THE NATURE OF THE MOST ISOLATED GALAXIES IN THE SLOAN DIGITAL SKY SURVEY

by

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This thesis has been reviewed by the research advisor, research coordinator, and department chair and has been found to be satisfactory.

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ABSTRACT

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Dark matter is one of the greater mysteries in astronomy. It is abundantly evident in galaxy rotation curves and galaxy cluster velocity dispersions. Computer models clearly indicate that the observed large-scale structure of the universe is shaped by it. These same models predict that galaxy voids may contain dark matter in places where galaxies have not yet formed. So studying voids and the galaxies that are most deeply embedded in them is a means of exploring dark matter itself. We have examined the Sloan Digital Sky Survey and have identified two true void galaxies defined as having no other cataloged neighbors within 12 Mpc. These are almost identical and show remarkably similar magnitudes, sizes, and colors. Although just a small sample of two objects, they provide evidence that smaller, dwarf-like galaxies can be found in voids as has been predicted by CDM models.

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Introduction

1.1 Introduction

The only viable theory of the formation of the universe is the "big bang". It explains most simply and straightforwardly the cosmological redshift, abundances of primordial clouds, and the evolution of galaxies with z [1]. It has been so successful that competing theories such as the "Hoyle-Narlikar" theory where mass changes with time, "tired light" where light loses energy with travel distance, and the "steady state" where the universe does not evolve with time are no longer taken seriously by nearly all cosmologists. Its emergence as the primary theory is a major step in cosmology.

But the big bang is still being fleshed out. Details of exactly how galaxies emerged are still sketchy. Deep Hubble pictures seem to indicate that they come together from medium-sized pieces rather than directly from primordial gas [2]. Furthermore, both theory and observation have made it obvious that galaxies are dominated by dark matter. Understanding dark matter is a critical next step in advancing our knowledge of both cosmology and galaxy formation.

1.2 Background

Dark matter is understandably a current topic of great interest. It was initially discovered by astronomers mapping the velocity curves of galaxies and the orbital velocities of galaxy cluster members [3]. They discovered that for individual galaxies, the velocity curves do not drop off with distance from the galaxy centers in the same way that the light does. In other words, galaxies have more light in their centers which tapers off toward the edges. If the light traces the mass, we can calculate the expected velocity curve from the light distribution and predict how this curve should taper off with distance from the center. The startling truth, however, is that the velocity dips a little, but recovers and maintains a value that is close to being constant out to distances where the light completely is gone. [See Fig. 1.1]. The conclusion is that all galaxies contain more mass at larger distances than is traced by their light. The mass that shows up through its gravity but not its radiation is the "dark matter".

Dark matter was discovered in the dynamics of galaxies. But its ramifications go well beyond just galaxies. The nature of dark matter plays a pivotal role in galaxy formation and evolution. When the universe was young it was homogeneous. Today, we observe a heterogeneous, lumpy universe. This change started from very small fluctuations in density after the inflationary epoch. In its young, smooth stage, the universe had none of these fluctuations. The universe expanded at a rapid rate with pieces of space that were about the size of an atom quickly growing to the size of a beach ball in about 1 nanosecond [4]. This swift growth created small, *essential* density discontinuities. As the universe continued to expand it cooled down. From the cooling came the clumping. Dark matter began to condense leading to condensation of regular matter. Thus, galaxies and stars began to form.

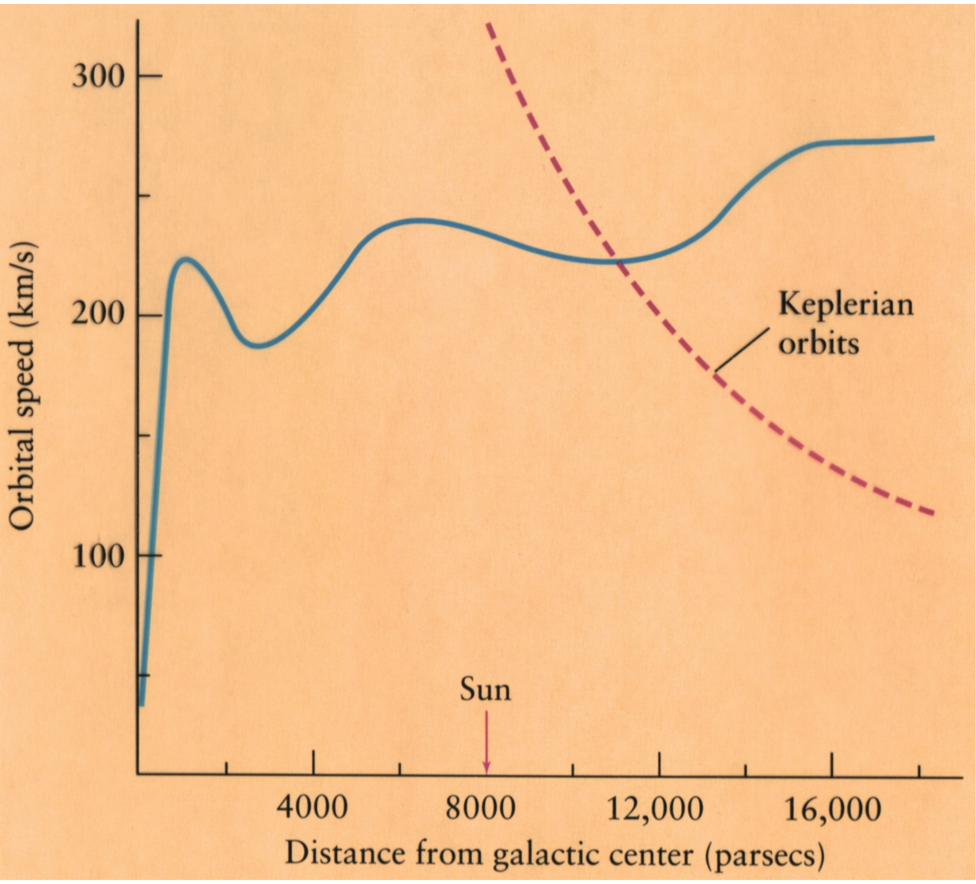

Figure 1.1 Keplerian vs. Observed rotation speeds. Observe how the Keplerian curve should drop off, but instead, we see that the velocity dips slighly, and then recovers to a higher velocity. Courtesy of the University of Oregon.

When we know the role of dark matter in galactic formation we can discover its role in the Big Bang. We can learn more about the early stages of the universe and come to understand one of the most interesting time periods in our universe, however brief it may have been. Learning about dark matter gives us insights into the formation of the universe itself.

1.3 Galactic Evolution

An area of cosmology that is not well understood is the era between the Big Bang and the emergence of galaxies. In this era the quasars were first formed as were the oldest galaxies that we see as ellipticals today. Galaxy formation continued presumably for several billion years until today, where we see more than 100 billion galaxies existing in the known universe. These magnificent structures clump together and form “neighborhoods”, called clusters, or “cities”, called superclusters. This behavior was modeled by the Millenium Run, pictured in Fig 1.2. With this natural grouping, empty areas arise. These are called voids. Within them we find hermits of space, called void galaxies. Galaxies are called “void” galaxies when the local density approaches 10% of the mean. [5]

1.4 Dark Matter

In the 1930s the astronomer Fritz Zwicky found that individual galaxies in rich clusters orbited with speeds that were too large for the observed matter to keep them together. He hypothesized that either a dark matter held the clusters together gravitationally, or they were dynamically unstable and rapidly flying apart. In the end, it was discovered that there must be some undetected mass that holds the galaxy together - dark matter.

The effects of dark matter are numerous. We see it in galaxy formation, galaxy structure, and the Cosmic Microwave Background (CMB) [6]. Dark matter is not detectable by conventional methods (i.e. using electromagnetic radiation detection). It also does not interact through electromagnetic forces, just gravity.

There are other ways to determine the mass of a system like a galaxy or a cluster, besides rotation curves. For example, some galaxies or clusters are filled with X-ray bright gas whose temperature and profiles can be measured [7] Since gas temperature

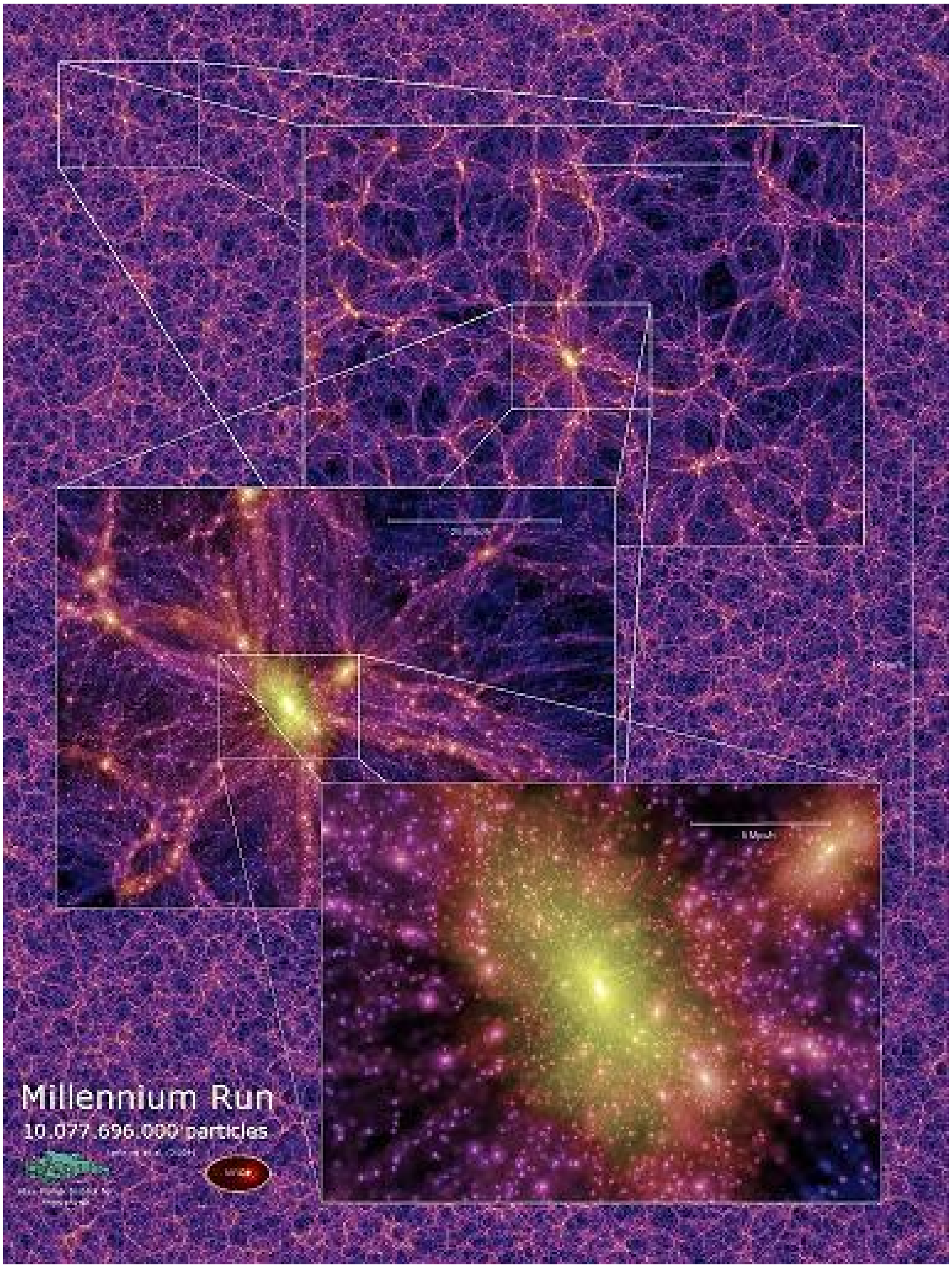

Figure 1.2 The Millenium Run (pictured above) is a computer simulation of more than 10 billion particles tracing the evolution of the universe in a 2 billion light-year cube. Notice how galaxies group and clump, giving rise to voids. Courtesty of MPA.

arises from gravitational compression which, in turn, depends on the total mass, the system mass can be modeled uniquely. What we discover is that roughly *five times* more mass exists in these systems than is evidenced by their radiation.

From cosmological modeling of the bumps detected by the Wilkinson Microwave Anisotropy Probe (WMAP) we estimate that 22% of the universe is composed of dark matter [see Fig. 1.3]. But this is only a first order determination which tells us nothing about the form the matter can take. Because we do not know exactly what dark matter is composed of, we have problems determining what experiments to design to detect it. Research proceeds empirically while we continue to refine the possible forms it can have.

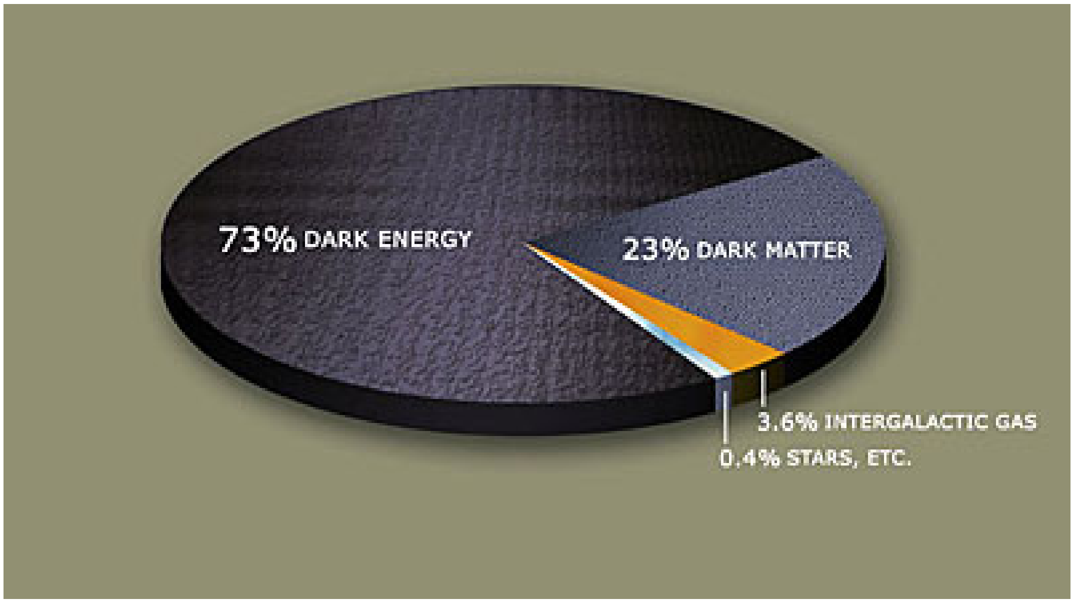

Figure 1.3 Observable matter makes up a small of fraction of the universe. Courtesy of NASA Online.

Recall that while dark matter concentration varies greatly from galaxy to galaxy and cluster to cluster, roughly five times the mass is non-luminous. This is quite a bit of matter to not "see". However, its effects are seen. Gravitational lensing occurs when light curves around a massive object. The gravitational force from the object distorts space and light curves around the object [see Fig. 1.4]. This lensing was confirmed during a solar eclipse in 1919 by Arthur Eddington, who noticed that the position of the few stars closest to the solar limb were out of place [8]. Dark matter can also curve space-time. The strong gravitational lensing we see near rich galaxy clusters supports the notion that galaxy clusters are composed of 90% dark matter.

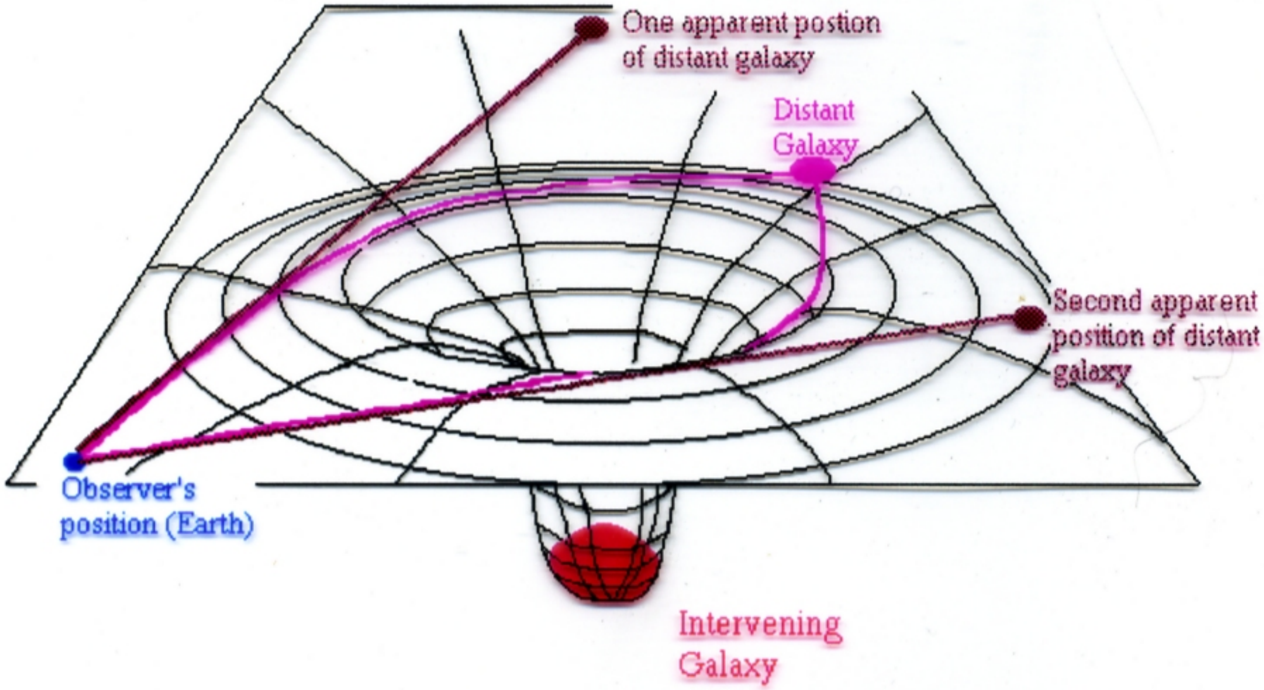

Figure 1.4 Objects with enormous mass create greater distortions in the fabric of space. This figure demonstrates the effects of gravitational lensing. Courtesy of Washington University in St. Louis.

1.4.1 Hot vs. Cold Dark Matter

The scenarios that describe the era between the Big Bang and emergence of galaxies divide into two camps: hot dark matter (HDM) and cold dark matter (CDM). CDM theory states that dark matter is made up of more massive particles that move slower. HDM is the theory that the particles of dark matter are lower mass and move at speeds comparable to the speed of light (v $\sim$ c).

HDM favors the "top-down" theory, in which large structure forms in the primordial gas first and then smaller structures like star clusters emerge later [9]. Imagine, for instance, a large cloud of gas rotating uniformly. If top-down theories are correct, then this gas would begin to crunch in on itself forming structures in accordance with the physics of gas dynamics. The likely candidate for HDM is the neutrino.

CDM favors the theory where dark matter particles move at speeds much less than the speed of light (v$\ll$c). The formation theories for CDM are called "bottom- up". This is the exact opposite of HDM theories. Imagine the same cloud of gas, only this time it first forms stars and star clusters. These "particles" at the center of the cloud mix and jumble together in accordance with the law of gravity. The galaxy clusters that form in CDM models are smaller than those in HDM and are also closer to what is observed. CDM models are the favored theory among astrophysicists today.

Because HDM cannot describe how galaxies were formed at the beginning of the big bang - the ultra-relativistic particles move too fast to begin small scale clumping - HDM is typically only seen in mixed models. However, CDM models have their own set of issues. They cannot adequately describe galaxy centers as we observe them, and they overestimate the observable number of dwarf galaxies within the Local Group [10]. CDM models also have trouble pinning down the exact nature of the particles that must exist in order for CDM to dominate [11]. Many current models favor a mix of hot and cold dark matter.

1.4.2 MACHOs and WIMPs

A current hypothesis on dark matter is that it may be nonbaryonic matter (matter not composed of proton, neutrons, and electrons). This can include massive neutrinos (a less likely candidate) and other super-symmetric particles [11]. However, there is no theory that invokes only nonbaryonic matter. Both nonbaryonic and baryonic particles are necessary to explain dark matter - at least for now.

There are many theories on the nature of dark matter and its role in galaxy formation. The two dominant theories are humorously called MACHOs and WIMPs. MACHOs are Massive Astrophysical Compact Halo Objects. These are bodies that hover around the galaxy, well outside the plane, but still gravitationally bound to it. They could be objects like white dwarfs, neutron stars, black holes, very faint stars, or other non-luminous objects like planets, dwarf planets, and asteroids - baryonic matter, in other words. This theory, however, does not seem to have a strong case. Gravitational lensing studies [12] have ruled out a significant abundance of halo objects in the Milky Way. Their conclusions are that only a small fraction of the missing mass can be attributed to MACHOs [13]. Therefore, another theory came up, dubbed WIMPs.

WIMPs (Weakly Interacting Massive Particles) are particles composed of nonbaryonic matter. They are particles like axions and neutralinos that are hypothesized to exist but have never been detected. Nonbaryonic matter, if real and supersymmetric, can have a detectable annihilation signature. When a particle and antiparticle pair combine the two particles are destroyed, but their kinetic and rest energies may combine to form new particles (with total mass equal to E/c^2). In fact, since the antiparticles have opposite quantum numbers, it is possible to create a new particles with quantum numbers equal to zero, as long as conservation laws are obeyed. An example of this is when positrons and electrons annihilate and form gamma rays. This radiation is detectable, and may be a way to detect dark matter indirectly.

WIMPs are hypothesized to interact through gravity and the weak nuclear force, giving us a means to detect them directly. Particle accelerators like the Large Hadron Collider (LHC) in Switzerland will work at energies large enough to detect particles like the Higgs boson - a theoretical particle that is key to the theories that predict WIMPs. So, WIMPs have never been detected but this may change in the coming decade.

1.5 Voids

When galaxies come together in clumps, sheets, or filaments, they separate according to type [14]. Filaments are dominated by spiral type galaxies while about 80% of the galaxies in rich clusters at intersections between filaments are composed of elliptical galaxies. This segregation by type is important to understanding galaxy formation, and how interactions between galaxies force certain features to become apparent.

Galaxy groups and clusters line vast areas of empty space, called voids (see Fig. 5). Voids themselves are most likely completely empty, although we can only say that they are empty to the magnitude limit they have been searched. Galaxies are found on their edges, of course, with a density that tapers off as you enter the void. These are the galaxies discovered by Moody et al. (1987), [15], Weistrop et al. (1989) [16] and others which were thought by some to inhabit voids. More recent studies of SDSS data by Rojas et al. (2004) [17] have shown that they are best treated as "edge" galaxies even though the nomenclature used is "void" galaxy. They do not inhabit the voids but properly define their edges. Rojas etc. define wall galaxies as those structures which are part of a cluster or supercluster, and they line the void. Void galaxies reside away from any structure, but are not in the middle of the void. Studying void galaxies gives pertinent information on dark matter models because the percentage of dark matter in void edges is likely to be different than in cluster centers.

Void galaxies have been studied thoroughly by astrophysicists and they conclude

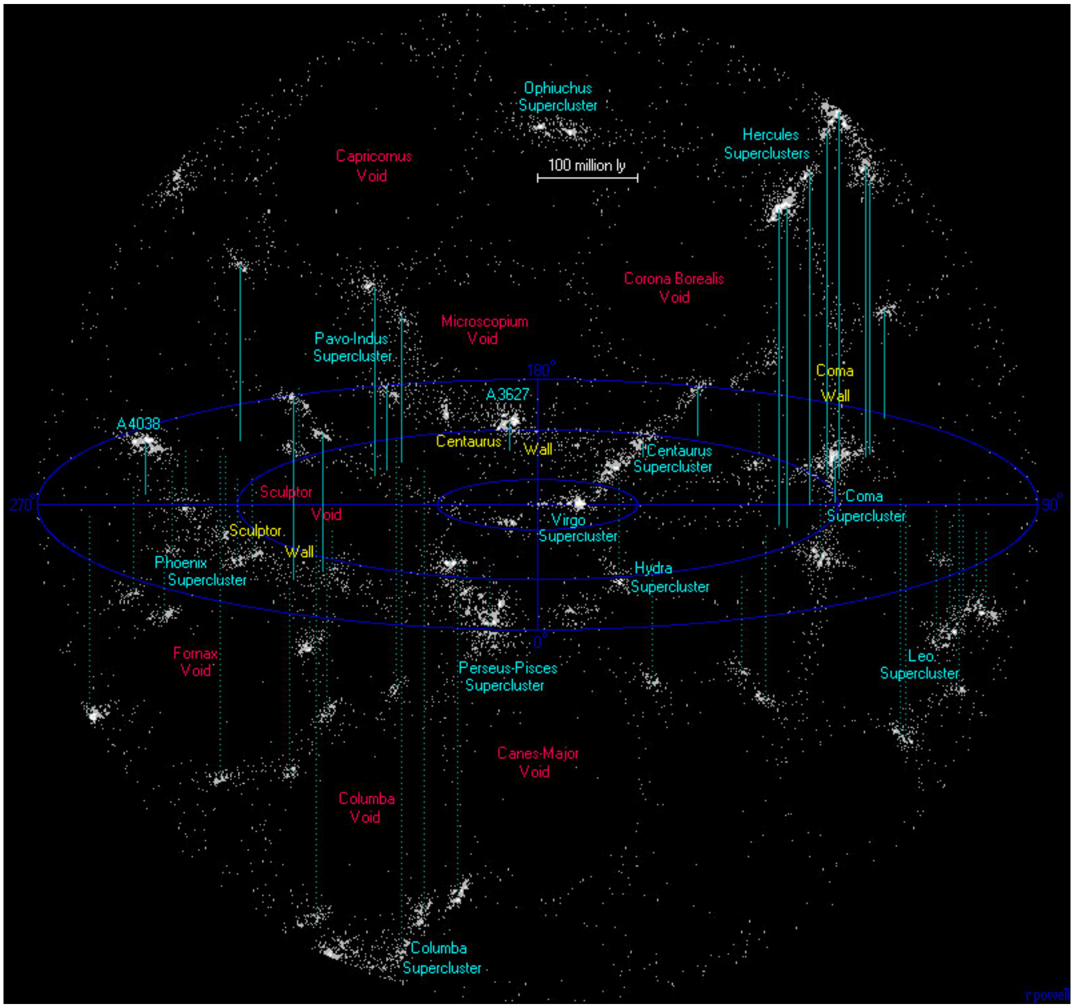

Figure 1.5 This 3D diagram illustrates our local area and the observable voids. Courtesy of Richard Powell, *Atlas of the Universe*.

that void galaxies are (on average) blue late-type galaxies with higher star formation rates (SFRs) [17]. While this may be an observational bias, it is still curious because from the current understanding of galaxy formation, astronomers know that high SFRs are produced from interactions between galaxies and anything else that causes density waves to propagate through a galaxy. The question, then, is how did these galaxies obtain high SFRs if they are significantly separated from other objects in space?

While the exact details of galaxy formation are not known, it is assumed that material in their vicinity must reach a certain density before galaxy formation can occur. Below this threshold (which must be related to the Jeans mass) stars do not form and hence galaxies do not form either. The Jeans mass is a determining factor in formation [18] If a star or galaxy does not have enough internal gas pressure to withstand gravitational forces, then the system collapses. The nature of edge galaxies traces the density threshold necessary for galaxy formation. This is called the "bias factor" which is also used to determine CDM behavior. Because of this important link, studying void galaxies tells us about dark matter.

1.6 Isolated Galaxies

Studying galaxy voids is difficult because we must first have a large, complete data set extensive enough to outline the main galaxy supercluster strips and sheets. Fortunately, the recently completed Sloan Digital Sky Survey (SDSS) is such a set and void galaxies have been studied extensively in it. [e.g. Rojas et al. 2004, Hoyle et al. 2002] However, there is much more work to be done. The SDSS, like all surveys, is magnitude limited. As such, galaxies can appear to be isolated when they are in fact surrounded by galaxies that were simply too faint to make the survey. Because of this observational bias, determining whether any specific void galaxy is truly isolated is a challenge. In order to get data on isolated galaxies we must be certain that the galaxies are unquestionably isolated.

Therefore, we found and studied the most isolated void galaxies from the SDSS Data Release 7, which was made public in 2008 and is the most complete data set. This database provides photometric redshifts, sizes, color, and magnitudes of each galaxy in it and spectroscopic redshifts for the brightest objects. Redshift data define which galaxies are most isolated. We first identified those then examined them to see if similar companions exist nearby. Galaxies with similar traits may have similar formation histories and similar objects may actually be companions. Therefore, these galaxies may not be isolated. If this proves to be the case, it raises the question of how isolated galaxies really are.

Truly isolated void galaxies are influenced the most by dark matter, due to their lack of companions. If a galaxy has no neighbors to affect it gravitationally, then it remains to evolve naturally, and we can see the deepest effects of dark matter on these kinds of objects. The aim of this project is to find such galaxies and help find a solid conclusion on the nature of dark matter.

Chapter 2

Data and Analysis

2.1 Sloan Digital Sky Survey

We gathered the information for this research using the Sloan Digital Sky Survey (SDSS). SDSS is an ambitious project undertaken to obtain basic information about a large, complete sample of deep sky objects. From 2000 to 2005 the project obtained spectra for over 930,000 galaxies and 120,000 quasars. The survey includes roughly 12,000 square degrees of imaging data. (In contrast, the full moon occupies roughly 0.2 square degrees in the sky.) SDSS uses a 2.5 meter telescope at Apache Point Observatory, New Mexico. The camera images 1.5 square degrees of sky at a time. SDSS has imaged most of the northern hemisphere sky and dips into a 300 square degree strip in the southern hemisphere. It is the largest and deepest complete spectroscopic survey and redshift set to date that is appropriate to use for void studies.

2.1.1 Finding Void Galaxy Candidates

The SDSS is complete in redshifts to $r\sim17.2$. It samples reasonably out to $z\sim0.2$. Of course, sampling becomes more sparse at large distances. Because of this, we arbitrarily chose to limit our data set to z∼0.1. Using a program written by Brain Bucklein and refined by me, I searched through all spectroscopic data in the northern SDSS data set having a z∼0.1 to test for nearest neighbors. The program recorded the number of galaxies that were within 3, 6, 9, 12, and 15 Mpc of each galaxy. It then sorted them by the distance to the nearest galaxy.

Tables 2.1 and 2.2 show all galaxies with no neighbors within 12 Mpc. A glance at the table shows that most of them are distressingly close to the back-edge limit of z=0.10. Therefore they may have made the table only because their closest companions were excluded. Also, the fainter galaxies that are included in the mean volumes do not make the survey magnitude limits at the back edge, making it more sparse. So, isolated galaxies at the back edge are suspect.

Table 2.1 and 2.2 lists the the galaxies with z∼0.1. Out of more than 600,000, 10 of them had no detectable companions within 15 Mpc, and 46 of them had only a few companions within 15 Mpc. In the table we list their characteristics - RA, Dec, redshift (z), colors (G, U-G, G-R, R-I, I-Z), number of companions within 15 MPC (15), and the final column is the product of a function Brian Bucklein wrote to indicate the distance to the galaxy's nearest neighbor (NN). We used 'G' to describe a galaxy's color (rather than U, R, I, or Z) because 'G' is a good "middle-of-the-road" baseline for determining the brightness of the galaxy.

Observe in the table that different filters contain different values for magnitudes. This is due to the fact that each filter measures a flux ratio at two different wavelengths, and this produces a color! In data reduction techniques, the conventional method is to sort with the bluer color first (U - G). However, it is also a great starting point for this project, because void galaxies are classified as bluer galaxies.

Table 2.2 shows the rest of the 56 galaxies that we determined to be the most isolated in SDSS survey. Their objects are listed as most isolated to least isolated.

Table 2.1 Galaxies from SDSS-DR7 that were of initial interest because of their lack of companions. Ricky and Bobby are the first and second entries.

RA	Dec	z	G	U-G	G-R	R-I	I-Z	15	NN
252.633*	38.258	0.0452	17.557	1.29	0.53	0.25	0.20	6	13.3210
256.108*	65.163	0.0474	17.666	1.36	0.47	0.21	0.16	2	13.5204
156.454	7.2690	0.0914	17.619	1.78	0.90	0.36	0.31	0	12.1235
173.231	7.8230	0.0583	18.334	1.66	0.73	0.49	0.29	0	12.2633
176.450	7.8076	0.0557	16.803	1.47	0.64	0.35	0.22	0	12.2926
238.925	8.9243	0.0983	17.612	1.35	0.71	0.41	0.26	0	13.9117
250.538	44.389	0.0919	18.527	1.74	0.92	0.46	0.33	0	15.2605
165.545	60.481	0.0995	18.311	1.68	0.84	0.33	0.30	0	15.4155
178.321	43.467	0.0989	18.481	1.16	0.66	0.39	0.23	0	15.7906
208.550	29.342	0.095	17.908	1.32	0.63	0.36	0.22	0	15.8498
193.712	25.460	0.0998	18.156	1.64	0.84	0.39	0.29	0	17.3132
209.512	-2.165	0.0997	17.433	1.36	0.66	0.39	0.28	0	18.9843
139.763	-0.496	0.0958	18.116	1.27	0.67	0.40	0.26	1	14.0542
131.474	-0.336	0.0919	18.475	1.43	0.68	0.37	0.28	1	14.5529
156.663	23.316	0.0934	17.786	1.37	0.65	0.37	0.22	1	12.3792
205.236	66.482	0.0853	18.245	1.44	0.72	0.44	0.30	1	14.8497
201.875	53.922	0.0732	17.566	1.34	0.50	0.31	0.15	1	13.3702
161.612	66.720	0.0906	18.323	1.77	0.92	0.39	0.36	1	14.9366
120.682	45.057	0.0901	17.949	1.20	0.61	0.43	0.20	2	13.2450
211.933	30.403	0.0965	18.174	1.27	0.60	0.38	0.22	2	13.2481
150.261	70.172	0.0771	18.290	1.27	0.61	0.35	0.18	2	12.5251
144.860	20.397	0.0995	18.552	1.67	0.94	0.40	0.30	2	12.2762
164.278	34.215	0.0869	17.115	1.00	0.38	0.31	0.14	3	13.2495
171.818	39.850	0.0992	18.517	1.77	0.89	0.40	0.31	3	12.8567
216.650	7.7914	0.0996	18.245	1.38	0.63	0.39	0.27	3	13.6974
204.133	36.117	0.0998	18.077	1.56	0.93	0.47	0.36	3	12.2035
203.336	13.707	0.0994	18.585	1.58	0.79	0.42	0.33	3	12.5504
146.747	48.770	0.0948	18.324	1.28	0.65	0.39	0.20	3	12.5063
203.336	13.707	0.0994	18.585	1.58	0.79	0.42	0.33	3	12.5504

Table 2.2 Galaxies from SDSS-DR7 that were of initial interest because of their lack of companions.

RA	Dec	z	G	U-G	G-R	R-I	I-Z	15	NN
220.714	-2.184	0.0949	17.761	1.32	0.56	0.32	0.14	4	13.1950
156.254	33.453	0.0651	17.676	1.39	0.65	0.37	0.26	4	12.1742
145.553	68.480	0.0532	17.777	0.96	0.23	0.18	0.13	4	13.8436
248.425	24.736	0.0802	18.221	1.18	0.52	0.33	0.17	5	13.8459
173.281	11.807	0.0587	16.706	1.65	0.77	0.36	0.28	5	12.5588
191.003	15.160	0.0999	18.584	0.76	0.32	0.28	-0.03	5	12.2162
187.454	44.548	0.0919	17.176	1.89	0.94	0.44	0.36	5	12.2299
246.927	10.211	0.0678	18.655	1.39	0.81	0.39	0.28	5	12.6773
255.673	22.423	0.096	17.692	1.77	0.92	0.43	0.36	6	12.5493
175.694	40.691	0.0995	18.065	1.10	0.39	0.30	0.15	6	13.5102
170.023	13.241	0.0958	18.176	1.11	0.49	0.30	0.21	6	13.7358
229.733	57.079	0.0978	17.692	1.09	0.53	0.39	0.19	6	13.3180
145.892	18.140	0.0819	18.241	1.27	0.54	0.31	0.17	6	12.8659
214.195	34.706	0.0914	17.768	1.05	0.30	0.17	0.20	7	12.5440
147.197	10.608	0.0905	18.421	1.39	0.70	0.46	0.28	8	12.7834
158.879	15.400	0.0755	17.939	2.24	0.88	0.50	0.40	9	12.5479
204.349	53.824	0.0923	18.398	1.18	0.63	0.40	0.20	9	12.0054
165.520	31.327	0.0914	17.878	1.48	0.76	0.43	0.32	10	13.5023
168.822	51.457	0.0899	18.190	1.38	0.73	0.38	0.24	10	12.3251
133.325	64.796	0.0506	18.456	1.29	0.58	0.33	0.25	10	12.3400
184.407	68.743	0.1	18.234	1.10	0.62	0.38	0.21	10	12.0072
201.719	44.777	0.0961	18.220	1.97	0.91	0.38	0.32	11	13.8296
167.526	66.062	0.0926	17.613	1.20	0.53	0.39	0.22	12	12.1243
114.782	23.922	0.0614	17.888	1.78	0.81	0.45	0.27	14	12.4173
230.059	47.141	0.0912	18.624	2.04	0.93	0.44	0.36	17	12.6611
252.651	37.860	0.0806	18.017	1.11	0.45	0.29	0.18	20	12.1781
208.084	51.023	0.0763	17.675	1.16	0.50	0.27	0.15	21	12.0415
138.972	27.470	0.0566	18.386	1.55	0.67	0.32	0.27	22	12.0903

Observe how table 2.2 galaxies have quite a few more companions in their set, even for small changes in the NN value.

To be sure of the galaxies we investigate, we first condensed our search to galaxies with low redshifts. This way, we know they are closer to us and their companions are less likely to be too dim to make the survey. Their proximity increases the potential for discovering true void galaxies.

2.1.2 Ricky and Bobby

Two galaxies stood out, the only ones with a $z<0.05$. Affectionately named Ricky and Bobby, these two galaxies have remarkably low redshifts, peculiarly similar colors, and few companions within 12 Mpc. We decided that they are the best candidates to begin our investigation on void galaxies. In table 2.1, they are marked with a $*$.

Ricky and Bobby's redshifts are 0.0452 and 0.0474 respectively. In a data set where anything below 0.09 is rare, these two raised questions. Upon further investigation, we see that their colors are similar, Ricky has six companions in 15 Mpc and Bobby a mere two. Other galaxies in the sample set of similar brightness and larger redshift have quite a few more companions (see Table 2.2), so how are these so isolated? Are their companions truly too faint to make the survey magnitude limit? Were the galaxies that counted as companions for distant objects just visual companions? Either way, Ricky and Bobby display characteristics that are entirely unique, and deserve to be investigated as possible tracers for dark matter.

Table 2.1 shows the galaxies that are most isolated. Their NN values are the highest in all the tables, and we see that many have no companions within 15 Mpc. Ricky is the first entry and Bobby is the second. Observe how closely their colors correlate. We use this correlation later in the project.

We believe that objects that are companions to Ricky and Bobby will have similar characteristics and formation histories. If they have similar colors, we can deduce that they are potential candidates for void galaxies, and thus worth further investigation. Further discussion on Ricky and Bobby follows in section 2.3.

2.2 Methods

In order to insure these galaxies were isolated before we begin investigating, we must be careful in our considerations. Companion galaxies have similar formation histories and evolution. This means that their redshift, colors, distances, and sizes would all be linked. We must work backwards in this project. Searching for galaxies with similar colors to Ricky and Bobby should reveal other void galaxy candidates.

Can an isolated galaxy have a companion? Doesn't this defy the very idea of a galaxy being isolated? In our case, it might. For this research, however, we must simply redefine our idea of an isolated galaxy. Instead of the galaxy itself, our research would turn to the small clump of galaxies that formed apart from massive filaments and clusters. In fact, this could even explain how normal these galaxies seem (their spiral nature, bluish color, and high SFR rates). However, at this time our aim is solely to determine whether or not Ricky and Bobby are completely alone. Either way, both outcomes are unique and worthy of further investigation.

2.2.1 Distances

Determining distance is a crucial part of the project. If a galaxy is farther away, it is more likely to be biased in observations. That is, we will not detect companions or other significant features. Therefore, accurate distance measurements are vital. However, we cannot use the simple distance modulus equation (Eq. 1).

$$m_1 - m_2 = -2.5log(f_1/f_2) \tag{2.1}$$

Where m is an apparent magnitude of the objects, and f represents flux. Because of the inverse square law (Eq.2), we can replace the ratio of fluxes with a ratio of distances.

$$\frac{F_1}{F_2} = \frac{L}{4\pi d_1^2}\frac{4\pi d_2^2}{L} \tag{2.2}$$

We use this modified equation for different filters and a color index (Eq. 3).

$$m_1 - m_2 = -2.5log(d_2/d_1)^2 + (C_1 - C_2) \tag{2.3}$$

Ricky and Bobby have redshifts of 0.0452 and 0.0474 respectively. These two objects stand out significantly because out of more than 600,000 objects, they alone had no observable companions within 12 MPC, and both had considerably small redshifts. We allow a range of ±0.1 in their color and redshifts as we sort out possible companions. For example, the U-G value for Ricky is 1.29. Therefore, anything beyond 1.19 and 1.39 will be excluded in our data set as likely companions. A similar procedure is used for the redshift. This goes back to the link that similar objects have similar formation histories, and photometric redshifts. Also, redshift can be used to calculate distance through the Hubble Law (Eq. 4, Eq. 5). Thus, we can see how close similar objects are to us, and to each other.

$$v = cz \tag{2.4}$$

$$D = v/H_o \tag{2.5}$$

Through these means we know Ricky and Bobby are significantly closer to us than other objects in the survey. Since that is the case, we would also expect to see companions if there are any to be found. Whereas most objects in SDSS have a redshift of roughly 0.9 (±0.07), Ricky and Bobby's low z indicate their proximity to us. Therefore, they become even more interesting because they are bright, isolated and close. Ricky and Bobby are prime candidates for this research.

2.2.2 Size

The next criteria we will deal with is size. SDSS provides multiple ways of determining the size of any object; major axis, minor axis, flux ratio, surface brightness, isophotal, DeVaucouleurs fit scale radius, etc. We narrowed down the search for the right size to three types: Petrosian radius, Isophotal, and DeVaucouleurs. Each type is best for a specific type of galaxy. Petrosian is best for spirals, DeVaucouleurs works with elliptical, and Isophotal is good for the unknown.

Starting with the Petrosian radius, SDSS defines it as the shape of the average azimuthal light profile. From their website: "The Petrosian radius is defined as the radius at which [the Petrosian ratio] equals some specified value - 0.2 in our case." While Petrosian radius may be best for spirals, we are not sure that Ricky and Bobby can be classified as such, and are wary of using only this source for size determinations. Also, SDSS states that there are a number of complications from using Petrosian radius, ranging from noise, substructure, and finite sizes causing objects to have no Petrosian radius.

Next, the Isophotal radius, which is best for galaxies of an unknown type, is based off of the light measured from a specified surface brightness that also corresponds to about 1% of the average sky brightness [Sussex, 2000]. Isophotal radius is used only for galaxies. It measures a smaller fraction of the light of galaxies at high redshift and of low surface brightness [Eq. 6].

$$\frac{I}{(1+z)^{-4}} \tag{2.6}$$

Lastly, DeVaucouluers (DV) radius is best for elliptical galaxies. DV defines the radial light profile of an average elliptical, describing how the light varies as a function of distance from the center. This is shown in Eq. 7.

$$I(r) = I_0 e^{-7.67[(r/r_e)^{1/4}]} \tag{2.7}$$

In SDSS, the DV radius has a higher signal-to-noise ratio than the Petrosian radius, especially at fainter magnitudes. Also, SDSS has some weak model parameters in configuring the DV radius, which they say has yet to be fixed.

2.3 Images and Discussion

In the images below, Ricky and Bobby are circled in their first two images. Clearly, these objects are distant and faint. They are much too small to do any significant size or structure analysis. Without knowing the types of galaxies Ricky and Bobby are, it would be pointless to try and classify their supposed companions. Zooming in on the pictures shows other similarly small and more faint companions. It is impossible to know, however, whether these galaxies are only visual companions or if there is a real gravitational or evolutionary influence. Their size and faint luminosity suggests that they are most likely background objects. The frames below were taken with the 36 telescope at Brigham Young's West Mountain Observatory. They were all obtained May 30 2010.

In these images, we see different characteristics pop out in both the high and low resolution shots. High resolution yields details on morphology, neighbors, and

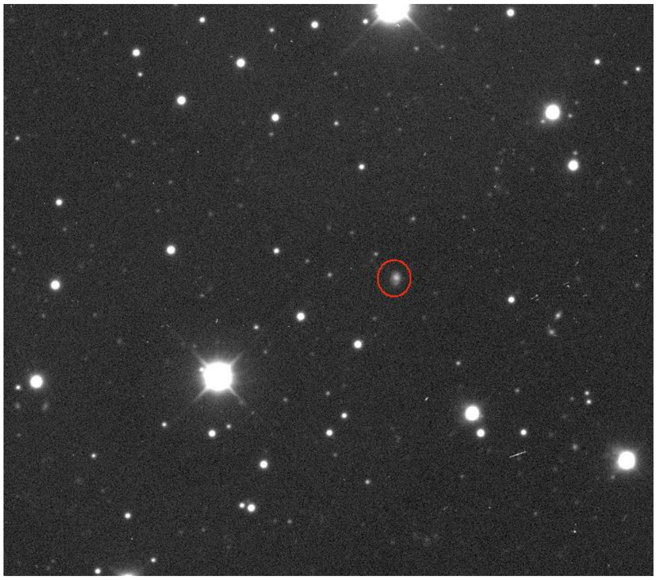

Figure 2.1 Potential void galaxy Bobby in high resolution. Image taken in the R filter. This was a 15 minute exposure.

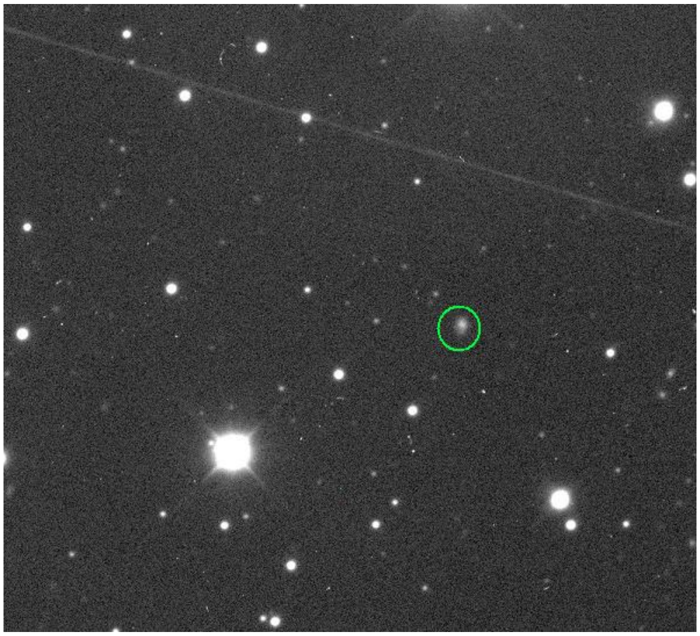

Figure 2.2 Potential void galaxy Bobby in high resolution. Image taken in the V filter. This was a three minute exposure.

possibly color. Here, however, the only thing we learn is about color. The faintness of Ricky and Bobby, even in high resolution, show that companions are few (if any)

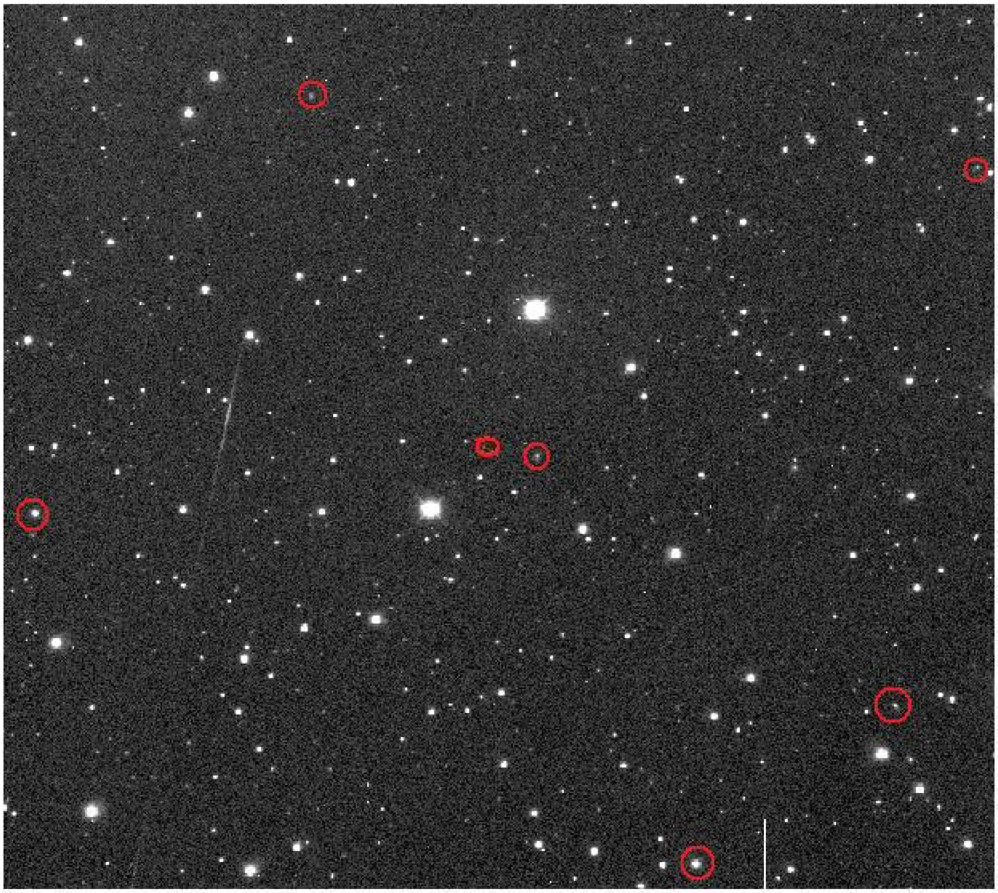

Figure 2.3 Potential void galaxy Bobby in low resolution. Image taken in the R filter. This was a three minute exposure, and is 20 on each side. Possible candidates for further void galaxy studies are also circled.

and structural details are not easily definable.

In the low resolution images, we see a much larger field and distribution of objects around Ricky and Bobby. Most of these objects are foreground stars with some galaxies in the mix. In the low resolution images, other objects of similar magnitude and size are circled. These objects are also good candidates for follow-up spectroscopy and study. If, when evaluated, they show properties similar to Ricky and Bobby, then the implications of so many void galaxies or void clusters in a small area is profound. It implies that there are many void galaxies in the universe. In that case, the possibility of gleaning more information about dark matter increases dramatically.

This particular data is somewhat inconclusive. This project requires high resolution, long exposures of Ricky and Bobby. In the future we plan to obtain better images of our two candidates. From there we can clearly define their physical characteristics and see any neighbors they might have. Any potential neighbors will also be prime suspects in seeing how dark matter affects evolution - whether they evolved in an isolated group, or as a truly isolated galaxy.

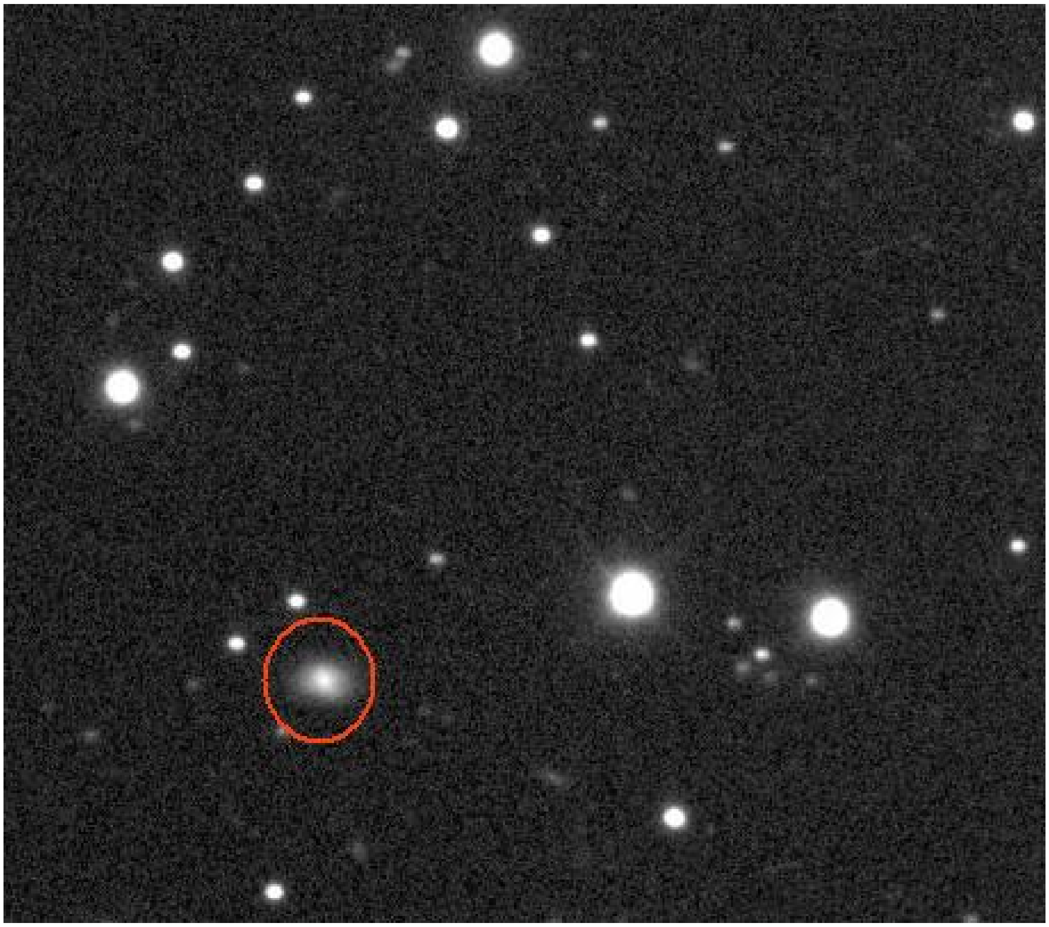

Figure 2.4 Potential void galaxy Ricky in high resolution. Image taken in the R filter. This was a 45 minute exposure.

The next course this research must take is to branch out from Ricky and Bobby and investigate their companions. Here, SDSS is magnitude limited, making it difficult to detect any neighbors. If, upon further research, we discover that Ricky and Bobby's

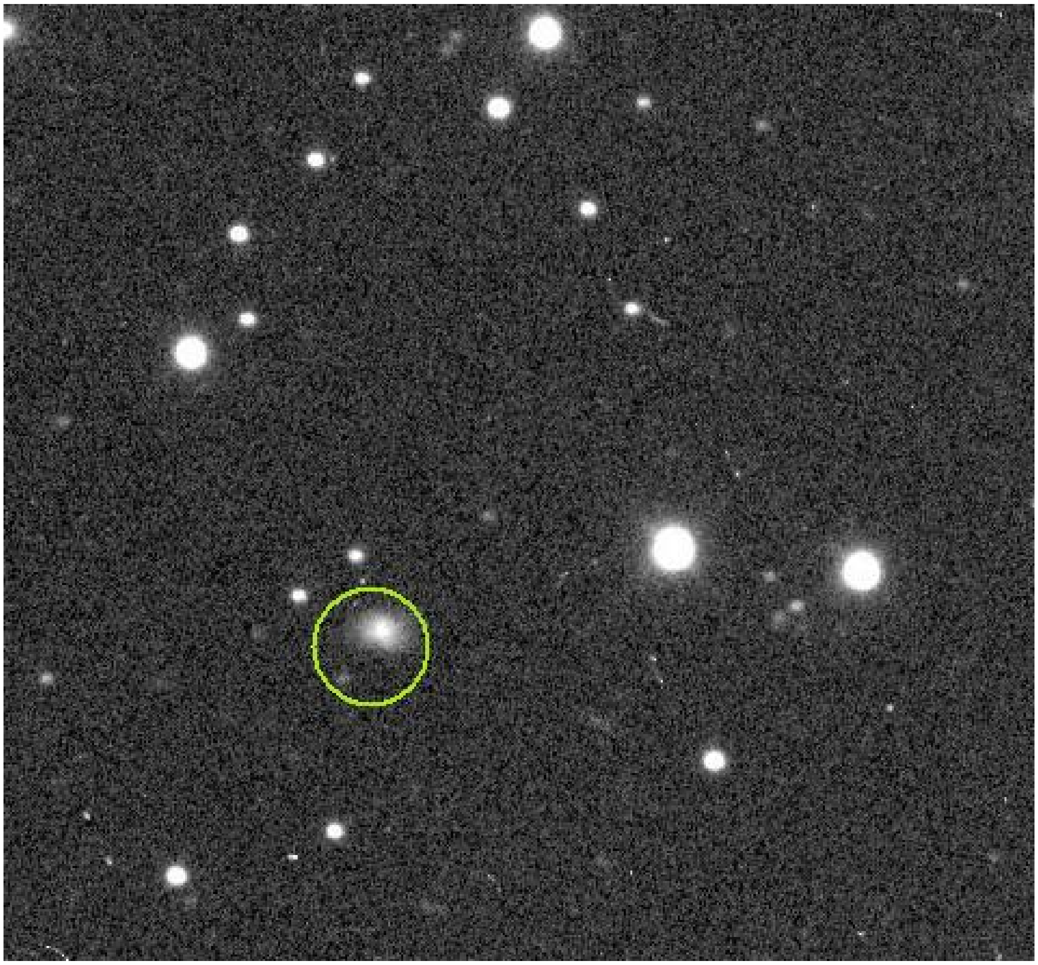

Figure 2.5 Potential void galaxy Ricky in high resolution. Image taken in the V filter. This was a nine minute exposure

companions are similar in magnitude, size, distance, and other photometric features, then we can conclusively state that these galaxies are possible tracers for the effects of dark matter.

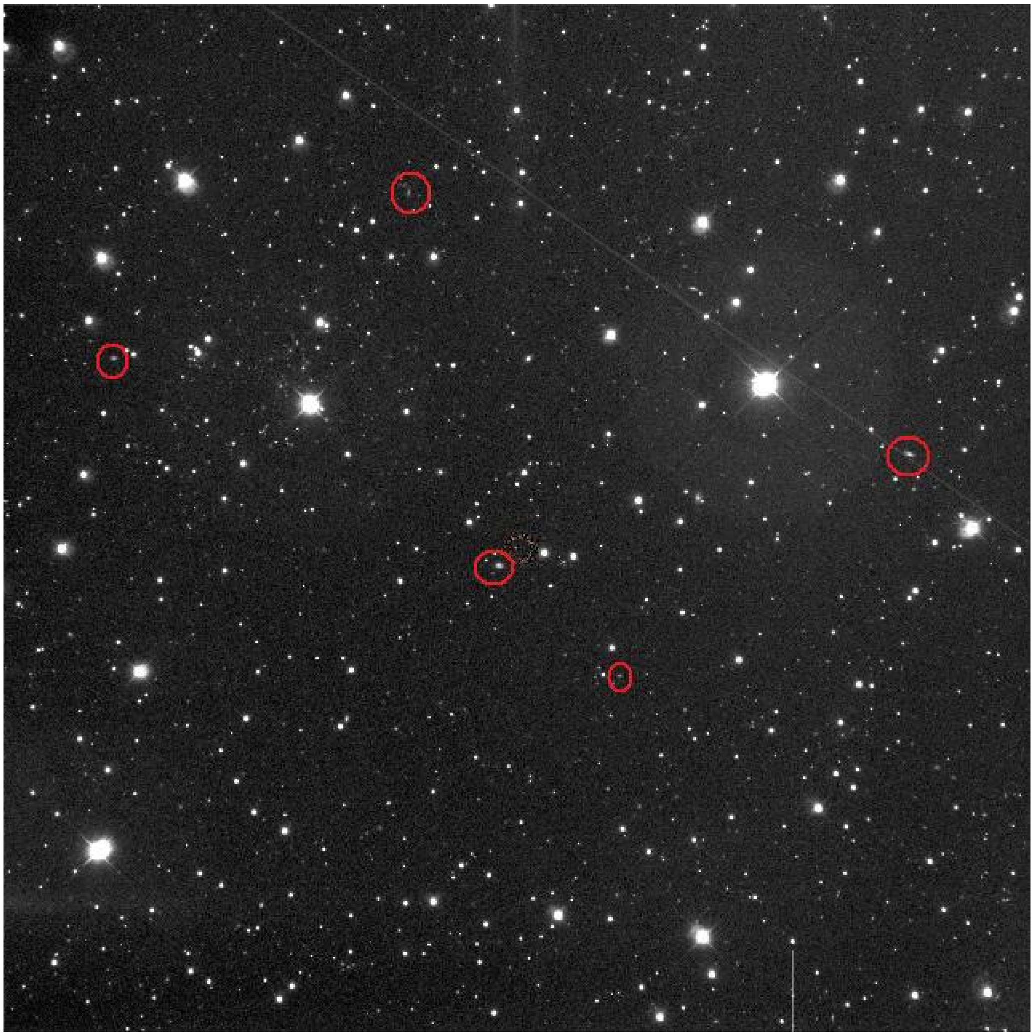

Figure 2.6 Potential void galaxy Ricky in low resolution. Image taken in the R filter. This was a 45 minute exposure, and is 20 on each side. Possible candidates for further void galaxy studies are also circled.

Chapter 3

Conclusion

3.1 Further Research

We aim to discover if the neighbors of Ricky and Bobby have significantly affected the structure and evolution of Ricky and Bobby. Whether or not they have is crucial. Among other things this will shed light on whether spiral structure demands companions (truly isolated spirals would argue against this), on the minimum gas density required for galaxy formation, and on the role of mergers in building up larger systems (void galaxies likely form later and would not have as much time to build up, thus being smaller). This research is significant to advancing understanding in the field of cosmology, and we believe it will shed light on many important details on galactic evolution.

The best candidates for isolated galaxies will be those with z less than about 0.08, in order to avoid the back edge of the magnitude limited survey and a no neighbors closer than 12Mpc. These candidates should be the starting point for spectroscopic and imaging studies to determine what companions they have. In this data set, Ricky and Bobby are the best candidates. Determining sizes of Ricky and

Bobby's companions is the final step in figuring out which galaxies are the most likely neighbors.

3.1.1 Conclusion

Void galaxies provide astronomers with unique and useful information about galaxy formation and evolution. This branch of astronomy has yet to be understood thoroughly. Our aim is to study these objects with more depth and hopefully discover the nature of dark matter. The work that has been accomplished so far serves as a stage-setter for the future research. In articulating the problem, searching through the literature, and identifying two viable candidates, we hope to see this project continue to develop. The cosmological community already knows that dark matter exists and that it actively affects our environments; this project aims to discover how.

This project is crucial because of the possible implications. If the scientific community is able to discover what dark matter is, and how it affects formation, evolution and mass distribution in galaxies, we are much closer to understanding the very nature of the beginning of our universe, as well as it's future. Dark matter also has inseparable ties to dark energy, which is believed to make up 75% of the universe. Through this research we come to understand more about the large-scale structure of the universe and its environment.

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