THE ALFALFA-SDSS SURVEY
OF THE REGION AROUND THE RICH GROUP
Zw Cl 1400.4+0949

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Astronomy 2233 “Science with the Big Dish in the ‘Jungle’: the Arecibo Telescope” was taught during the fall semester of 2008 by Professors Don Campbell and Martha Haynes with the always willing and able assistance of Astronomy graduate student Kassie Wells. In addition to providing an overview of the diverse science that is based on observations made with the Arecibo telescope, Astronomy 2233 is intended to provide students interested in majoring or concentrating in astronomy with an introduction to current forefront topics in the field and also to expose them to aspects of a professional research career such as the current class research project and “symposium”.

In April 2004, the 305 m antenna at the Arecibo Observatory, the world’s largest collecting area at centimeter wavelengths, was equipped with a 7-beam “radio camera” known as the Arecibo L-band Feed Array (ALFA). The Arecibo Legacy Fast ALFA (ALFALFA) survey, led by members of the Cornell ExtraGalactic Group (EGG), commenced 10 months later. To date, ALFALFA has surveyed about 4000 square degrees of sky, conducting a census of gas-rich objects in the universe out to a distance of 250 Mpc (815 million light years). When complete, the ALFALFA catalog of extragalactic atomic hydrogen sources will contain more than 25000 objects. Among its objectives are the study of galaxy evolution in different environments within the local large scale structure. During the second half of the semester, we, as a class, accessed the preliminary ALFALFA catalog and complementary data from the Cornell EGG data archives, the NASA Extragalactic Database and the Sloan Digital Sky Survey (SDSS; including the Data Release 7 which became public on November 1) to explore the properties of galaxies around the cluster ZwCl 1400.4+0949. This work was original research, and during the last weeks, we performed the first analysis of this multiwavelength dataset. There is still more to be done, but this volume presents our preliminary results on the impact of environment on galaxy properties, the definition of large scale structure in the region, and the differences between optical and HI selected galaxy samples.

The papers contained herein represent the students’ (and my) original work, with minor editing mainly to conform to the style used in producing this volume. The students are asked to forgive me for modifications made in the editorial process.

I especially wish to compliment the authors on their contributions, on their diligence and enthusiasm, and on their patience as we explored together a small volume of the universe using data hot off the telescope.

Martha P. Haynes

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1. The Arecibo Legacy Fast ALFA Survey

Martha Haynes\(^1\)

**ABSTRACT** The Arecibo Legacy Fast ALFA (ALFALFA) survey, currently on-going with the Arecibo 305 antenna aims to obtain a census of extragalactic HI 21 cm line sources within 7000 deg\(^2\) of high galactic latitude sky. ALFALFA exploits Arecibo’s superior sensitivity, angular resolution and digital technology to improve on previous blind extragalactic HI surveys, using a simple drift-scan technique to deliver high observing efficiency and data quality. The local extragalactic sky to be covered by ALFALFA is rich including the filamentary structures connecting the Coma and Abell 1367 clusters of galaxies and their associated supercluster and foreground and background regions, prime volume for the study of the impact of environment on galaxy properties and evolution. One of the first regions of study is the rich group/poor cluster known as ZwCl 1400.4+0949. In this class project, we combine the HI dataset available from ALFALFA with optical photometric imaging and spectroscopic data from the Sloan Digital Sky Survey to take a first look at the large scale structure and its impact on the properties and evolution of galaxies in the ZwCl 1400.4+0949 region.

1.1 Introduction

Just as the introduction of wide field charge coupled devices (CCDs) revolutionized the survey capabilities of optical and infrared telescopes in the 1980’s, HI line astronomy is undergoing a similar renaissance with the advent of multi-beam receivers on the large single-dish telescopes, enabling blind HI surveys that cover wide areas. Most recently, the 305 m antenna of the National Astronomy and Ionosphere Center’s Arecibo Observatory has been equipped with a seven beam system known as ALFA, the Arecibo L-band Feed Array, which is being used to conduct wide area surveys in galactic, extragalactic and pulsar research. Among the surveys being conducted with ALFA, the Arecibo Legacy Fast ALFA (ALFALFA) survey is an on-going second generation blind extragalactic HI survey which is led by members of the Cornell ExtraGalactic Group. ALFALFA exploits Arecibo’s superior sensitivity, angular resolution and digital technology to conduct a census of the local HI universe over a cosmologically significant volume and will have important applications in observational cosmology and studies of galaxy evolution, especially as they are impacted by their local environment.

1.2 Introduction to ALFALFA

ALFALFA is a two-pass, fixed azimuth spectral line survey which aims to map 7000 deg\(^2\) of high galactic latitude sky over the HI velocity range from −1600 to +18000 km s\(^{-1}\). As illustrated in Figure 1.1, when the ALFA instrument is rotated by 19\(°\), the beams sweep out tracks that are equally separated in declination. ALFALFA exploits a “minimum intrusion” drift-scan technique designed to maximize data quality (Giovanelli et al. 2005) by limiting telescope motion. Each position is visited twice as illustrated in Figure 1.2. For the second pass, we want the beams to produce drift scan tracks that are halfway between the ones of the first pass, producing a final spacing of 1.05\(°\). And since Beam 0 is more sensitive (higher gain) than the outer beams, we center it for the 2nd pass 7.3\(′\) from its 1st pass location. We schedule the 2nd pass three to nine months after the first so that we can use the Earth’s motion around the Sun to discriminate cosmic signals (which will move in fixed frequency space) from terrestrial sources of radio frequency interference (which will not).

Sources are identified using an automated Fourier domain signal extraction algorithm (Saintonge 2007). When complete in 2–3 years, ALFALFA will detect more than 25,000 extragalactic HI line sources out to z 0.06, and

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its catalog will be especially useful in synergy with wide area surveys conducted at other wavelengths. Already, three ALFALFA data releases have appeared in the literature (Giovanelli et al. 2007; Saintonge et al. 2008; Kent et al. 2008a) and a fourth has been submitted for publication (Martin et al. 2008). Catalogs, spectra and associated data are being made available from the Cornell Digital HI Archive http://arecibo.tc.cornell.edu/hiarchive/.

ALFALFA is detecting HI masses as low as $10^6 \, M_\odot$, and as high as $10^{10.8} \, M_\odot$ with positional accuracies typically better than 20″, allowing immediate identification of the most probable optical counterpart to each HI detection (Giovanelli et al. 2005). In the region of the Virgo cluster of galaxies, a number of optically dark HI sources have been found (Haynes et al. 2007; Koopmann et al. 2008; Kent et al. 2008). These all lie in the outskirts of the cluster and could be tidal or “harassment” debris, the result of high speed gravitational encounters. First ALFALFA results already indicate, in agreement with the suggestions of previous, more limited studies, that there is not a cosmologically significant population of optically dark but HI rich galaxies. However, the majority of ALFALFA detections are too optically faint or of low surface brightness to have been included in previous targeted HI surveys. ALFALFA promises a wealthy dataset for the exploration of many issues in near-field cosmology and galaxy evolution studies, setting the stage for future extension of these investigations to higher redshifts with the Square Kilometer Array.

1.3 The Rich Group/Poor Cluster ZwCl 1400.4+0949

The local extragalactic sky to be covered by ALFALFA is rich, containing the central longitudes of the Supergalactic Plane in and around the Virgo cluster, the main ridge of the Pisces–Perseus Supercluster, and the extensive filaments connecting A1367, Coma and Hercules. Among the first regions targeted was the sky region the includes the prominent density enhancement around $14^h, +09^\circ, \, cz \sim 6000 \, \text{km s}^{-1}$, recognized by Gregory
& Thompson (1978) to be connected by loose filamentary structure to the Coma-Abell 1367 supercluster. This same overdensity has been identified as a “rich group” or a “poor cluster” by various studies. It is known variously as Zwicky Cluster ZwCl 1400.4+0949 (Zwicky et al. 1961-8), the NGC 5416 group (Thompson et al. 1978; Chincarini et al. 1979), MKW 12 (Morgan, Kayser & White 1975) and WBL 486 (White et al. 1999).

Figure 1.3 shows an image of the central region of the ZwCl 1400.4+0949 = NGC 5416 group = MKW 12 region, taken from the SDSS public image site. As evident in the image, the cluster has a high spiral fraction, making it an ideal candidate for an HI line survey. In fact, Thompson & Gregory (1978) estimated a spiral fraction of 53%.

1.4 A Class Research Project

As a major work for Astro 2233 in the fall semester of 2008, we have undertaken an analysis of the current multiwavelength data available for galaxies in the region. The principal datasets we have used are:

- the Arecibo General Catalog, a private extragalactic database generated and maintained by the Cornell ExtraGalactic Group (M.P. Haynes & R. Giovanelli, private communication). The AGC provides positions, morphologies and cross references with other databases.

- the ALFALFA survey catalog, including preliminary versions under development by members of the ALFALFA team at Cornell. The ALFALFA dataset contributes integrated HI line fluxes, redshifts and observed HI line velocity widths.

- the Sloan Digital Sky Survey photometric and spectroscopic databases, including Data Release 7, which became available on November 1, 2008. The photometric database provides magnitudes in five SDSS filter (wavelength) bands, optical sizes and ellipticities. The spectroscopic database, constructed for a subset of the photometric sample, includes redshifts and equivalent widths for a number of spectral lines.
The SDSS data were acquired via the CAS Jobs server using SQL queries specifically designed to provide the parameters needed for this study. Part of the objective of our class effort was to determine what parameters were needed, what corrections were necessary to use them in practice to derive galaxy properties and what problems might arise in using large, public datasets. Because this was real research being undertaken for the first time, we discovered that some data were bad at worst, faulty at best. We also explored methods for analyzing the data to determine statistical significance of results. The work presented here is preliminary and not complete, but it is original and a first step towards a significant analysis of galaxy properties and large scale structure in the region of the ZwCl 1400.4+0949 region.
1.5 Summary

In the rest of this volume, we will report on the results of our investigation of the newly available data from the SDSS dataset and the ALFALFA survey. First Katie Hamren investigates the large scale structure in the region and identifies the membership of galaxies in the cluster known as MKW 12. Then, Luca Zatreanu studies the ALFALFA catalog detections in the region, calculates HI and dynamical masses, and begins the investigation of relative HI content. Russell Wolf constructs a color-magnitude diagram and explores the difference between samples selected by the HI flux versus the overall population. Finally, Sarah Morrison investigates the star formation rates and incidence of active galactic nuclei using the SDSS spectroscopic dataset. As you will see, we have made real progress towards understanding the large scale structure and the properties of the galaxies including their stellar, gas and dynamical masses, star formation rate and nuclear activity.

1.6 References

2. Quantifying Environment around ZwCl 1400+09

Katie Hamren

ABSTRACT The poor cluster – or rich group – known as ZwCl 1400.4+0949, the NGC 5416 group or MKW 12 among others, lies amid a filamentary structure which merges with the prominent Coma-Abell 1367 supercluster. Recent redshift surveys have contributed many new velocity measurements permitting a new, more robust analysis of large scale structure in the region. Examination of the redshift and sky distributions reveals that the projected galaxy density enhancement which constitutes the ZwCl 1400.4+0949 overdensity is actually, in part, the superposition of multiple structures in redshift space. Here, we examine the large scale structure and identify the main features and estimate their extents and masses. Because of the complex projection, ZwCl 1400.4+0949 is not actually as rich as previously thought.

2.1 Introduction

Understanding the environment in and around the ZwCl 1400.4+0949 cluster, hereafter Zw 1400+09, is the first step to understanding its more interesting and complicated characteristics. Quantifying this environment involves separating the cluster from galaxies in the foreground and background, as well as investigating both nearby large-scale structure and the general properties of member galaxies.

Previous research has done some basic classifications of the Zw 1400+09 cluster and its environment. Surrounding large-scale structure was first seen by Gregory & Thompson (1978). In their study of the environment around the Coma and Abell 1367 clusters, they found a previously unstudied cluster surrounding the galaxy NGC 5416 and identified by Zwicky et al. (1968) as Zw 1400+09, with similar characteristics as its richer neighbors. By comparing the recessional velocity-derived distances of the member galaxies, these three clusters and a number of solitary galaxies were shown to be part of a somewhat filamentary supercluster connecting the two rich clusters Coma and Abell 1367 but also extending out to encompass Zw 1400+09. This extensive supercluster must be kept in mind while evaluating the region containing Zw 1400+09; large scale structure plays a very prominent role in the galaxy distribution in this volume of the universe.

The cluster has been included in numerous catalogs of clusters identified by various authors using different algorithms designed to pick out overdensities in the local galaxy distribution. Zw 1400+09 was first cited as the “poor cluster” MKW 12 by Morgan et al. (1975), and again as WP 30 by White (1978). It was later classified by White et al. (1999) as the poor cluster WBL 486, with “poor” denoting a surface density of galaxies less than $10^{3.3}$, photographic magnitude per galaxy less than 15.7, and a total population greater than three. That paper notes that Zwicky clusters often contain WBL clusters, as in the case with Zw 1400+09/WBL 486. While these three papers each identified the Zw 1400+09 cluster, they were relatively large surveys that did not delve deeply into specific characteristics of the individual clusters they catalogued.

2.2 Analysis of the 2008 Redshift Data

Since the earlier studies, many new redshifts have been acquired in this region making a new analysis of the redshift distribution in the region worthwhile. To begin the current study of the environment of Zw 1400+09, its
basic structure was mapped using position and velocity data for all the galaxies included in the Cornell Extra-Galactic database known as the Arecibo General Catalog (AGC; Haynes & Giovanelli, private communication). The cone diagram shown in the upper panel of Figure 2.1 shows all galaxies with $v_{helio} < 18200$ km s$^{-1}$ in the AGC covering 90° in right ascension and found within a six degree “slice” in declination. The red symbols identify galaxies which have been detected in the 21 cm HI line by the Arecibo Legacy Fast ALFALFA (ALFALFA) survey; see further discussion in the following paper by Luca Zatreanu in this volume. The extra radial lines outline the 6° centered on the Zw 1400+09 cluster. It can be seen easily that the cluster lies embedded in a larger filamentary superstructure and that the HI line detected galaxies well sample the cluster environment. Such structure fits the picture of the over-arching supercluster illustrated by Gregory & Thompson (1978). In addition, there are areas with no evident galaxy population: voids.

The lower panel of Figure 2.1, a cone diagram of velocities less than 9100 km s$^{-1}$, and Figure 2.2, a plot of right ascension versus projected radial distance from cluster center, both show these aspects in greater detail. In the former, both the highlighted and un-highlighted galaxies around 7000 km s$^{-1}$ are clearly part of a larger filament extending across a number of degrees in declination, while the area around the “finger of god” contains
FIGURE 2.2. Velocity versus radial distance from the center of ZwCl 1400+09 for galaxies within 6° of the cluster. Redshifts are taken from the November 2008 version of the AGC. The large red circles outline the two main clusters: the Zw 1400+09 group at \( cz \sim 6000 \) km s\(^{-1}\), and the rich cluster Abell 1839 at \( cz \sim 17000 \) km s\(^{-1}\).

many fewer galaxies. Figure 2.2 shows Zw 1400+09 as the group of galaxies around 5500 km s\(^{-1}\) within one degree of the center. In addition, it shows many galaxies focused around the lines of 7000, 12000 and 16000 km s\(^{-1}\) with very few galaxies in the intervening space. The second indicated cluster is at 15000 km s\(^{-1}\) and so too distant to be related to Zw 1400+09.

The center of the Zw 1400+09 cluster used in Figure 2.1 has been determined following the reasoning of Koranyi & Geller (2002). Those authors identified the center of a cluster as the pixel of peak X-ray emission using the X-ray data from Price et al. (1991) for MKW 12. Figure 2.3 shows the Price et al. (1999) X-ray image of N 67-336/MKW 12 as taken from Image Proportional Counter instrument frames from the Einstein Observatory archives. The computed center, after transposition to the J2000 epoch, is R.A. = 14h02m48s, Dec. = +09°19′48″ which corresponds almost exactly to the position as noted in the NASA Extragalactic Database for WBL 486 = MKW 12.

An additional structural element evident in Figure 2.1 is a distinct gap between the group of galaxies at the 7000 km s\(^{-1}\) and the “finger of god” extending along the line of R.A. = 14h. Figure 2.4 shows histograms of the velocities of galaxies within 1.3° of the cluster center. The left panel shows all galaxies with \( V_{\text{CMB}} < 18200 \) km s\(^{-1}\), while the left panel zooms in on the velocity range between 4000 and 9000 km s\(^{-1}\). Two distinct and prominent peaks are evident in both, one at \( V \sim 6200 \) km s\(^{-1}\), and a second at \( V \sim 7300 \) km s\(^{-1}\).

Figure 2.5 shows histograms of the two separate structures plotting galaxies within a radial distance of 0.68 deg (1 Mpc for a distance of 83.7 Mpc). The left panel identifies a nearer cluster with a population of 45 galaxies, all with CMB velocities between 5600 and 6600 km s\(^{-1}\), while the right histogram identifies a second more distance structure with 29 galaxies between 6600 and 7600 km s\(^{-1}\). The lower velocity group is identified with the MKW 12 cluster, and has a mean velocity of 5861 km s\(^{-1}\) and a sigma of 241 km s\(^{-1}\). For a Hubble constant of 70 km s\(^{-1}\) Mpc\(^{-1}\), this corresponds to a distance of 83.7 Mpc. The second structure lies behind MKW 12,
and has a mean velocity of 6890 km s$^{-1}$ (98.4 Mpc) and a velocity dispersion $\sigma = 201$ km s$^{-1}$. The histograms displayed in Figure 2.5 each exhibit the Gaussian distribution typically associated with a cluster. All galaxies within the two redshift ranges are superimposed in the sky distribution shown in Figure 2.6, regardless of cluster membership. Different colors denote the MKW 12 and background filamentary structure. The 29 background galaxies are clearly part of a larger and more uniform spread, complete with mild filamentary structure.

2.3 Dynamical mass of the cluster

The cluster population and group characteristics for MKW 12 were then used to generate a plot of dynamical mass as a function of radius. The total dynamical mass was calculated using the projected mass estimator (Heisler et al. 1985):

$$M_{pm} = \frac{f_{pm}}{G(N - \alpha)} \sum_i V_{zi}^2 R_{Li}$$

(2.1)

with the constant of proportionality ($f_{pm}$) depending on galaxy orbits. Because little is known about the orbits in Zw 1400+09, the value $f_{pm} = 32/1$ was used. In addition, the value $\alpha = 1.5$ was used to account for $V_{zi}$ and $R_{Li}$ being measured with respect to the centroid instead of the center of mass. To account for the third dimension, only galaxies between 5600 and 6600 km s$^{-1}$ were considered for membership. The function of cumulative mass ($M(< R)$ for radial distance from the cluster center between 0 and 8 degrees is shown in
2. Quantifying Environment around ZwCl 1400+09

FIGURE 2.4. Histograms of AGC galaxies found within 1.36° of the center of Zw 1400+0949. Left: full velocity range. Right: only those galaxies with $4000 < V_{\text{CMB}} < 9000$ km s$^{-1}$.

FIGURE 2.5. Histograms of AGC galaxies found within 0.68° of the center of Zw 1400+0949 and in the redshift intervals from $5200 < V_{\text{CMB}} < 6800$ km s$^{-1}$ (left; MKW 12) and from $6200 < V_{\text{CMB}} < 7800$ km s$^{-1}$ (right; the background filament).

Figure 2.6, with mass plotted on a logarithmic scale. The mass function begins to stabilize around a radius of one degree, as there are fewer galaxies at larger distances from the center. This indicates that the radius of the
cluster is just under a degree, and roughly $10^{14}$ $M_\odot$. As the mass of the richer Virgo cluster is $10^{15}$ $M_\odot$, this estimate is well within a practical limit.

### 2.4 Conclusion

In summary, Zw 1400+09 is a relatively poor cluster in an interesting environment. This environment includes distinct, filamentary large-scale structure, voids with no galaxy population, and a second cluster in the immediate background. A good deal more research can be done on this second cluster, as it embedded in much large field of galaxies all with comparable CMB velocities. In addition, this paper did not discuss the voids, and did not delve deeply into the role of the supercluster found by Gregory & Thompson (1978).
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FIGURE 2.7. The plot of dynamical mass on a logarithmic scale calculated using Equation 2.1 as a function of the project radius from the cluster center. As the radial separation grows, the cumulative mass stabilizes, as outliers contribute negligibly.

2.5 References


2.6 Appendix

This study uses data from the Arecibo General Catalog (AGC), developed by Cornell Universitys Extragalactic Group. The AGC provides an identification number, right ascension, declination, and heliocentric velocity for hundreds of galaxies observed by the Arecibo telescope. The specific position ranges for the Zw 1400+09 region were $207.5^\circ < \text{R.A.} < 214.5^\circ$ and $+05 < \text{Dec.} < +12^\circ$. Position data was used for cone diagrams, and to
determine galaxies’ distances from the cluster center. These distances were used to create histograms, and to generalize the function of total dynamical mass with respect to cluster radius.

The heliocentric velocities given in the AGC were first corrected into the frame of the cosmic microwave background (CMB). Kogut et al. (1993) gives the motion of the Sun with respect to the CMB as 369.0 ± 2.5 km s\(^{-1}\) in the direction galactic longitude \(l = 264.31 ± 0.19\) degrees and galactic latitude \(b = 48.05 ± 0.1\) degrees. Thus, a correction of +260 km s\(^{-1}\) is added to the galaxies in the Zw 1400+09 region. The CMB velocity divided by the Hubble Constant was used as a measure of distance, assuming the Hubble Constant to be 70 km s\(^{-1}\) Mpc\(^{-1}\). Distances to galaxies outside the clusters were calculated using their individual CMB velocities, while cluster members were all assumed to have the clusters average velocity (5861 and 6890 km s\(^{-1}\) for MKW 12 and the background filament respectively). With these distances in mind, galaxies outside of the range of \(-500\) to \(+18000\) km s\(^{-1}\) were excluded entirely.
3. The ALFALFA HI Catalog in the ZwCl 1400.4+0949 Region

Luca Zatreanu

ABSTRACT This work focuses on the current ALFALFA catalog of HI line sources in the region of the ZwCl 1400.4+0949. The HI line data contribute integrated HI line fluxes, redshifts and rotational velocities (when corrected for viewing angle). In combination with optical redshifts, sizes and morphologies, these parameters can then be used to derive the distance, HI mass and total dynamical mass and to estimate the relative HI content of galaxies in different environments. We find that the galaxies in the region around ZwCl 1400.4+0949 tend to be slightly HI deficient, that the sample seems to be somewhat biased toward late-type galaxies, and that the HI mass to dynamical mass ratio increases slightly with morphological type. Three peculiar early-type galaxies with considerable HI mass are likely to be the results of galaxy-galaxy interactions during which there was a transfer of gas, and two galaxies without optical counterparts are not isolated dark galaxies. Finally, the entire sample fits very well within the Tully-Fisher relation.

3.1 Introduction

Astronomy, as it is well known, is an observational science. Whereas chemists or biologists can formulate hypotheses and subsequently test them by conducting tangible experiments, astronomers rely on clever observational methods to answer some of the most fundamental questions regarding the nature of our existence. Though observing is colloquially used to describe the interpretation of visible light, astronomers and astrophysicists observe objects in the sky along many parts of the electromagnetic spectrum in order to gain a more complete understanding. One very important phenomenon that is commonly measured by radio astronomers in order to learn about the composition of space is the 21 cm neutral hydrogen line, also known as the HI line. The HI line refers to a spectral line that is formed when the electron within a hydrogen atom whose spin is parallel to that of the proton makes a transition to the antiparallel configuration, thereby assuming a lower (and preferred) energy state. Even though the probability of this phenomenon occurring is very small for each hydrogen atom, the extremely large number of hydrogen atoms in the universe makes this a rather common event. HI lines occur in the microwave part of the electromagnetic spectrum and are detected by radio telescopes, of which the Arecibo Observatory is a major player. HI data can provide crucial information about galaxies and galaxy clusters.

3.2 “Standards” of HI Content and Dynamical Mass

Galaxies are interesting structures in their own respect, but observing what happens when galaxies interact with each other is arguably more valuable to astronomers. In a rough sense, one can think of a system of galaxies like a larger and more complex version of the system of our planets revolving around the Sun. Each planet rotates about its axis while orbiting the Sun, and the entire solar system revolves around a common center of mass. On a much larger scale, galaxies behave rather similarly. Each galaxy is composed of many rotating stars orbiting a massive galactic nucleus, and many galaxies together form a cluster, with more galaxies in the center of the cluster and fewer galaxies on the periphery. Within and around the galaxies are many neutral hydrogen atoms. These HI clouds tend to be found in the spiral arms in the disks of galaxies and their properties provide information about the galaxy. Scientists realized in the 1970s that HI profiles are powerful tools and they

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3.3 HI Deficiency

Galaxies, just like any other celestial objects, are influenced by their environments. As HG84 describe, there are many events that can disrupt the “normal” structure of a galaxy, including collisions between galaxies, tides, or ionization of the interstellar gas in “hostile environments”. Such galaxy interactions are very interesting since they can provide insight into how larger scale structures form. But in order to fully understand clusters and groups, one should perhaps start at the level of the properties of their constituents, that is, of individual galaxies.

In an attempt to gain an appreciation of single galaxies and to establish a standard of normal HI content, HG84 selected 324 “isolated” galaxies that were known to lie in the far peripheries of superclusters, and were thus not affected by galaxy-galaxy interactions. Of these 324 surveyed, HI lines were detected for 288; the remaining 36 probably had emissions that lay outside of the frequency range searched by the 21-cm observations. By studying the HI properties of these galaxies in conjunction with their optical parameters, the authors gathered information such as the position of the galaxies in the supercluster, their morphological type, inclination, heliocentric velocity, HI flux, 21 cm linewidth, luminosity, and size. Some of these data, like the total HI line flux and the linear diameter, were then used to compute the total HI mass. The authors found that the linear diameter of a galaxy’s spiral disk is a much better diagnostic parameter for HI mass than the galaxy’s morphological type, and that an HI-mass-to-linear-diameter ratio is a better diagnostic tool for HI content than is a mass-to-luminosity ratio. It should be noted, however, that the diameters that the authors used were optical diameters, and for most galaxies optical diameters are known to be smaller than HI diameters, yet, just how much smaller is unknown. Still, the findings enabled HG84 to define a “normalcy” of HI content, deviations from which could be termed HI “deficiencies”.

HI deficiency occurs mainly in two ways, both resulting from interactions between galaxies: (1) upon a collision between two galaxies, the front ends of the HI clouds get compressed and the resulting heat generated in this area leads to rapid star formation (which uses up gas), and (2) gas in the tail-end and on the periphery of the HI clouds gets ejected into the interstellar medium upon impact. Either scenario leads to a reduction in hydrogen gas.
3.4 Galaxy Morphology

In 1927, Edwin Hubble created a classification system for galaxies that distinguished at least four different morphological types: elliptical, lenticular, spiral, and barred spiral. Because of its “tuning fork” shape, some people incorrectly believe that it depicts an evolutionary sequence, with galaxies progressing from elliptical, to lenticular, to spiral (Figure 3.1). Though such a progression does not occur, the galaxies can be further divided, based to a rough extent on their age. Early-type galaxies (ellipticals and lenticulars) are generally considered to be older, having formed their stars long ago, while late-type galaxies (spirals and irregulars) are typically younger. Since stars are formed from the hydrogen gas and dust in a galaxy, early-type galaxies are normally HI deficient, having already used their gas to create their large population of stars, whereas late-type galaxies are often the sites of young stars and star formation, especially in their disks. To facilitate quantitative analysis, galaxy morphologies are given numerical values in the Third Reference Catalog (de Vaucouleurs et al., ranging from $-5$ (ellipticals) to 10 (irregulars).

3.5 Previous HI Observations of ZwCl 1400.4+0949

Of particular interest to the current project is the Zwicky cluster ZwCl 1400.4+0949, also known as the NGC 5416 group. Chincarini et al. (1979) studied 25 galaxies from this cluster – of which 16 were detected in HI – and suggested that it may be an extension of the Coma supercluster. Although substantially more data have been released on this part of the sky since the publishing of that paper, it is important to briefly summarize what Chincarini et al. (1979) discovered and the methods they employed.

Chincarini et al. specifically picked 25 galaxies from the Zwicky cluster that they wanted to analyze and then used a “beam switching” technique with the Arecibo telescope to observe them. To accomplish this, the Arecibo beam was placed directly on each galaxy, tracing its movement in the sky for five minutes, a technique known as ON-sourcing. The beam was then backtracked and put in the same azimuth and zenith configuration as the initial ON-sourcing, but because of the Earth’s rotation, the whole sky appeared to have shifted, and the galaxy of interest was no longer at the original location in the sky (see HG84 for a description of this technique). The beam then followed for five minutes the same trajectory as it had during ON-sourcing, this time essentially observing everything in that part of the sky minus the galaxy of interest – a technique known as OFF-sourcing. The reason for doing this was to establish a baseline for noise that could be subtracted from
The ALFALFA HI Catalog in the ZwCl 1400.4+0949 Region

In studying ZwCl 1400.4+0949, the researchers observed “standard” HI-mass-to-luminosity ratios, indicative of the fact that the sample population had experienced only minimal hydrogen depletion. However, the virial mass-to-luminosity ratio for the entire cluster was about an order of magnitude larger than those of individual galaxies, suggesting that, if the group is bound, there is extra matter somewhere between the galaxies. This extra mass is presumed to be dark matter.

As mentioned above, many new data have been released since the publishing of these papers. More specifically, instead of 16, there are now 262 known galaxies in the 6\(^\circ\) X 6\(^\circ\) area around the Zwicky cluster. Data today are also more precise and fainter galaxies with less HI emission can be detected. Observing techniques have also changed, thanks to ALFALFA. Rather than picking out galaxies to study, the Arecibo Observatory is fixed in place and makes observations along whole regions of the sky as the sky drifts by. Furthermore, optical parameters of galaxies, such as linear diameter, that are needed to study HI properties are now being provided by the Sloan Digital Sky Survey (SDSS), which is a much more precise collection of data than was available to Chincarini et al. in 1979. Though the majority of the galaxies detected by the SDSS were also detected by ALFALFA, there are two objects in ALFALFA which currently do not have optical counterparts (AGC 238652 and AGC 249137). It is currently believed that these galaxies are not, in fact, dark galaxies. This issue will be discussed in more detail further in this paper.
3.6 2008 Data Analysis of ZwCl 1400.4+0949

HG84 were able to determine standards of HI content for the 288 galaxies that they detected based on the linear diameters for those galaxies. Though the general principle for establishing the HI content for the galaxies in ZwCl 1400.4+0949 is the same today, such an analysis has not yet been performed. When the analysis is undertaken, however, the larger data sample should enable scientists to redo and refine the standard established by HG84. In the meantime, without a technical calibration of the relation between the two data sets no numerical value can be assigned to deviations from a standard of HI content for ZwCl 1400.4+0949. Nonetheless, general trends in HI deficiency can be observed.

More specifically, plotting the log of the HI mass versus the log of the optical linear diameter for each galaxy gives a relative idea of HI content for the galaxies (3.2). As can be seen in Figure 3.2, there are two noteworthy trends in our sample population. First, it appears that the galaxies in the cluster tend to lie on the lower side of the distribution, though the trend is rather weak. This suggests that the galaxies in ZwCl 1400.4+0949 are mildly HI deficient since their HI mass is relatively low compared to their linear diameter. Second, the galaxies from our cluster that lie the most beneath the distribution are early-type galaxies, an observation that is consistent with the expectation that ellipticals and lenticulars be relatively deficient in hydrogen gas since their stars formed long ago.

Another useful way of displaying relative HI deficiency is to plot the ratio of the HI mass to dynamical mass versus morphological type. Such an analysis allows us to note if there are any trends in our sample population. Figure 3.3 shows this relationship, and what is immediately apparent when looking at the graph is the abundance of late-type galaxies, and more specifically, Type 3 (Sb). This should not be taken to mean that Type 3 galaxies are the most prevalent in this part of the universe (nor in our cluster). Rather, the HI emissions from these galaxies were most readily detected by ALFALFA. Thus, our sample seems to be somewhat biased toward late-type galaxies. Furthermore, there is considerable variation within each morphological type. Nevertheless, there appears to be a slight positive slope for the data points in the graph, suggesting that the $M_{HI}$ to $M_{dyn}$ ratio increases with morphological type, a trend that supports the fact that late-type galaxies normally have more neutral hydrogen gas than early-type galaxies. Put differently, early-type galaxies tend to be more HI deficient.
3. The ALFALFA HI Catalog in the ZwCl 1400.4+0949 Region

3.6.1 The Peculiar Three

Having described the general trends in the ALFALFA sample, we can now turn our attention to three peculiar galaxies in the ZwCl 1400.4+0949 cluster: AGC 8940, 8956, and 240019. They are all early-type galaxies, with RC3 morphological values ranging from -5 to 0, yet they have substantial HI mass. As was described earlier, early-type galaxies have stars that formed long ago, so they normally have little or no neutral hydrogen gas. In trying to understand the conundrum of the three galaxies, the color of these galaxies was initially compared to those of other galaxies of similar morphological types. The theory behind this approach is simply that blue galaxies are known to have more star formation and new stars emit more ultraviolet and blue light than old stars, thus the galaxies appear bluer. Plotting the (u-r) color versus the absolute magnitude of the galaxies in the r band showed that, in fact, the three bizarre galaxies are bright and red, not blue (??).

One way to explain the presence of HI gas in the three bright red, early-type galaxies is to suggest that each of them had some form of a violent, tidal interaction with another galaxy in the past (probably a late-type galaxy), during which there was transfer of gas to the early-types. This phenomenon is known to happen in starburst galaxies. After a collision of two or more galaxies, the extra fuel in the form of the transferred gas leads to an increase in the star formation rate by a factor of 1,000. However, this rapid starburst only lasts for a relatively short period of time, usually a few hundred million years (miniscule on universal scales). More research needs to be conducted to determine with more certainty if the three galaxies in the cluster are the results of such tidal interactions.
3. Dark Matter?

The two objects in our sample which do not have optical counterparts (AGC 238652 and AGC 249137) are probably not “dark galaxies” and are not as interesting as initially hoped. The reason for this is that neither of the two is isolated. Both are surrounded by several other galaxies that are within five arc minutes of each other and are moving at similar velocities with respect to the cosmic microwave background. It is likely that the HI emission we detected with ALFALFA from these galaxies is in some way related to the HI emissions of the nearby galaxies. Therefore, there is probably some sort of interaction between these galaxies. Higher resolution mapping of this area would be necessary to determine with more certainty whether or not this is true. Nonetheless, it is rather evident that AGC 238652 and AGC 249137 are not isolated, dark galaxies.

3.6.3 The Tully-Fisher relation

The Tully-Fisher (T-F) relation is a well-known scaling relation between the rotational velocity [of a galaxy] and its optical luminosity. It is especially useful as method of determining the distance to spiral galaxies by a method that does not rely on redshift. Typically, there is a positive correlation between the optical luminosity and the rotational velocity. As evident in Figure 3.5, galaxies in our ALFALFA sample conform very well to this relationship, thus reinforcing the usefulness of the T-F relation.
3.7 Conclusion

Twenty-one centimeter line surveys of the galaxies in ZwCl 1400.4+0949 have demonstrated that the galaxies tend to be slightly HI deficient, that the sample seems to be somewhat biased toward late-type galaxies, and that the HI mass to dynamical mass ratio increases slightly with morphological type (supporting the common wisdom that late-type galaxies normally have more neutral hydrogen gas than early-type galaxies). Furthermore, the three peculiar early-type galaxies with considerable HI mass are likely to be the results of galaxy-galaxy interactions during which there was a transfer of gas, and the two galaxies without optical counterparts are not isolated dark galaxies. Finally, the entire sample fits very well within the Tully-Fisher relation.

3.8 References


3.9 Appendix

The parameters contained in the file used for the analysis presented here are as follows:

- **AGC**: The Arecibo General Catalog is a private database containing information about the positions, sizes, magnitudes, morphologies, redshifts and HI properties of several hundred thousand galaxies. Each galaxy is assigned an “AGC number.” It was compiled and is maintained by Martha Haynes and Riccardo Giovanelli at Cornell.

- **V21**: HI velocity, usually given in units of km s\(^{-1}\) corrected to the rest frame of the CMB. The midpoint of a galaxy's emission profile gives the systemic velocity of the galaxy as a whole. This, in turn, can be used to make an estimate of the redshift distance using Hubble's Law (the redshift in light coming from distant galaxies is proportional to their distance from the observer); \(V = H_0 D\), where \(D\) is the distance to the galaxy (in Mpc), and \(H_0\) is Hubble's constant taken here to be 70 km s\(^{-1}\) Mpc\(^{-1}\).

- **eV21**: Refers to estimated error in the value of V21, such that the real value of V21 is somewhere between V21-eV21 and V21+eV21.

- **Width**: The width (\(\delta V\)) of the HI line profile (in km s\(^{-1}\)) corrected for inclination angle, which gives the observed Doppler broadening due principally to the rotation of the galaxy. In combination with an estimate of the galaxy's size and inclination on the plane of the sky, it can be used to make an estimate of the total mass (total dynamical mass) according to the following formula:

\[
M_{\text{system}} = \frac{R_{\text{system}}V_{\text{rot}}^2}{G}
\]  

(3.2)

Where \(V_{\text{rot}}\) is the observed width of the HI line profile, \(G\) is the gravitational constant, and \(R\) is the linear diameter.

- **eWid**: Refers to estimated error in the value of Width, such that the real value of Wid is somewhere between Wid-eWid and Wid+eWid.
3. The ALFALFA HI Catalog in the ZwCl 1400.4+0949 Region

- **Flux**: ALFALFA detects the HI spectral profile of a galaxy, that is, its HI line flux over the frequency range which corresponds to the radial velocities of all the HI atoms in the galaxy. The total HI line flux (∫ F dV, in Jy·km s⁻¹) can be used to derive the total HI mass (in solar masses) using the distance (in Mpc) estimated by Hubble's Law according to the following formula:

\[
M_{HI} = 2.36 \times 10^5 D^2 \int F \ dV \ M_\odot
\]  

- **eFlux**: Refers to estimated error in the value of Flux, such that the real value of Flux is somewhere between Flux-eFlux and Flux+eFlux.

- **SNR**: Signal-to-noise ratio is a measure of the peak strength of the HI line signal relative to the rms noise level of the spectrum nearby. A weak signal has a low SNR; a clear, strong signal has a high value.

- **RMS**: Root-mean-square value (the +/- standard deviation) for data that is used to describe random noise, or a system’s “noise power.” The rms is calculated by taking the root mean square of all the flux values in the signal-free part of the spectrum. It therefore is a measure of the sensitivity of the HI spectrum, i.e., the most sensitive signal one can hope to detect. As one integrates longer on a spot on the sky, the rms noise will go down, theoretically as \( \text{sqrt}(\text{integration time}) \), all other things being equal.

- **Code**: “Code” refers to classification of the ALFALFA source detection, expressed as either “1” or “2.” A “1” means SNR > 6, therefore the signal is of good quality and there's a high probability that the source is real. A “2” means a lower SNR than that limit, but the detection is coincident with an optical counterpart with a known velocity which is the same as the HI velocity (called a “prior”). Such a source is believed to be real despite lower SNR because of the optical coincidence.
4. Photometric Analysis with SDSS and ALFALFA

Russell Wolf

ABSTRACT An analysis of the photometric properties of galaxies in the region of the ZwCl 1400.4+0949 is performed using the Data Release 7 of the Sloan Digital Sky Survey (SDSS). Corrections are applied to the raw magnitudes for galactic and external extinction and a color-magnitude diagram is constructed. Not unsurprisingly, the ALFALFA catalog sample consists principally of star forming galaxies from the “blue cloud”, with only a few members of the ”red sequence”.

4.1 Summary of Previous Work

Photometric analysis gives us a relationship between color and magnitude for a population of galaxies. This is analogous Hertzsprung-Russell diagram commonly used to analyze stellar populations, but applied to galaxies. Baldry et al. (2004b: B04) who perform this analysis using Sloan Digital Sky Survey (SDSS) data. B04 find that there appears to be a bimodal distribution among SDSS galaxies – a redder population and a bluer one – which each have their own color-magnitude relation. The red population appears to be elliptical galaxies with little star formation, and the blue populations spiral galaxies actively forming new stars.

In their survey, B04 measure color using the difference between the u and r filters. This was chosen because it appears to best divide the two populations they identified. Specifically, they measure $C_{ur} = (u - k_u) - (r - k_r)$, which they generally refer to as $u - r$. Here u and r are magnitudes in their respective bands, and $k_u$ and $k_r$ are k-corrections which take into account the redshift. Our analysis will assume no k-corrections, because they will be small and introduce unnecessary sources of error. Absolute magnitude is measured by comparing apparent magnitude with distance. The r filter is used to measure magnitude, because it contains the peak of the light curve for most SDSS galaxies – using the filter which collects the most light reduces potential error. The magnitude is calculated as

$$M_r = r - k_r - 5 \log \left( \frac{D_L}{10} \right)$$

(4.1)

where $D_L = cz/H_o$ is the distance in Mpc associated with a Hubble constant taken here to be $H_o = 70$ km s$^{-1}$ Mpc$^{-1}$.

Once again our analysis will not use a k-correction the way B04 did.

To begin the analysis, it is necessary to select the population of galaxies to analyze. B04 note specifically that there are limits on the magnitude in the r filter and the mean surface brightness at 50% radius $\mu_{r,50}$ in order for SDSS to classify an object as a galaxy. These limits are $r < 17.77$ and $\mu_{r,50} < 24.5$ mag/arcsec$^2$. For their paper, B04 set further limits. First they use $13.5 < r < 17.77$, which reduces the population of SDSS galaxies to ones for which a majority (around 94%) have redshift measurements. Many objects without spectra in this group are missed due to fiber collisions in the plates SDSS uses to take spectra. B04 used Data Release 2 of SDSS, which missed more objects due to such issues. Our data comes from Data Release 7 (released during the semester just when we needed it), which returned and got spectra on many previously missed objects, so we have a larger population of galaxies with spectra. Within the spectroscopic sample population, 99.5%

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4. Photometric Analysis with SDSS and ALFALFA

FIGURE 4.1. Color-magnitude diagram for the Baldry et al. (2004a) sample. The red dotted line denotes the region of the "red sequence" while the blue one marks the ridge of the "blue cloud". From Baldry et al. 2004a.

have redshift measurements, and B04 select galaxies with $0.004 < z < 0.080$ and $-23.5 < M_r < -15.5$. The redshift limit in particular was kept low to minimize the effect of galactic evolution, which could bias the color-magnitude relations. In any case, it’s a good match with the ranges available to the ALFALFA survey, and with the location and magnitude of our cluster, so it is useful as a model for our own analysis.

B04 then made contour plots of $u-r$ versus $M_r$ in their selected population of SDSS galaxies. They found what they determined to be two separate populations among the galaxies: a red population and a blue one. There is significant overlap between the two populations when plotted together, making it difficult to distinguish which population a given galaxy belongs to based on the color-magnitude data alone. However, the distribution is clearly bimodal, indicating that two populations do exist.

Figure 4.1 from B04 shows the bimodality of the distribution along with best-fit curves for each. Each population was fitted to the sum of a linear and a tanh function:

$$T(M_r) = p_0 + p_1(M_r + 20) + q_0 \tanh \left( \frac{M_r - q_1}{q_2} \right)$$  (4.2)

This form was a good fit for the data (much closer than a polynomial with the same number of parameters, for example), and B04 interpreted it as a linear relationship with a transition in color occurring at some magnitude. Similar transitions seem to appear as bends in main-sequence stars in the Hertzsprung-Russell diagram. In order to determine the values for these parameters, B04 separated the galaxies into bins based on $M_r$ and $u-r$. In each magnitude bin, plots were made of counts of galaxies in each color bin. These plots were each fitted to a sum of two gaussian distributions, a red and a blue. One such plot is reproduced in Figure 4.2 from B04.
FIGURE 4.2. Distribution on color index for one particular bin of absolute magnitude showing the bimodal nature reflective of the differentiation into the blue cloud and red sequence. From B04.

The y-axis is counts and the x-axis is u-r.

<table>
<thead>
<tr>
<th>distribution</th>
<th>$p_0$</th>
<th>$p_1$</th>
<th>$q_0$</th>
<th>$q_1$</th>
<th>$q_2$</th>
<th>$(q_1/M_\odot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_r$</td>
<td>2.279 ± 0.006</td>
<td>-0.037 ± 0.006</td>
<td>-0.108 ± 0.017</td>
<td>-19.81 ± 0.07</td>
<td>0.96 ± 0.16</td>
<td>1.8×10^{10}</td>
</tr>
<tr>
<td>$\sigma_r$</td>
<td>0.152 ± 0.006</td>
<td>0.008 ± 0.006</td>
<td>0.044 ± 0.018</td>
<td>-19.91 ± 0.18</td>
<td>0.94 ± 0.40</td>
<td>2.0×10^{10}</td>
</tr>
<tr>
<td>$\mu_b$</td>
<td>1.790 ± 0.014</td>
<td>-0.053 ± 0.008</td>
<td>-0.363 ± 0.029</td>
<td>-20.75 ± 0.05</td>
<td>1.12 ± 0.10</td>
<td>2.6×10^{10}</td>
</tr>
<tr>
<td>$\sigma_b$</td>
<td>0.298 ± 0.004</td>
<td>0.014 ± 0.007</td>
<td>-0.067 ± 0.014</td>
<td>-19.90 ± 0.07</td>
<td>0.58 ± 0.19</td>
<td>0.9×10^{10}</td>
</tr>
</tbody>
</table>

FIGURE 4.3. Image of table showing fits to color index distributions. From B04.

The means and standard deviations of each were assumed to vary as T(M_r) above, and bounds on each parameter were computed. The table of values for $\mu_r$, $\sigma_r$ and $\mu_b$, $\sigma_b$, the respective means and standard deviations for the red and blue populations, is reproduced below in Figure ?? from B04. Also included is the value $(q_1/M_\odot)$, a measure of the midpoint of the transition in terms of solar masses. This is the mass of a galaxy at the middle of the bend in the best fit lines shown in the first figure.

4.2 Constructing a color-magnitude plot for the ZwCl 1400+0949 region

Figure 4.4 is a rendition of the color-magnitude relation among galaxies in the field within 3° of the cluster ZwCl 1400+09. It was created using the photometric data obtained from the SDSS Digital Sky Survey Data Release 7 available in November 2008. It plots the r-band absolute magnitude on the y-axis vs the (u-r) color index on the x-axis, and this is not oriented the same as the B04 color magnitude diagram shown in Figure 4.1. All units are in magnitudes.

The lower half of this plot is the red population of galaxies, around u-r < -20 and 0.5 < r_{mag} < 2.5. Above is the blue population, around u-r > -19 and 0.5 < r_{mag} < 2. This plot tells us nothing new compared to B04. It simply repeats their plot on a small (but still equally diverse) section of the sky.

Plotting galaxies accurately on the color-magnitude diagram requires making a number of corrections to the raw color and magnitude values measured by the SDSS. All color filters of the SDSS dataset must individually
be applied each one. The first is a correction for galactic extinction. This is to correct for the light lost due to intervening dust in the Milky Way Galaxy. It is dependent on filter color and on direction (particularly, galactic latitude), as there is more dust looking through the disk of the galaxy than looking off of it. This results in a correction which is added to the u, g, r, i, and z magnitudes acquired from the SDSS. For the u-band, this correction is 0.16 and for r, it is 0.085.

Next we must make the equivalent correction for dust in the observed galaxy, known as internal extinction. This is more difficult, as it depends on the inclination we view the galaxy at. Inclination can be calculated from the observed axial ratio of the galaxy, which is determined by fitting an ellipse to the galaxy’s shape. From measurements of the semi-major (a) and semi-minor (b) axes we compute an axial ratio $r = b/a$. Here we use measurements made based on r-band data, consistent with the use of r-magnitudes elsewhere. As the galaxy is a three-dimensional object, an assumption must be made for its width. Specifically, we must assume a value for $p$, the ratio between thickness and major-axis length. We use $p=0.2$ for early type galaxies (Sbc and earlier) and $p=0.12$ for later types. Given $r$ and $p$ we have a trigonometric relation for the inclination angle $i$:

$$\cos^2 i = \frac{r^2 - p^2}{1 - p^2}$$

(4.3)

Now we can calculate internal extinction. In the i-band, SDSS supplies us with the correction $i = r - 1.2444(r-i)$-
4. Photometric Analysis with SDSS and ALFALFA

FIGURE 4.5. Color-magnitude diagrams for the full 6° × 6° region (left) and the members of Zw 1400+09 (right). In both diagrams the red symbols identify galaxies only in the SDSS sample while the ALFALFA detections are denoted by the blue ones.

0.382. Given this corrected i-band magnitude based on r-i color we can convert all other magnitudes and colors based on relations given in Schlegel, Finkbeiner & Davis (1998, ApJ 500, 525).

A final correction to make would be a K-correction for redshift. However, these are difficult to estimate and can introduce undesirable uncertainty. Our galaxies are relatively nearby so this correction is relatively small; the uncertainty introduced would likely be greater than the correction itself. Indeed Blanton et al (2003, AJ 125, 2348) note in their discussion of K-corrections, “We want to emphasize here that, while K-correcting to a fixed-frame bandpass is sometimes necessary in order to achieve a scientific objective, it is not always necessary or appropriate. Because K-corrections are inherently uncertain (the broadband magnitudes do not uniquely determine the SED), they should be avoided or minimized when possible.” Thus we avoid making a K-correction, and so are done considering corrections to apparent magnitudes.

With corrected color band magnitudes we can compute the galaxies’ absolute magnitudes in each color band. This requires a calculation of distance. We use the mean redshift of the cluster cz=5861m/s and a Hubble constant $H_0 = 70$km/s/mpc, and compute distance as $d = \frac{cz}{H_0}$. We get a distance of 83.7mpc to the cluster. Taking $M_{corr, f}$ to be the corrected magnitude in a given filter f, absolute magnitude can now be computed: $M_{abs, f} = 5 + M_{corr, f} - 5 \log(10^6 \times d)$

Note the $10^6$ correction to account for the conversion of megaparsecs to parsecs. We then use the r-band magnitude as the representative magnitude of our plot, and compute $u-r$ for the color. These two values give the plot shown at the beginning of this section.

4.3 Analysis of color-magnitude plots

Figure 4.5 shows separately the galaxies detected by ALFALFA in blue and the others in red. Further a delimiter suggested by B04 is included to separate the red and blue population. This is represented by the curve

$$(u - r) = 2.06 - 0.244 \tanh \left( \frac{M_r + 20.07}{1.09} \right)$$

given as equation 11 in B04. Note the red population is above this curve and the blue below. Further, we limit the range of the plot slightly to deemphasize outliers in the plot, which a scan of the SDSS image database
shows are due to poor photometric data in galaxies that are dim, irregular, or interacting.

This plot is complex and not that useful as is. We instead want to limit this to the cluster in question, ZwCl 1400+0949. Background and foreground galaxies are no longer useful to our analysis now that we have an understanding of the galactic population at large. Cluster membership is determined by adopting a center and an acceptable distance from this center. We find the center from the peak X-ray emission in the cluster, and define it to be at (RA, Dec) = (210.70, 9.33) with all coordinates in degrees. We allow a galaxy to be in the cluster if it is within a radius of 0.68° of the center, which corresponds to a distance of a megaparsec. In the third dimension, we set membership in the cluster to only galaxies with recessional velocities between 5600 km s$^{-1}$ and 6600 km s$^{-1}$. This eliminates a foreground grouping of galaxies as well as a lane of background galaxies very close behind our cluster. The color-magnitude diagram is now reduced:

We see more ALFALFA detections on the blue side of the divider than on the red. The HI galaxies on the red side (which have $M_r$ near $-22$) can likely be accounted for as overlap between the two populations – they are likely actually part of the blue population and not the red. Our delimiter is an approximation B04 produce as a best fit to split the two sets, but they are not fully disjoint. This can be seen in the following contour plot from B04 which shows this overlap and where our divider lies. The dotted line is the blue population and the solid line the red.

Galaxies without HI detections on the blue side of the delimiter on the other hand do not appear to be in a region that can be accounted for by population overlap. Instead, these are likely blue late-type galaxies which are not forming stars, perhaps due to running out of hydrogen gas.

We want to check how the bimodal distribution of galaxies matches their morphological type in the cluster. The AGC uses a measure known as the numerical Hubble stage, based on the system used in the Third Reference Catalog of Bright Galaxies (RC3: de Vaucouleurs et al. 1991) to label morphology, where a negative number from $-6$ to $-1$ is an early type elliptical or lenticular, and a positive number from 0 to 10 is a late spiral or irregular. The AGC database uses 20 to delineate a galaxy whose morphological type could not be determined. Figure 4.7 is a plot of galaxies in our cluster, with early types plotted red and late types blue. Galaxies for which the AGC has no morphological information are black.
4. Photometric Analysis with SDSS and ALFALFA

FIGURE 4.7. Color–magnitude diagram for the galaxies deemed to be members of the Zw 1400+09 cluster. Red symbols denote objects with early morphological types, blue symbols identify late types, and black symbols show unclassified objects.

We note that there is an abundance of late-type galaxies in the cluster. Those early types that do exist in the cluster are mostly in the overlap region, but we note that much of the blue side of the Baldry delimiter is unclassified. Unclassified galaxies are mostly dimmer, and seem to be distributed relatively evenly by color, with perhaps a slight tendency toward blue.

We also might ask where galaxies of each type are located, perhaps expecting to find interactions near the center of the cluster affecting galaxy type and color.

We find instead a relatively even distribution of red and blue galaxies throughout the cluster, with perhaps a slight tendency for redder galaxies to be closer to the center.

4.4 Summary and Future Work

The SDSS photometric database provides valuable information on the magnitudes, and hence colors, of 700 galaxies in the 6° × 6° region around Zw 1400+09. In order to derive true galaxy colors, it is necessary to correct the observed magnitudes for galactic and internal extinction, and in our case unnecessary, redshift. Once that process is performed, we can calculate true colors, absolute magnitudes and luminosities. A color-magnitude diagram can then be constructed such as has been done for much large samples of SDSS galaxies by B04. We find that the ALFALFA HI line sources tend to be members of the “blue cloud”; few red sequence galaxies are detected by ALFALFA. Future work will involve the construction of stellar masses for the SDSS sample and their comparison with HI masses and dynamical masses.

4.5 References

4. Photometric Analysis with SDSS and ALFALFA


4.6 Appendix

The following are descriptions of values in the SDSS photometric database. For most derived quantities, we use the red filter (r) because it receives the greatest amount of light for most SDSS objects.

- **AGC**: The Arecibo Galactic Catalog number for this galaxy. This is usually a 6-digit identifier (but note that a portion of galaxies in this sample have 4-digit AGC numbers).

- **RA**: The Right Ascension coordinate of the galaxy’s position in the sky, measured in degrees. This should be between about 208 and 214.

- **Dec**: The declination coordinate of the galaxy’s position in the sky, measured in degrees. This should be between 6 and 12.

- **z**: The galaxy’s redshift, measured from spectral lines. The recessional velocity can be calculated by multiplying this number by c, the speed of light. This is approximately \(0.02 - 0.04\) for most objects in this dataset.

- **zerr**: The error in the measured value for redshift. This can be used for plotting error bars.

- **petroR90_r**: The radius encompassing 90% of the light from this galaxy, using the SDSS r filter.

- **petroR50_r**: The radius encompassing 50% of the light from this galaxy, using the SDSS r filter.

- **expAB_r**: This is an exponential fit for the ratio a/b of the semimajor-axis to the semi-minor axis observed in the galaxy’s shape, using the SDSS r filter. This can be used to calculate the galaxy’s inclination.

- **petroMag_u**: The apparent magnitude of light from this galaxy in the SDSS u filter. “Petro” refers to the Petrosian magnitude model, which fits light curves to extended objects (i.e., objects like galaxies which are not point sources) in order to calculate their total magnitudes. Along with the r-band magnitudes, I use this value for calculating galaxy colors.

- **petroMag_g**: The Petrosian magnitude of light from this galaxy in the SDSS g filter.

- **petroMag_r**: The Petrosian magnitude of light from this galaxy in the SDSS r filter. Along with the u-band magnitudes, I use this value for calculating colors. I also use it for calculating magnitudes.

- **petroMag_i**: The Petrosian magnitude of light from this galaxy in the SDSS i filter.

- **petroMag_z**: The Petrosian magnitude of light from this galaxy in the SDSS z filter.

- **lnLExp_r**: A measure of the goodness of an exponential model for the light curve of the galaxy. Generally, fainter ellipticals have a better exponential fit.

- **lnLDeV_r**: A measure of the goodness of a De Vaucouleurs fit for the light curve of the galaxy. A large luminous galaxy generally is better described by a De Vaucouleurs fit.

- **isoA_r**: This gives the isophotal major axis in the r filter in pixels. This can be used to calculate linear diameter.
• **isoPhi<sub>r</sub>:** This gives the position angle of the galaxy, that is, the rotation angle of the semimajor-axis.

• **zWarning:** If this is not 0, then there is an issue with this galaxy’s redshift measurement and we should ignore this source. This is due to, for example, missing spectra, abnormally low or high redshifts, or low signal-to-noise in a particular color filter.

• **objID:** A unique identifying number assigned to all objects in the SDSS database. We have to use caution with these numbers as many spreadsheets by default do not hold enough digits in a cell to fully store this number. All galaxies in this sample do not have objID numbers ending in 000. If this is seen, it is because the spreadsheet you are using has not stored the number fully. In practice, this number is not too important to us anyway, as position or AGC number serve to uniquely identify most objects instead.

• **separc**: The separation in arcseconds between this object’s position in the SDSS and in the AGC. This number should be less than about 3.

My analysis involves in particular two derived values:

• **u-r:** The value petroMag<sub>u</sub> - petroMag<sub>r</sub> which describes a galaxy’s color

• **M:** The absolute magnitude of the galaxy in its rest frame, calculated as petroMag<sub>r</sub> −log(<i>c</i>/10<sub>Ho</sub>) for <i>c</i> in kilometers per second and <i>Ho</i> in kilometers per second per Megaparsec.

A plot of these values allows me to examine the population of red elliptical galaxies and blue star-forming galaxies in the cluster.
5. Galactic Activity around the ZwCl 1400.4+0949 Cluster

Sarah Morrison

ABSTRACT Using spectroscopic data from the Sloan Digital Sky Survey (SDSS) as well as ALFALFA HI detections for the area containing the cluster Zw 1400+0949, the galaxies of the area are classified as passive, star forming, or containing active galactic nuclei (AGN). ALFALFA has a larger proportion of star forming galaxies than those in the SDSS data set alone, perhaps due to the ALFALFA survey detecting more star forming galaxies on the basis that it is an HI survey. The most common star formation rate in the galaxies detected in ALFALFA is also slightly higher than those only in SDSS. Little correlation, however, is found in the star formation rates of galaxies in either survey with their u-r color indices.

5.1 Introduction

The region between 207.95 and 214.15 right ascension, 5.86 and 12.15 declination is home to large scale structure including a cluster that goes by many names: Zw 1400+0949, MKW 12, WBL 486, and more. Using spectral data from the Sloan Digital Sky Survey (SDSS) for the region of this cluster, we can characterize the activities of the galaxies that reside within the cluster itself and its environs.

Targets for spectral observation are determined by their photometric characteristics. According to Strauss et al. (2002), galaxies in the main galaxy sample with r-band Petrosian magnitudes of less than or equal to 17.77 and r-band Petrosian half-light surface brightnesses of less than 24.5 magnitude/second are spectral targets. Luminous red galaxies are selected based on their color and magnitude rather than the flux as in the main galaxy sample (Eisenstein et al. 2001). These target criteria effectively eliminate stellar contamination and confine the observations to extended sources, not point sources.

The data of interest for spectral analysis include line dispersions and equivalent widths for objects in both the SDSS DR7 and ALFALFA datasets (the ALFALFA sample), as well as those that are in SDSS, but not ALFALFA (the SDSS sample). These data sets include the line dispersions and equivalent widths of Hα λ 6565 Å, Hβ λ 4363 Å, [OIII] λ 5008 Å, and [NII] λ 6585 Å, as well as the redshift measured from Hα (and the error associated with these measurements). Each object is referred to by its AGC number, SDSS ObjID, and its location in right ascension and declination. Using the ratios in the equivalent widths of the four spectral lines mentioned above, galaxies can be identified as having active galactic nuclei (AGN) or star formation regions. With both of these data files, we can compare the percentage of AGN and star forming galaxies of galaxies detected in ALFALFA versus those in the overall SDSS sample in the same region as well as the percentage of AGN and star forming galaxies within the Zw 1400.4+0949 cluster.

Before beginning this analysis, sources of error in the spectra should be considered. Because the spectral lines for [NII] and Hα are close together, sometimes it can be difficult to obtain emission line ratios. If a galaxy also has heavy stellar absorption, this could hide emission of the same element and vice versa. Aside from challenges in spectral line identifications, there are also errors from the spectral observations themselves (discussed in Hao et al. (2005), Hopkins et al. (2003) and Miller et al. (2003). If there are foreground objects, these objects could partially obscure the spectral measurements of the object behind it. An underestimation of the emission flux could also arise because emission from an object could be partially absorbed by foreground dust. The SDSS optical fibers are also only 3 arcseconds in diameter, so there is a limited amount of emission that can be detected within the fiber. In measuring the ratios for diagnosing between AGN and SFG, however, Miller et

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5.2 Determining Galactic Activity

The main types of galactic activity that can be readily classified are whether galaxies have AGN or star forming regions. The BPT diagram (Baldwin et al. 1981; Osterbrock 2006), which plots emission line ratios of \([\text{OIII}]/\text{H}\beta\) versus \([\text{NII}]/\text{H}\alpha\) on logarithmic axes, is the traditional method of differentiating the two. The borderline that separates star forming galaxies from AGN varies depending on star formation models. The model used in Kewley et al. (2001) classifies more galaxies as star forming, whereas the model used in Kauffmann et al. (2003) asserts that star forming galaxies have strong correlations in ionization parameter and metallicity and do not have as much scatter on the BPT diagram as Kewley et al. (2001) assumed.

This paper will use the Kauffmann et al. (2003) model which characterizes AGN by the inequality \(
\log([\text{OII}]/\text{H}\beta) > 0.61/\left(\log([\text{NII}]/\text{H}\alpha) - 0.05\right) + 1.3
\). In both models, however, AGN can often be identified by only one of these ratios if the ratio is sufficiently above the borderline as illustrated in Figure 5.1. A comparison of the borderlines for two models is shown in Figure 5.2 plotted with the diagnostics for the Zw 1400+0949 region.

al. (2003) found no correlation between the line ratios and the total light in the fiber.
Given that this model holds true for emission line emissions, absorption line galaxies are not included from the MKW 12 region as well as any galaxies that have outlying [OIII]/Hβ and [NII]/Hα ratios or redshift warnings in order to eliminate any galaxies with erroneous spectra. Figure 5.2 contains the BPT diagrams for the region surrounding MKW 12. The ALFALFA sample contains a higher percentage of star forming galaxies than the SDSS sample (61% of all galaxies in the ALFALFA sample versus 47% in the SDSS sample and 77% of active galaxies in the ALFALFA sample versus 70% in the SDSS sample). Figure 5.3 shows the distribution of galaxies on the sky and clearly shows a higher density of galaxies at the right ascension and declination of the MKW 12 cluster given by NASA’s Extragalactic Database (NED).

To further understand the properties of the galaxies present in both samples, the star formation rates for galaxies deemed to be active are also calculated. The star formation rate (SFR) is given by:

\[
SFR(M_\odot/\text{year}) = 7.9 \times 10^{-42} L(H\alpha)
\]

where \(L(H\alpha)\) is the luminosity of the Hα line in ergs/s (Kennicutt 1998). \(LH\alpha\) is proportional to the equivalent width of Hα, but must be modified by several correction factors. Accounting for Hα stellar absorption, we apply a 1.3 Å correction, which is an intermediate value as discussed by Hopkins et al. (2003). The aperture correction mentioned in the introduction is also needed since only one emission line is being used versus a ratio as in the Miller et al. (2003) paper. Currently this adjustment consists of a fiber-to-Petrosian scaling aperture correction, but may need to be modified in the future. A histogram of the SFRs in Figure 5.4 shows that there are peaks in the number of galaxies with a common SFR for both the SDSS and ALFALFA samples. Though the actual calculated SFRs may change in the future with the addition of more corrections, the relative rates will remain the same so the Gaussian distribution of SFRs seen in the histogram will still be present.

Combining the SFRs calculated from the SDSS spectroscopic data with the u-r corrected color index from the
FIGURE 5.3. Location on the sky of galaxies in different subsamples. The top plot shows the ALFALFA HI detections only. The bottom two panels show the galaxies in the SDSS sample, with the middle panel including only AGN and star forming galaxies, while the bottom adds passive galaxies.

SDSS photometric data, it is possible to look for a correlation in the color of a galaxy and its SFR. In the distributions plotted in Figure 5.5, many galaxies seem to be concentrated where the log(SFR) is between 0 and 1 with a color index between 1 and 2 in both the SDSS and ALFALFA samples. A histogram of galaxies in the SDSS photometric sample and the ALFALFA sample in Figure 5.6 also shows a peak of galaxies within
5. Galactic Activity around the ZwCl 1400.4+0949 Cluster

5.3 Discussion and Conclusions

Since ALFALFA is an HI survey, it is expected that detected active galaxies will be predominately star forming and have slightly higher SFRs than the main SDSS sample. This seems to be the case since star forming galaxies comprise 77% of active galaxies in the ALFALFA sample versus 70% in the SDSS sample. The peak in the SFR histograms is also shifted toward a higher SFR for ALFALFA than SDSS. With increased star formation, galaxies would have been expected to have a larger population of O and B stars and thus be bluer. The scatter plots of SFR versus color index, however, show little correlation between the two for either sample. The common range of SFRs and color indices as seen by the distribution in the scatter plots is also revealed in the histograms, so, once again, this distribution may not show any relation between SFR and a galaxy’s color. The SFRs also seem to be low overall for a cluster (the most common SFR appears to be only one solar mass per year, which is the same SFR for the Milky Way) which may be an indication of more correction factors needed to the original equivalent widths of Hα from SDSS. Relative comparisons of the SFRs should not be affected.

Though the classifications of active galaxies did not discriminate in redshift (and distance), the distribution of galaxies on the sky still alludes to a cluster at the previously established location for MKW 12 from NED. Further differentiating in distance could allow for a more detailed comparison between the SDSS and ALFALFA datasets as well as the proportions of active galaxies and SFRs for galaxies in the cluster itself versus those
5. Galactic Activity around the ZwCl 1400.4+0949 Cluster

FIGURE 5.5. Scatter plot of SFRs versus (u−r) color index. The blue points represent the galaxies in the SDSS sample which the red points denote galaxies in the ALFALFA catalog.

in the clusters surroundings. Higher SFRs and proportions of active galaxies should be observed within the cluster if interactions between galaxies can spur activity.

5.4 REFERENCES

5.5 Appendix

5.5.1 Data Analysis

The data of interest for spectral analysis include line dispersions and equivalent widths for objects in both the SDSS DR7 and ALFALFA datasets, as well as those that are in SDSS, but not ALFALFA. These data files include the line dispersions and equivalent widths of Hα, Hβ, [OIII], and [NII] as well as the redshift measured from Hα (and the error associated with these measurements). Each object is referred to by its AGC number, SDSS ObjID, and its location in right ascension and declination. Using the ratios in the equivalent widths of the four spectral lines mentioned above, we can produce an AGN/star forming diagnostic diagram as discussed in the body of this paper. The velocity dispersions can also be used to compare activity given that broadening of a spectral line is indicative of the motions of the sources that create that spectral line. With both of these data files, we can compare the percentage of AGN and star forming galaxies of galaxies detected in ALFALFA versus those in the overall SDSS sample in the same region as well as the percentage of AGN and star forming galaxies within the Zw 1400+0949 cluster.
5.5.2 Querying the SDSS Database

In order to retrieve the spectroscopic datasets discussed in this paper, an SQL query on the SkyServer for the Sloan Digital Sky Survey (http://cas.sdss.org/astro/en/) was used. The following is a sample query that could be used to retrieve the same information for Hα and Hβ:

```
SELECT s.ra, s.dec, s.z, s.zerr,
       'Ha', L.ew, L.ewErr, L.sigma, L.sigmaErr, L.continuum
       'Hb', L2.ew, L2.ewErr, L2.sigma, L2.sigmaErr, L2.continuum
FROM PhotoObj p, SpecObj s, SpecLine l
WHERE
   p.SpecObjID = s.SpecObjID AND
   p.SpecObjID = l.specobjID AND
   s.specClass = 2 AND
   l.lineID = 6565 AND
   l.lineID = 4863
   s.ra >= 207.95 AND s.ra <= 214.15 AND
   s.dec >= 5.86 AND s.dec <= 12.15 AND
   s.z <= 0.061
order by s.ra
```
6. Summary and Future Work

Martha Haynes

ABSTRACT This work presents preliminary results on the large scale structure and properties of galaxies in region around the overdensity known as ZwCl 1400.4+0949. An analysis of the redshift distribution shows the presence of two superposed structures. One is identified with the cluster known as MKW 12 which lies at 83.7 Mpc and appears to be part of a filament extending from a larger scale structure towards the foreground. Two galaxies detected by ALFALFA have no obvious optical counterparts; both however are found near to other galaxies at similar redshifts and may represent tidal debris. In general, the galaxies detected by ALFALFA tend to be blue and star-forming. Future work will refine this analysis and compare the properties of galaxies in this region with those of the entire ALFALFA–SDSS sample.

6.1 Introduction

During the latter half of this semester, we have compiled observational data obtained at optical and radio wavelengths from publicly available datasets of galaxies in the region of ZwCl 1400.4+0949 region. We analyzed the large scale structure in the region and identified the main hierarchical units. We also studied how to convert observed parameters into intrinsic galaxy properties including stellar and HI masses, dynamical masses, colors, star formation rates and measures of nuclear activity. Here we summarize results.

6.2 Large Scale Structure in the ZwCl 1400.4+0949 Region

An important aspect of this work is the availability now, through the ALFALFA survey and the SDSS public database, of many more measurements of galaxy properties than were available to previous studies. As discussed by Luca Zantream in this volume, that 1979 study by Chincarini et al. of the ZwCl 1400.4+0949 cluster resulted in only 16 HI line detections, versus the 262 detections in the new ALFALFA catalog. The first determination of the mass, made by Thomson et al. (1978) was based on only ten redshifts. Katie Hamren here is able to analyze the redshift distribution of more than 700 galaxies to identify two separate peaks in the redshift distribution at \( \sim 6000 \) km s\(^{-1}\), and determines the mass of the feature identified as MKW 12 from 49 members. From this analysis, we realized, somewhat to my surprise, that the large scale structure in the region is more complex than we had anticipated. In fact, MKW 12 seems to lie just in the foreground of a more extensive filamentary structure which connects in the background to Coma-Abell 1367 as is clear from the cone diagram seen in Figure 2.1.

6.3 Galaxy Properties

The ALFALFA catalog contributes integrated HI line fluxes, recessional velocities and HI line widths as well as positions of each radio detection. The SDSS photometric dataset includes magnitudes in each of the five SDSS filter bands as well as sizes and axial ratios, while the spectroscopic survey contributes redshifts and equivalent widths for the most useful spectral lines visible in the optical portion of the spectrum. In order to understand

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the current state and past history of the galaxies we need to combine this information to derive stellar, HI and
dynamical masses, to determine the current rate of star formation and gas content and to identify objects which
have active galactic nuclei. The papers by Luca Zatreanu (HI properties), Russell Wolf (SDSS photometry) and
Sarah Morrison (SDSS spectroscopy) present the first attempt to analyze the properties of galaxies detected by
the ALFALFA survey in combination with the sample extracted from the SDSS sample in the same region. Not
unsurprisingly, we find that the galaxies detected by the ALFALFA survey tend to be blue and are undergoing
star formation.

A major objective of this preliminary analysis of the combined ALFALFA-SDSS dataset was to explore the
differences between galaxies detected by a blind HI survey like ALFALFA with those extracted from an optical
magnitude-limited sample like the SDSS-spectroscopic sample. Indeed, about 20% of the galaxies detected by
ALFALFA do not have SDSS spectroscopy. Indeed, Luca found two objects detected by ALFALFA without HI
counterparts, but since they lie in regions where there are several nearby optical galaxies, we hypothesize that
the HI sources are associated with tidal debris from recent interactions.

6.4 Future Work

Further work remains to refine the methods by which we convert from observational parameters to intrinsic
galaxy properties. For example, the derivation of stellar masses requires more detailed modeling of the stellar
populations using all the available SDSS colors. Future analysis will build on the steps undertaken here,
combining the full ALFALFA catalog to explore systematic effects and to derive, for example, a standard of
HI content based on the available SDSS diameters, updating and refining work done using older, less precise
datasets. Many of the most interesting objects – HI detections without optical counterparts, fast rotators,
low mass dwarfs, high HI mass–to–luminosity ratio galaxies – will require followup multiwavelength studies
to understand their exceptional natures. Ultimately, we hope to be able to explore and understand all that
ALFALFA and SDSS can reveal about the evolutionary histories of the entire HI+optical galaxy populations
and how they are dependent on their local environment. It seems that we could be busy with this for years to
come.

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ALFALFA is awesome.