCS inhibited our ability to derive the parameters of interest accurately as a function of redshift.

Although the Radial Spokes filament finding algorithm did a good job of expanding our filament catalog beyond those that we chose through purely visual means, it assumes that filaments are geometrically linear, when simulations indicate that they can have a substantial curvature. A next step in a supplementary study would be to devise a more sophisticated filament finding algorithm, especially one that could find arced filaments. Simulations of filaments also indicate that there exists a bulk motion of galaxies towards the nearest cluster, so one might expect a correlation in velocity dispersion or dynamics of filament galaxies. Although we made an unsuccessful attempt to incorporate velocity information into our filament finding algorithm, we suspect that an elusive correlation in filament galaxy dynamics still exists; a more sophisticated algorithm would hopefully make use of this relationship.

A further investigation into the physical mechanisms acting on filament galaxies is needed, as the conjectures made in this study about the filament-specific quenching mechanism and the filament tidal forces were sometimes speculative. A galaxy survey specifically targeting filaments, that provides detailed spectroscopic information would allow us to further quantify the unique behaviors observed in these environments. X-ray observations of known filaments would help to uncover the filament specific quenching mechanism; by providing more information about the intrafilamentary medium, we could further quantify the ability of the IFM to exert ram pressure on galaxy halos.
REFERENCES


