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Galactic Building Blocks: Searching for Dwarf Galaxies Near and Far

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Galactic Building Blocks:
Searching for Dwarf Galaxies Near and Far

Andrew Lipnicky

A dissertation submitted in partial fulfillment of the requirements for the
degree of Doctor of Philosophy in Astrophysical Sciences and Technology
in the College of Science, School of Physics and Astronomy

Rochester Institute of Technology

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July, 2017
Galactic Building Blocks: Searching for Dwarf Galaxies Near and Far

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Advisor: Dr. Sukanya Chakrabarti

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Astrophysical Sciences and Technology in the College of Science, School of Physics and Astronomy

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Dr. Jeyhan Kartaltepe
For my father.
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My work has been supported by the National Radio Astronomy Observatory under the Student Observing Support program project GBT 16B-285 and from National Science Foundation grant number 1517488.
I, ANDREW LIPNICKY ("the Author"), declare that no part of this dissertation is substantially the same as any that has been submitted for a degree or diploma at the Rochester Institute of Technology or any other University. I further declare that this work is my own. Those who have contributed scientific or other collaborative insights are fully credited in this Dissertation, and all prior work upon which this Dissertation builds is cited appropriately throughout the text. This Dissertation was successfully defended in Rochester, NY, USA on June 21, 2017.

A Chapter of this Dissertation has previously been published by the Author in a peer-reviewed paper appearing in the *Monthly Notices of the Royal Astronomical Society* (MNRAS):


A Chapter of this Dissertation will be submitted for peer-review and publication:

- **Chapter 3** is based on a paper entitled *Scaling Relations for Neutral Hydrogen Studies of Spiral Galaxies: Relating Density Structure to Passing Satellites* (in preparation), co-authored with Sukanya Chakrabarti (the Dissertation advisor), and collaborator Phillip Chang.

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- **Chapter 5** is based on a paper entitled *The First Detection of Neutral Hydrogen in Emission in a Strong Spiral Lens* (MNRAS, submitted), co-authored with Sukanya Chakrabarti (the Dissertation advisor), and collaborators Melvyn C. H. Wright, Leo Blitz, Carl Heiles, William Cotton, David Frayer, Roger Blandford, Yiping Shu, and Adam S. Bolton.
1. *The First Detection of Neutral Hydrogen in Emission in a Strong Spiral Lens*

2. *Galactoseismology: Discovery of a cluster of receding, variable halo stars*

3. *Is the vast polar structure of dwarf galaxies a serious problem for $\Lambda$ cold dark matter?*
The prevailing model of structure formation that describes how matter is distributed throughout the Universe is known as the $\Lambda$ cold dark matter paradigm. A key component of this paradigm is dark matter, which has so far gone undetected in laboratory experiments but is inferred from a wide variety of astrophysical observations. Although the cold dark matter paradigm is extremely successful on large scales, there are significant differences between what computer simulations predict and what we observe on galaxy scales. The purpose of the work presented in this Dissertation is to address some of the issues surrounding the current structure formation paradigm and further develop some tools for investigating small scale structure. An issue that has caused recent controversy is known as the Planes of Dwarf Galaxies problem which describes the curious alignment of the Milky Way’s dwarf galaxies into a thin planar structure. We have investigated this structure through time by integrating their orbits using the latest proper motion data as well as compared the distribution with current cosmological simulations and found no significant difference between the Milky Way distribution and simulations.

Through analysis of observations of the disturbances in the extended neutral hydrogen disks of spiral galaxies, one can characterize dark matter substructure and the dark matter halo of a host galaxy. This process is called Tidal Analysis. Using a simple test particle code to model satellite interactions with a gas disk, we have developed a scaling relation to relate the observed density response of the disk to the mass and pericenter of a satellite. With this relation, observers can now immediately infer the recent interaction history of a spiral galaxy from neutral hydrogen studies. Changing gears to observational studies of small scale structure, we report observations of Cepheid variables in a putative dwarf galaxy located along the line of sight of the galactic plane that was first predicted through the use of Tidal Analysis. Observations are still ongoing; however, preliminary results indicate that the Cepheids are part of structure that is moving independently of the Milky Way. Finally, in an effort to use Tidal Analysis on other galaxies to constrain substructure, we have begun a 21-cm radio observing campaign of a set of spiral galaxies at redshift $z \sim 0.1$ to obtain their total mass in neutral hydrogen. This unique set of galaxies also act as strong gravitational lenses, thus allowing us to use both Tidal Analysis and gravitational lensing together for the first time. We report a secure detection and mass measurement for one of our sources and six upper mass limits.
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1.1 The Birth of Dark Matter

As early as the 1930’s, we have seen evidence of dark matter. One of the first scientists to observe its effects was Fritz Zwicky (1933, 1937) when he measured the radial velocities of the galaxies within the Coma cluster and found that they had velocities on the order of 1000 km $s^{-1}$. Although their velocities appeared great enough to escape the cluster, the cluster was clearly a gravitationally bound structure. When he added up the mass from all the luminous material within the cluster, he found that it was insufficient to contain these fast moving galaxies. From their motions, he deduced the amount of mass within the cluster that would be needed to contain them and it was well in excess of the mass deduced from light. He called this large amount of missing mass in the cluster “dunkle Materie” and thus coined the term “dark matter.” Jan Oort (1927) also saw evidence of dark matter by observing the rotational velocities of local stars in the Milky Way and found them to be traveling faster than would be predicted.

In a theoretical study of disk galaxies, it was noted by Ostriker & Peebles (1973) that disk galaxies are extremely unstable and should disrupt or show large scale bar-like structures unless there is a large halo of material present. However, distinct evidence of a large halo of material
Figure 1.1: The data shown is a model fit to radial velocity observations of four galaxies presented in de Blok et al. (2001). This level feature of the velocity curve is seen in almost all spiral galaxies and leads to the term “flat” rotation curves.

was not observed until Bosma (1978) and Rubin et al. (1978) measured of the rotation curves of spiral galaxies. These observations were the first clear indication for the presence of dark matter in individual galaxies. As seen in the solar system typical of Keplarian motion, it was expected that stars and gas far from the galactic center would travel more slowly than material closer to the center. However, it was seen that far beyond the scale length of typical spirals (~few kiloparsecs [kpc]), material travelled at a more-or-less constant speed up to very large distances, leading to the term “flat” rotation curves (Fig. 1.1). It became apparent that either we did not fully understand gravity at very low accelerations or that there must be much more mass beyond the optical edge of galaxies in the form of dark matter. This second option further implies that each galaxy must reside inside a massive dark matter “halo” of material, which we can only observe through its gravitational effects. It was not immediately clear what mechanism caused such flat rotation curves, whether there was matter that was not easily detectable such as binaries, dust, black holes, etc. (Einasto et al., 1974; Ostriker et al., 1974) or something more exotic.

Soon after Vera Rubin’s discovery, it was found that the smallest galaxies around the Milky
Way, the dwarf spheroidals, also showed signs of being located within larger dark matter haloes (Aaronson, 1983; Faber & Lin, 1983). These galaxies are very metal poor, have extremely low surface brightnesses, contain very few stars, almost no gas, and their stars travel well in excess of inferred escape velocities yet they still remain bound. If these objects only contained baryonic mass in the form of stars, then typical escape velocities would be $v_{\text{esc}} \sim \text{few km s}^{-1}$ while measured velocity dispersions are on the order of $\sigma_* \sim \text{tens km s}^{-1}$ (Simon & Geha, 2007; McConnachie, 2012). Recent observations have provided even further evidence for large amounts of dark matter in these objects with some dwarf galaxies having dark matter halo masses $\sim 1000$ times greater than the amount of baryonic mass (e.g., Willman et al., 2005; Belokurov et al., 2006; Walsh et al., 2007; Willman et al., 2011; Koposov et al., 2015).

In the late 1920’s, another strange phenomenon was discovered: distant galaxies appeared to be uniformly moving away from us. Albert Einstein’s field equations of general relativity (Einstein, 1915) had predicted a non-static universe that would either expand forever or contract back upon itself due to gravity; however, Einstein himself disliked this solution and thus included a “cosmological constant”, $\Lambda$, that forced the universe to be static. However, evidence of expansion was seen in 1929 when Edwin Hubble published his findings of the radial velocities of 46 distant galaxies (Hubble, 1929). He saw a clear, linear relation between radial velocity and distance, with more distant galaxies receding from us faster than nearby galaxies. This became known as “Hubble’s Law” where the Hubble constant, $H_0$, is observed to be $H_0 \sim 70$ km s$^{-1}$ Mpc$^{-1}$. We now know that the universe is expanding at an accelerating rate from the observations of distant supernova and therefore $\Lambda$ has a positive value (Riess et al., 1998; Perlmutter et al., 1999). We call this constant “dark energy” which acts like a universal pressure, pushing the universe apart making the distances between gravitationally bound structures grow.

In order to explain the existence of dark matter, the expansion of the universe, elemental abundances, the abundance of structure in the universe, and a slew of other astrophysical phenomena, Lambda Cold Dark Matter ($\Lambda$CDM) theory was introduced (White & Rees, 1978; Pagels & Primack, 1982; Blumenthal et al., 1982, 1984). In this theory, locally over dense regions of cold dark
matter ("cold" referring to its ability to collapse i.e., kinematically cold) collapsed into spherical structures before the recombination of baryons occurred. The dark matter is thought to consist of some as-of-yet unknown particle that interacts with baryonic matter only through gravity and has an interaction cross section that is extremely small. According to theory, just after the creation of the universe, photons had enough energy to ionize atoms (mostly hydrogen and helium) and radiation pressure supported the universe against collapse. At that time, dark matter began to collapse into spherical halo structures since it is unaffected by baryonic matter. Eventually, the photons cooled enough for atoms to recombine at which point the universe became transparent and baryonic matter was able to collapse. The radiation that previously supported the universe against collapse escaped and became the cosmic microwave background that we observe today – the most distant light that we can observe (Penzias & Wilson, 1965). The dark matter halo structures that had formed created gravitational potential wells into which baryonic matter fell. These haloes were the seeds of the first galaxies and in the hierarchical scheme of \(\Lambda\)CDM, small galaxies and clumps of matter merged to create larger and larger galaxies. Thus, dwarf galaxies reside in small dark matter haloes that have not yet merged with larger ones.

1.2 Gravitational Lensing

Further evidence for dark matter was also seen in gravitational lensing analyses. Much like a glass lens refracts light rays as they travel through the material, Einstein predicted that light would be deflected by massive objects which could act as a type of lens (Fig. 1.2). This deflection would be twice as large as expected from Newtonian mechanics due to general relativistic effects and in 1919 the effect was seen during a solar eclipse when the positions of the stars of the Hyades star cluster were deflected by almost 2" (Dyson et al., 1920). The amount of lensing which occurs is directly proportional to the amount of mass contained within the lens as defined by the Einstein
angle below:

\[
\theta_E = \left( \frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S} \right)^{1/2},
\]

(1.1)

where \( G \) is the gravitational constant, \( c \) is the speed of light, \( M \) is the mass of the lens, \( D_{LS} \) is the distance between the lens and the source, \( D_L \) is the distance between the observer and the lens, and \( D_S \) is the distance between the observer and the source. Because of this direct relation between deflection angle and mass, when we look at galaxies and galaxy clusters that are gravitationally lensing a background object the amount of deflection gives us a direct measure of the mass contained within the Einstein angle. This mass is always much larger than the visible baryonic matter. However, due to the low probability of alignments and the small scale at which light becomes bent, it was not until Walsh et al. (1979) that the first observational evidence of strong gravitational lensing was found. Since then, advances in technology and large scale surveys have led to the discovery of hundreds of strong lensing systems from galaxy clusters to individual galaxy sized lens systems.

Depending on how well the background and foreground sources align, the background source may be either brightened (magnified) or dimmed (demagnified). For very well-aligned lenses, we can obtain a wealth of information about the distant object, gaining knowledge about highly redshifted objects that we normally would not have access to (e.g. Livermore et al., 2015). We will see later in Chapter 5 the difficulties associated with observing neutral hydrogen in the relatively nearby universe \((z \lesssim 0.2 \text{ or } \lesssim 1 \text{ Gpc})\); however, with upcoming radio interferometers it may be possible to observe neutral hydrogen out to a redshift of \( z \gtrsim 2 \) with the help of strong lensing (Deane et al., 2015). By examining the structure of the bent light, it is possible to determine the properties of the galaxy acting as the lens. Assuming that the host galaxy acting as a lens has a smooth potential, substructure will cause fluctuations that are detectable as anomalous structure in the lensed images. This type of analysis has led to the detection of substructure in distant galaxies (e.g.
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![Diagram of gravitational lensing](image)

Figure 1.2: A schematic of strong gravitational lensing. Light from the object on the right is emitted in all directions. As it travels away from the source, it encounters the strong gravitational field of a massive object (the large, light blue sphere around the “Deflector”) and changes direction due to the presence of the lens. Because of this interaction, light that would have missed the observer in the absence of a deflector (the dashed lines) gets observed instead. A perfect alignment, as shown here, will create a ring of light around the Deflector known as an Einstein ring.

Vegetti et al., 2012; Inoue et al., 2017). At high redshifts ($z > 2$), strong gravitational lensing can also be used to constrain different models for the dark matter particle due to the presence of structure along the line of sight (Inoue et al., 2017; Li et al., 2017; Nierenberg et al., 2017; Sawala et al., 2017)

With the advent of high quality panoramic imaging cameras, microlensing events can now be detected and studied. These events occur when a dark foreground object passes along the line of sight to a distant star. For a short period of time the distant star appears to grow brighter due to the magnification effect of gravitational lensing before returning to its former state. These events are also extremely rare due to the need for precise alignment of two point sources. However, it was suggested that a large amount of baryonic material in the form of black holes, neutron stars, brown dwarfs, and white dwarfs, could explain much of the missing mass in the haloes of galaxies (Paczynski, 1986). These objects were termed MACHOS for “Massive Compact Halo Objects”. However, this scenario was soon ruled out as very few events were detected and theory placed tight
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constants on the amount of baryonic matter that was allowed in the universe (Graff & Freese, 1996; Alcock et al., 2000; Fields et al., 2000; Tisserand et al., 2007). These results indicated that no more than a few percent of the dark portion of the galactic halo consists of MACHOS and a more exotic explanation of dark matter is necessary.

The final form of gravitational lensing is in the form of weak lensing. Since most lines of sight through the universe do not pass by a strong gravitational lens, the deflection of light due to the gravity well of a cluster or galaxy is very slight. This slight deflection, known as shear, causes the shape of background galaxies to elongate. If we assume that there is no preferred direction in the universe, averaging the projected shapes of randomly oriented galaxies should yield a circle, but in the presence of lensing the averaged signal yields an ellipse. Therefore the effect is undetectable in individual background galaxies but when averaged over ~thousand galaxies, it is clearly seen (Massey et al., 2010).

Weak gravitational lensing has provided some of the most definitive evidence for the existence of dark matter through the observations of merging galaxy clusters. During mergers of galaxy clusters, the dark matter and individual galaxies are effectively collisionless. Meanwhile, the massive, extended X-ray haloes of the clusters are affected by ram pressure and are therefore displaced towards the center of mass of the two systems while the dark matter and galaxies remain spatially coincident (e.g. Tormen et al., 2004). If there were no dark matter in these systems, weak lensing would show that the majority of the mass lies in the X-ray gas; however, in ΛCDM the mass of the X-ray gas is small (~10%) compared to the mass in dark matter. Weak lensing has shown in many systems that the concentration of the mass lies with the galaxies and not in the center of mass, definitively showing that large amounts of dark matter must be present in these systems (Clowe et al., 2004; Markevitch et al., 2004; Bradač et al., 2008; King et al., 2016).
1.3 Simulations

1.3.1 Dissipationless $N$-body Codes

The nature of cold dark matter and the growth of structure in the universe is a well-posed problem that lends itself extremely well to large $N$-body simulations. These simulations consist of billions of particles that feel the gravitational effect of every other particle in the simulation and therefore model dark matter particles extremely well. Since the inception of ΛCDM, astronomers have worked to model the universe via such large numerical simulations (e.g. Davis et al., 1985; Warren et al., 1992; Navarro et al., 1997). Some notable examples include the Millennium simulations (Springel, 2005; Boylan-Kolchin et al., 2009), the Aquarius Project (Springel et al., 2008), and Bolshoi (Klypin et al., 2011) simulations but many others exist. These very large N-body simulations assume initial conditions motivated by the analysis of the cosmic microwave background radiation as observed by the Wilkinson Microwave Anisotropy Probe satellite (WMAP) (Bennett et al., 2003; Spergel et al., 2007; Larson et al., 2011; Bennett et al., 2013; Hinshaw et al., 2013) and earlier probes of the cosmic microwave background (Bennett et al., 1996). Since dark matter particles are thought to not interact directly with baryonic matter except through gravity, the inclusion of baryons was originally neglected, making these simulations dissipationless meaning that gas dynamics and dissipative effects are not included. The simulations start at large redshifts ($z \sim 1100$), with an overall smooth distribution of particles with small perturbations. As the simulation marches forward in time, these small perturbations are amplified by gravity producing the rich structures that we see at low redshift.

These codes have led to the discovery of the universal nature of the dark matter halo. From dwarf galaxy to galaxy cluster scales, the density profile of the dark matter halo is consistent in simulations and is now known as the NFW halo (Navarro, Frenk, & White, 1997). Simulations have also given detailed predictions for the large scale structure of the universe. One of the most successful simulations at recreating large scale structure is the Millennium simulation, which was able to successfully recreate structures such as the Sloan Great Wall, filaments, and loops as well
as exceptionally matching the observed two-point correlation function, which describes the large scale distribution of galaxies probabilistically (Springel et al., 2005, 2006).

These large scale simulations often take months to complete because they are so computationally expensive. In order to keep computation time reasonable, each particle represents millions of solar masses \( (M_\odot) \) of material. As a result, while these simulations have been exceedingly successful on large scales, many problems exist when comparing simulations to observations on scales less than 100 Mpc. Some examples of the more famous issues at small scales are the Missing Satellites, Planes of Satellites, and Cusp-Core problems, all of which call into question the validity of \( \Lambda \)CDM as the correct structure formation theory and will be discussed in detail in Section 1.4. However, it was argued that at these resolutions, small scale structure cannot be adequately reproduced since, for example, the smallest dwarf galaxies cannot be resolved as some dwarfs only weigh a few million solar masses (Mateo, 1998) and would therefore have to be represented by only a few particles. Thus, many of the problems appeared to stem from the lack of adequate resolution on small scales. Furthermore, typically only dark matter was considered in these large-scale simulations which, as we will see later, neglects very important physical processes.

### 1.3.2 Hydrodynamic Codes

Recently, there has been a large push to include baryonic physics in simulations to overcome the many problems seen in pure dark matter simulations. Some groups have attempted to use smoothed-particle hydrodynamics (SPH, Gingold & Monaghan, 1977; Lucy, 1977) codes which model fluids as particles that carry information about their environment. Using these codes, one can model the effects of radiative cooling, star formation, energy feedback from star formation and supernova, gas accretion, metallicity evolution for various elements, and other physical processes (e.g. gadget, Springel, 2005). However, these codes fail to properly model shocks and contact discontinuities that arise during supernova, star formation, and mergers (Springel, 2010). Another method that has been applied has been the use of adaptive mesh refinement (AMR) to solve the Eulerian equations of fluid dynamics. These simulations take place on large grids where each grid
cell is solved individually, if enough material is contained within a cell to exceed some predefined criteria, the cell gets split up into smaller and smaller sections so that it has finer resolution where it is needed and computation time is not wasted on empty areas of space. However, these codes fail to accurately model structure formation when it is driven by very small gravitational instabilities along with many other problems related to the maximum level of refinement and the discontinuous way AMR handles resolution (O’Shea et al., 2005; Heitmann et al., 2008). Currently, the best simulations use a combination of both SPH and AMR known as a “moving mesh” method which allows the grid to change shape depending on fluid motions and allows for better handling of the downfalls of each method described above (e.g. AREPO, Springel, 2010).

To date, the largest simulation to include both dark and baryonic matter is the ILLUSTRIS simulation, which followed galaxy evolution through time spanning the age of the Universe (Genel et al., 2014; Vogelsberger et al., 2014). However, it too suffers from resolution issues for the smallest of dwarf galaxies (Haider et al., 2016). In order to overcome resolution issues and to better understand our own galaxy for which we have the best observational measurements, many groups have attempted to model the Local Group in isolation with both dark matter only and dark matter+baryonic codes (e.g., Diemand et al., 2007a; Springel et al., 2008; Garrison-Kimmel et al., 2014; Schaye et al., 2015; Crain et al., 2015). However, even with many different models, no one group has successfully reproduced the Local Group and solved all the many problems at small scales. The continuing issues that ΛCDM theory has with reproducing the observed Local Group in simulations has called into question its validity as the correct structure formation theory (e.g., Kroupa et al., 2010; Boylan-Kolchin et al., 2012; Kroupa, 2012; Pawlowski & McGaugh, 2014; McGaugh, 2015).

In the following sections, we will discuss the many issues that ΛCDM faces at small scales that arise in simulations and their current statuses.
1.4 The Many Problems With ΛCDM at Small Scales

1.4.1 The Missing Satellites Problem

Perhaps the most famous issue with ΛCDM, and an issue that we will discuss at length, is known as the Missing Satellites problem. According to simulations, hundreds of dark matter subhaloes\(^1\) reside around large, Milky Way-sized haloes and yet only a small fraction of that predicted number has been observed in the Local Group (Klypin et al., 1999; Moore et al., 1999). Furthermore, observations out to high redshifts ($z = 1.5$) show that Milky Way-like galaxies have consistent numbers of large dwarfs and, therefore, similar dwarf galaxy populations (Nierenberg et al., 2016). This has been deemed the “Missing Satellites” problem and poses a significant problem for ΛCDM cosmology. Large surveys such as the Sloan Digital Sky Survey (SDSS) have begun to alleviate this problem somewhat in the Milky Way as more of the sky gets mapped at deeper levels. Currently, SDSS is in its thirteenth data release and has only mapped 35% of the sky covering mostly the galactic poles, where the dust and gas in the plane of the Milky Way does not pose a problem for optical observations (Alam et al., 2015; SDSS Collaboration et al., 2016). Therefore, observational incompleteness is a factor that must be considered.

Recently, there has been a significant number of ultra-faint dwarfs discovered around the Milky Way through the use of various sky surveys (e.g. Willman et al., 2005; Belokurov et al., 2006; Zucker et al., 2006b,a; Willman et al., 2011; Bechtol et al., 2015; Kim et al., 2015; Koposov et al., 2015; Drlica-Wagner et al., 2016; Homma et al., 2016, 2017). One of the more recent discoveries by Homma et al. (2016) has shown that even a dedicated sky survey like SDSS, for the faintest of dwarfs, is only complete out to about 30 kpc. Due to survey incompleteness and obscuration from the Milky Way’s disk, it is estimated that nearly a third of the total population (Willman et al., 2004) of dwarfs could be hidden and some have even estimated the total number of dwarfs to be greater than 300 based off the current distribution (Walsh et al., 2009). However, even with

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\(^1\)A note on terminology: dwarf galaxies will be referred to as either dwarfs or satellites, while small scale structures seen in simulations will be referred to as either subhaloes or satellites. In general, theoretical satellites are subhaloes while the term “dwarf” is reserved for observed systems.
Figure 1.3: A cumulative histogram showing the number of satellites contained within a specific radius. Displayed in green is the number of dwarfs around the Milky Way that were known as of 2016. Displayed in red and blue are the numbers of subhaloes large enough to plausibly contain a dwarf galaxy from the Via Lactea II (red; Diemand et al., 2007a) and ELVIS (blue; Garrison-Kimmel et al., 2014) simulations.

the discovery of the many ultra-faint dwarfs, the predicted and observed numbers of galaxies do not agree. Fig. 1.3 shows how the number of dwarfs within a given radius around the Milky Way compares to two well known cosmological simulations: Via Lactea II (vlii; Diemand et al., 2007a) and Exploring the Local Volume in Simulations (ELVIS; Garrison-Kimmel et al., 2014). The number of dwarfs around the Milky Way contains all those dwarfs confirmed as of 2016. As you can see, there are just over 50 dwarfs within 300 kpc of the Milky Way, while simulations show up to ~800 subhaloes capable of containing a dwarf galaxy within 300 kpc.

Another potential solution for the Missing Satellites problem involves reducing the efficacy of dwarf galaxy production. In fact, many different processes are thought to inhibit dwarf formation. This is done through the inclusion of baryonic processes such as ultra-violet (UV) heating during
the era of reionization, supernova feedback, stellar winds, and tidal and ram pressure stripping. Photoionization of gas during early times of the universe suppresses gas cooling and raises the thermal pressure thus preventing gas from accreting onto small dark matter haloes (Simon & Geha, 2007; Okamoto et al., 2010; Boylan-Kolchin et al., 2012). As a subhalo that may have accreted mass travels through the interstellar medium of a larger host galaxy, ram pressure can strip the low mass halo of gas (Simpson et al., 2013) and then tidal stripping can remove dark matter from the halo (Kravtsov et al., 2004). Dwarf galaxies have shallow gravitational potential wells, therefore supernova winds can push gas out of galaxies along with strong winds from young stars (Wise & Abel, 2008; Okamoto et al., 2010; Boylan-Kolchin et al., 2012; Simpson et al., 2013). This process is also thought to be the reason that observations of the stars in dwarfs yield extremely low metallicities since the winds via supernovae inhibit further star formation thus suppressing further star formation.

All these mechanisms have proven effective at recreating the observed luminosity function of the Milky Way’s dwarf galaxy population, successfully giving the number of dwarf galaxies per luminosity interval; however, no unique solution exists (Nierenberg et al., 2016). Perhaps the most popular method of reducing the efficiency of dwarf galaxy growth is through the effect of reionization (Bullock et al., 2000; Somerville, 2002; Simon & Geha, 2007; Simpson et al., 2013; Weisz & Boylan-Kolchin, 2017). If material was not able to accrete efficiently onto smaller dark matter haloes after the universe reionized during the formation of the first stars, then only those subhaloes which had collected enough mass to form stars would be seen as dwarf galaxies today. The remaining subhaloes would thus only contain trace amounts of gas or be completely free of baryons (Tollerud et al., 2008). Some of the successful dwarfs would suffer from tidal effects and be stripped of material leading to the smallest dwarfs we see today, the ultra-faints. Simon & Geha (2007) investigated this effect and found that reionization worked extremely well at recreating the observed Milky Way population at the faint end but did fail at the high mass end.

In an attempt to understand why some dark matter haloes could have failed to form stars, Kravtsov et al. (2004) performed simulations where they considered tidal effects on dark matter
haloes. They arrived at the conclusion that many subhaloes suffered dramatic mass loss leading to a decrease in maximum circular velocity. Observations of the smallest dwarf spheroidals lead us to believe that there is little reason for stars to form in such shallow potential wells; however, if tidal stripping of the dark halo is considered then it is reasonable that these systems could form at earlier times when they were more massive. It was suggested that the most luminous dwarf galaxies belong to the most massive subhaloes (Kravtsov et al., 2004), which leads to the implication that there is a natural lower limit to the size a dark matter halo can be and still form a galaxy. However, it seems that this is not the case as kinematic studies do not support this (Simon & Geha, 2007; Boylan-Kolchin et al., 2011).

Another theory of how to create dwarf galaxies is through the process of tidal stripping of large galaxies; a factor that possibly inflates the Missing Satellites problem because it leads to the possible existence of tidal dwarf galaxies (e.g. Lelli et al., 2015). Through observations, it is obvious that interacting galaxies can be connected by streams of matter or “bridges” (Zwicky, 1956). These tidal tails experience forces from both galaxies and can collapse into bound structures. These structures can have large masses ($M < 10^9 \, M_\odot$) and can survive for timescales of about $10^9$ years with long lasting star formation; therefore, the structures in the tidal tails can become or be thought of as galaxies (Dabringhausen & Kroupa, 2013). In fact, it has been speculated by Dabringhausen & Kroupa (2013) that possibly all dwarf elliptical galaxies are in fact tidal dwarf galaxies devoid of dark matter and that a modified theory of gravity (Milgrom, 1983) must be used to explain their kinematics rather than dark matter.

1.4.2 Too Big To Fail?

The under-abundance of observed massive dwarfs around the Milky Way is also a known problem and has been dubbed the “Too Big To Fail” problem (Boylan-Kolchin et al., 2011, 2012). It arises from the fact that simulations predict the presence of many ($\geq 5$) massive subhaloes about the size of the Large Magellanic Cloud (LMC), far more than the observed number of massive dwarfs around the Milky Way (Wang et al., 2015). Although related to the Missing Satellites problem, this
problem arises from the fact that the satellites seen in dark matter simulations are extremely dense and therefore not susceptible to stripping of material either through tidal stripping or reionization processes. Thus, the largest satellites seen in simulations are incompatible with the largest dwarfs around the Milky Way and too large and dense to not have formed successful galaxies. Therefore, the Too Big To Fail problem is more related to issues of subhalo structure rather than abundance (Dutton et al., 2016). If these massive subhaloes actually exist around the Milky Way, how could they fail to successfully form dwarf galaxies?

It has been speculated that some of the problem may be caused by observational bias. Yniguez et al. (2014) studied the distribution of luminous dwarfs ($L_V > 10^5 \, L_\odot$) around both the Milky Way and our galactic neighbor, M31, and found that within 100 kpc the two distributions were equal but outside of 100 kpc the two distributions differed greatly. M31 has a more-or-less constant trend in the number of dwarfs per radius while the Milky Way has only a few luminous dwarfs at distances greater than 100 kpc. This led Yniguez et al. (2014) to conclude that this is evidence of an incomplete sample of luminous dwarfs around the Milky Way due to the presence of the obscuring disk of the Milky Way and lack of complete, deep survey data especially in the galactic disk. In Chapter 4 we will look at a large putative dwarf galaxy that has been reported by Chakrabarti et al. (2016); the possible dwarf lies directly in the plane of the Milky Way and has escaped previous detection due to its location.

Another potential solution to the Too Big To Fail problem comes from our knowledge of the mass of the Milky Way, which is currently very poorly constrained, and could help explain the scarcity of the missing massive satellites. Studies of the Milky Way’s mass have varied wildly (see Fig. 1 of Wang et al., 2015) but measurements lie within the range of $\sim (0.7 - 2) \times 10^{12} \, M_\odot$ (Watkins et al., 2010; Deason et al., 2012; Boylan-Kolchin et al., 2013; Wang et al., 2015). If the Milky Way is on the low mass side of the current observational limits, it would better agree with simulations that show that lower mass host galaxies have fewer massive satellites around them (Gibbons et al., 2014; Lovell et al., 2017).
1.4.3 Planes of Dwarf Galaxies

We have known for a long time that the distribution of bright satellites around the Milky Way is anisotropic (Kunkel & Demers, 1976; Lynden-Bell, 1976). The brightest satellites appear to be preferentially aligned in a thin distribution, perpendicular to the Milky Way’s stellar disk. It was originally deemed the “Magellanic Stream” and it was proposed that it may be the remnant of an encounter with a much larger Magellanic Galaxy that was broken into several smaller dwarfs and streams on a first passage around the Milky Way (Lynden-Bell, 1976). With the advent of modern surveys, it was seen that many more dwarfs also seemed to preferentially lie in the polar regions of the Milky Way. The curious alignment of the 11 brightest dwarfs, known as the “classical” dwarfs, came to be called the “Disk of Satellites” (Kroupa et al., 2005). The additional perpendicular alignment of some of the ultra-faint galaxies, globular clusters, and stellar and gaseous streams has been deemed the “Vast Polar Structure” (VPOS; Pawlowski et al., 2012).

Even more curious, the Milky Way does not seem to be alone in having an anisotropic distribution of dwarfs. The satellites of M31 are also distributed anisotropically (Metz et al., 2007) and also appear to form a thin plane (Conn et al., 2013; Ibata et al., 2013). Using distance measurements based on the red giant branch tip of dwarf galaxy stellar populations, Conn et al. (2013) and Ibata et al. (2013) were able to produce a three dimensional map of the dwarf galaxies around M31 out to 150 kpc. After a thorough statistical analysis of plane fitting, they found that 15 of the 27 dwarf galaxies around M31 are tightly constrained to a plane. This plane around M31 has been dubbed the “Great Plane of Andromeda” (GPoA; Pawlowski et al., 2014) but has also been referred to as the “Vast Thin Disk of Satellites” (Hammer et al., 2013) and the “Vast Thin Plane of Dwarf Galaxies” (Bahl & Baumgardt, 2014). Intriguing characteristics of these two planes are that most of the dwarf galaxies in the GPoA lie on the near side of M31, the GPoA is perpendicular to the Milky Way’s disk, the VPOS is orthogonal to the GPoA, and 13 of the 15 galaxies in the GPoA appear to be co-rotating (Ibata et al., 2013). With all these factors in mind, it has been speculated that M31 and the Milky Way have interacted in the past which caused tidal stripping and thus

\[ \text{Take a sneak-peak at Fig. 2.1 for an idea of what this structure looks like.} \]
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a tidal stream of dwarf galaxies (Hammer et al., 2013). If these dwarf galaxies are indeed tidal
dwarf galaxies then they should be nearly devoid of dark matter and thus have different character-
istics than dwarf galaxies formed inside dark matter halos. Also, if true, these galaxies would take
away from the number of observed dwarf galaxies formed in dark matter halos and therefore inflate
the Missing Satellites problem. However, observations by Collins et al. (2015) found no difference
between dwarfs on and off the GPoA.

Reaching even further into the Local Group, Shaya & Tully (2013) found that 43 of the ~50
Local Group satellites that were known at the time within 1.1 Mpc lie within four distinct planes.
Altogether, these structures may pose a significant problem for ΛCDM since the theory does not
inherently predict planar structures of dwarf galaxies or preferential alignment of subhaloes. This
intriguing topic will be explored in much more detail in Chapter 2 where we will investigate the Disk
of Satellites around the Milky Way to determine whether or not it presents a significant problem
to ΛCDM.

1.4.4 The Cusp-Core Problem

Dissipationless cosmological simulations (i.e. dark matter-only) show that the density structure
of dark matter haloes are universal and scale only with mass. In other words, no matter the size of
the halo, the internal structure and density gradient is the same. This is known as the NFW halo
(Navarro, Frenk, & White, 1997) and the density profile is well described by

\[
\rho_{\text{NFW}}(r) = \frac{\rho_0}{r/r_s(1 + r/r_s)^\alpha},
\]

where \(\rho_0\) is the characteristic density which is related to the density of the universe at the time
of halo collapse, \(r_s\) is the characteristic radius of the halo where the “inner” and “outer” halo
transition takes place, and \(\alpha = 2\) for an NFW halo. Many other forms of this profile also exist
which mainly vary by their choice of \(\alpha\). For example, the analytically derived Hernquist (1990)
profile has an $\alpha = 3$ form of the above equation which leads to the same inner density slope as an NFW profile but is steeper in the outer parts of the halo. Because of the form of equation 1.2, at very small radii, the density follows the form of $\rho \propto r^{\alpha}$ where $\alpha = -1$ and results in a dramatic density increase near the center. This sharp density increase in the central regions of dark matter haloes is known as a “cusp” or “cuspy” profile.

When looking at density profiles of dark matter haloes, marked differences occur between observations and simulations. Observational evidence from The H\textsuperscript{i} Nearby Galaxy Survey (THINGS, Walter et al., 2008) and its sister survey for nearby dwarf galaxies LITTLE THINGS (Oh et al., 2011; Governato et al., 2012) shows that the inner density slopes of galaxies follow a much shallower profile with $\alpha \sim -0.3$ in the inner regions. Low surface brightness (LSB) galaxies are generally featureless galaxies dominated by an exponential disk that shows little evidence of prior mergers or interactions. These galaxies also show remarkably flattened inner density profiles on the order of $\alpha \sim -0.2$ in their inner regions (de Blok, 2010, and references within). Recently, Collett et al. (2017) utilized strong gravitational lensing to infer the parameters of the mass distribution of a galaxy cluster at redshift $z = 1$. They also found that the inner density structure of the cluster followed a shallower density profile with $\alpha \sim -0.4$. Yet another recent set of observations and modeling of the Milky Way dwarf Erinaus II (Amorisco, 2017; Contenta et al., 2017) and the M31 dwarf Andromeda XXV (Amorisco, 2017) have shown that star clusters within those dwarfs would not be able to survive in the presence of a sharply peaked dark matter cusp as predicted by ΛCDM. These shallow inner density profiles found in observations are known as “cores” or “cored” profiles and are well described by the Einasto profile (equation 1.3; Einasto, 1965, 1968, 1969; Einasto & Hand, 1989) which varies continuously with radius and provides a more flattened density profile in the center (Merritt et al., 2006; Navarro et al., 2010; Governato et al., 2012).

$$\rho(r) = \rho_{-2} \exp \left[ \frac{-2}{\alpha} \left\{ \left( \frac{r}{r_{-2}} \right)^{\alpha} - 1 \right\} \right],$$ (1.3)
here, $\rho_{-2}$ and $r_{-2}$ are the density and radius where $\alpha = -2$, marking the transition between the inner and outer halo.

This discrepancy between simulations showing dark matter cusps and observations showing dark matter cores has been deemed the Cusp-Core problem and, just as the inclusion of baryons has helped reconcile the the Missing Satellites problem, baryons have also been invoked to help solve the Cusp-Core problem. It has been shown that adiabatic contraction of radiatively cooling gas drags dark matter inwards and increases the central density of the halo (Blumenthal et al., 1986; Gnedin et al., 2004). However, feedback from supernovae, active galactic nuclei, and dynamical heating can inject energy into the interstellar medium and dark matter particles causing the halo to expand (de Blok, 2010; Pontzen & Governato, 2012; Zolotov et al., 2012; Collett et al., 2017). More advanced simulations that include the effects of baryons have prescriptions for star formation: when an area gathers enough material so that the density is about equal to observed giant molecular clouds, star formation begins which will create a supernova explosion. After a supernova, the shockwave removes baryonic material and creates a low density cavity. The sudden drop in density causes dark matter particles to move outward while the cavity cools and is filled back in with material. The dark matter particles keep some of the extra energy gained by the sudden drop in density caused by the supernova and thus lower the dark matter density in the center (Pontzen & Governato, 2012).

Although the inclusion of baryons has been shown to relieve the Cusp-Core problem in galaxies, it may not be able to explain the lack of dark matter cusps in galaxy clusters unless the clusters that have been observed thus far are currently merging and thus not relaxed systems (e.g. Collett et al., 2017).

Clearly, the existence of this problem and its proposed solution highlights the importance of creating extremely accurate models for galactic systems. Although the inclusion of baryons is not a cure-all fix for all the problems we have discussed thus far (e.g., Planes of Satellites problem, although even here we will see in Chapter 2 that it may help), the inclusion of baryons and their effects can simultaneously help to solve several of the small scale problems facing $\Lambda$CDM and let us better understand them.
1.4.5 The Disk-Halo Degeneracy

Yet another problem which limits our understanding of the relationship between the dark matter halo and baryon content of galaxies is that spiral galaxy rotation curves can be equally well fit with either maximal or minimal baryonic components since the disk of the galaxy is mostly insensitive to the three dimensional shape of the galaxy (Deg & Widrow, 2014). Even though we have obtained high quality rotation curves for many spiral galaxies, our understanding of this relationship is limited by this so-called “Disk-Halo Degeneracy” that leaves the dark matter halo poorly constrained by utilizing kinematic data alone (e.g. Dutton et al., 2005). This point is illustrated in Fig. 1.4 where the “observed” rotation curve (the red line) can be fit equally well by a wide range of values for the dark matter (blue curve) and baryonic (green curve) components.

Clearly, kinematic data is not enough to fully describe the disk and halo; however, if used in conjunction with several different types of observations, galaxy model degeneracies can be relieved.

Figure 1.4: A toy model showing the effect of the disk-halo degeneracy. The green and blue curves represent the contributions to the observed velocity curve (red) from both dark and baryonic components. The shaded regions represent all the possible solutions. There is a large degeneracy between dark and baryonic contributions since a wide range of values for both components lead to nearly the same solution. The plot is displayed in arbitrary units.
somewhat since different methods probe different regions of the galaxy. Some observations that can be utilized include surface brightness measurements, gravitational lensing, proper motions, and kinematics. Stellar population models can place constraints on the stellar mass-to-light ratios yielding the baryonic contribution to the overall mass profile. However, there are many uncertainties in this analysis which limit its accuracy. These include systematic uncertainties in the stellar initial mass function, treatment of various stellar evolutionary phases in stellar population synthesis models, star formation histories, metallicities, and extinction (Dutton et al., 2011). For the Milky Way, stellar streams created by the tidal disruption of dwarf galaxies can be used to sample the potential over a range of radii (e.g. Law & Majewski, 2010; Deg & Widrow, 2014; Bovy et al., 2016); however, this is also plagued with uncertainties and is not applicable widely.

Strong gravitational lensing offers, perhaps, the most promise of constraining the dark matter halo when used in conjunction with kinematic data (Maller et al., 2000). This is due to the fact that kinematic data is sensitive to the mass enclosed within a spherical volume while gravitational lensing measures the projected mass within the cylinder contained within the Einstein angle (equation 1.1). The Sloan Lens ACS (Advanced Camera for Surveys) (SLACS) Survey (Bolton et al., 2006, 2008) set out to find strong, single galaxy gravitational lenses by using existing SDSS data and performing follow up observations with the *Hubble Space Telescope (HST)*. The follow-up Sloan WFC (Wide-field Camera) Edge-on Late-type Lens Survey (SWELLS; Treu et al., 2011) focused on finding spiral galaxies that were also strong gravitational lenses in order to help constrain dark matter and baryonic profiles of galaxies through detailed mass modeling. Dutton et al. (2011) and Trick et al. (2016) have shown the power of this type of analysis by analyzing two different late-type galaxies from the SWELLS survey and highly constrained the model for the disk and the halo. Although this combination is very powerful, single galaxy strong gravitational lenses are very rare; thus, this observational problem remains a significant issue for most spiral galaxies.
1.4.6 Dark Matter Halo Shapes

A further complication to the Cusp-Core problem and a direct result of the Disk-Halo Degeneracy is that the true shape of dark matter haloes remains unknown. Both the NFW and Einasto profiles assume spherically symmetric dark matter haloes, which is an oversimplification of their true shape since dissipationless dark matter simulations show strongly triaxial haloes (Bardeen et al., 1986; Barnes & Efstathiou, 1987; Frenk et al., 1988; Dubinski & Carlberg, 1991). Meanwhile, observations find mainly near-spherical haloes (Debattista et al., 2008). However, the observational constraints are based on modeling of the observed rotation curves of galaxies which are mostly insensitive to the halo shape and structure and thus fraught with degeneracies because of the Disk-Halo Degeneracy; thus, precise measurements of dark matter haloes are exceedingly rare (Deg & Widrow, 2014; Bovy et al., 2016). But it seems that baryons can, once again, rescue \( \Lambda \)CDM since the condensation of baryons to the centers of dark matter haloes has been shown to create rounder halos that are only mildly triaxial (Dubinski, 1994; Kazantzidis et al., 2004). Although, it may be the case that haloes become round only in their center region where baryons dominate and remain triaxial at large radii.

Observations of the Milky Way’s halo, show that it is almost certainly non-spherical to some degree although there is debate over its true shape. Constraining the shape of the Milky Way’s dark matter halo is mainly done through the use of stellar streams. Law & Majewski (2010) sought to fit a triaxial dark matter halo to observational data from the 2MASS (2 Micron All-Sky Survey; Skrutskie et al., 2006) and SDSS surveys but found a halo configuration that was proven by Debattista et al. (2013) to be unstable. Other groups have also fit the Milky Way distribution with non-spherical haloes (e.g. Loebman et al., 2012; Deg & Widrow, 2014; Bovy et al., 2016). With surveys such as Gaia (Gaia Collaboration et al., 2016), which recently provided extremely accurate three-dimensional proper motion measurements for over a billion stars, the potential of the Milky Way will be able to be mapped very accurately in the near future.
1.5 Alternative Solutions

The many problems that $\Lambda$CDM faces has led some researchers to consider alternate theories of dark matter. For example, in order to solve the Missing Satellites and Cusp-Core problems, some have considered the use of kinematically “warm” dark matter (Bode et al., 2001; Lovell et al., 2012, 2014). This version of dark matter involves a more energetic dark matter distribution that inhibits the formation of the smallest haloes, because of this there are fewer subhaloes around massive galaxies and the internal structures of subhaloes are naturally core-like. However, if the baryonic effects discussed earlier in Section 1.4 are present, this could cause the opposite form of the Missing Satellites problem where there is a catastrophic failure to create the observed number of dwarfs in simulations (Lovell et al., 2012).

Another popular alternative is through the use of self-interacting dark matter (Spergel & Steinhardt, 2000; Vogelsberger et al., 2012). In these models, the dark matter particle has a larger interaction cross-section. Thus, the central regions of galaxies, where dark matter is the most concentrated, would become cored after some time due to self-interaction which would act as a pressure and support the halo from collapse (Rocha et al., 2013; Peter et al., 2013). It is also possible that the self-interacting dark matter particle could be its own anti-particle and thus create gamma rays during an annihilation event (Bergström et al., 1998; Bergström, 1999; Baltz et al., 2000) . This theory has the exciting prospect of making the dark matter particle indirectly observable through the detection of gamma rays in dark matter dominated systems where there are few contaminant sources. Observations towards the galactic center of the Milky Way have yielded inconclusive but promising results in targeted studies (e.g. Daylan et al., 2016); however, targeted gamma ray searches towards the most dark matter dominated dwarf galaxies have yet to find any significant results.

The most drastic alternative solution states simply that there is no dark matter. Instead, Newton’s laws must be modified in the presence of extremely small accelerations so that Newton’s laws would work perfectly for systems like the solar system, but not near the edges of galaxies.
This theory is called Modified Newtonian Dynamics (MOND; Milgrom, 1983). MOND works by modifying the gravitational force law so that in high acceleration, it reduces to the standard Newtonian result but in low accelerations a different behavior is seen. This is done by replacing Newton’s standard $F = ma$ equation with:

$$F = m\mu \left( \frac{a}{a_0} \right) a,$$

where $F$ is force, $a$ is the acceleration, $m$ is the gravitational mass of a body, $\mu(a/a_0)$ is an unspecified function that must match Newtonian results at high accelerations (i.e. $\lim_{a/a_0 \to \infty} \mu(a/a_0) = 1$) and “turn on” at low accelerations (i.e. $\lim_{a/a_0 \to 0} \mu(a/a_0) = a/a_0$), and $a_0$ marks the acceleration boundary between Newtonian and “MONDian” regimes and has a value of $a_0 \approx 1.2 \times 10^{-10}$ m s$^{-2}$. Because of the form of this equation, flat rotation curves (Fig. 1.1) are a natural result once the acceleration due to a massive object is below the value of $a_0$. Following equation 1.4 in the limit of $a \ll a_0$ and solving for circular velocity gives:

$$v_c^4 = GMa_0.$$  (1.5)

Thus the velocity of an object in a circular orbit around a massive object of mass, $M$, has a velocity that is independent of distance. MOND is therefore very good at reproducing the rotation curves of spiral galaxies. Furthermore, it has been successful in many other ways such as: matching the observed Tully-Fisher relation (Tully & Fisher, 1977), which relates the total baryonic mass of a galaxy to its rotation velocity; naturally stabilizing disk galaxies without the need for dark matter (Ostriker & Peebles, 1973) and thus offering a solution to the “disk-halo conspiracy” which is the problem that dark matter halos appear to “know” how to form so that rotation curves of galaxies remain perfectly flat (Bahcall & Casertano, 1985); and explaining the Planes of Dwarf galaxies problem as a natural result of tidal interactions (Kroupa, 2014).
MOND has been very successful at explaining the features of the Universe on small scales; however, it faces many problems at large scales. One problem is that it cannot completely eliminate the need for dark matter since investigations of galaxy clusters using MOND still show mass discrepancies; although, the mass discrepancy is smaller than what $\Lambda$CDM faces and could be explained with baryonic matter (e.g. neutrinos; Angus et al., 2007). Another problem involves MOND’s inability to explain systems such as the Bullet Cluster (Clowe et al., 2004), which is a pair of merging galaxy clusters. Weak lensing has definitively shown that the concentration of mass in the system lies far away from the baryonic center of mass where MOND would predict the most mass to be (see Section 1.2). Yet another issue lies in the exact value of $a_0$ since a single value has not been found which fits all rotation curves (Kent, 1987). Furthermore, MOND is not a complete theory derived in the general relativistic limit but rather an empirically motivated substitute to Newton’s law of gravity. For an excellent review of both the $\Lambda$CDM and MOND paradigms, see McGaugh (2015).

The simple, elegant solutions that MOND offers for issues such as the Planes of Satellites problem and its explanation of flat rotation curves is remarkable; however, the observational evidence for dark matter is overwhelming. Because of the successes of both theories ($\Lambda$CDM on large scales, MOND on small scales) some have suggested unique models of dark matter that bring together both theories. These models typically induce a dark matter particle that is capable of superfluid states at galaxy scales, thus showing MOND characteristics. At cluster scales, it is heated because of the larger velocity dispersions of galaxies and thus shows characteristics of dark matter (Sikivie & Yang, 2009; Bettoni et al., 2014; Berezhiani & Khoury, 2015; Das & Bhaduri, 2015). However, until the dark matter particle is directly observed, differentiating between different dark matter theories is not likely.

1.6 Dissertation Synopsis

Simulations have reproduced the large scale structure of the observed universe to an extremely high degree of accuracy. However, as outlined above, there is currently plenty of controversy
surrounding the ΛCDM paradigm at small scales. High resolution simulations that include both baryonic and dark matter have begun to bridge the gap between observations and theory, yet there still remain many unsolved problems at small scales. This Dissertation aims to find and characterize dark matter substructure in the Universe through a variety of methods.

In the next chapter, we will discuss in detail the VPOS around the Milky Way, paying special attention to the classical dwarf galaxies. We perform a plane fitting analysis of these dwarfs and compare the results to two different dark matter simulations to determine the significance of the structure in the context of ΛCDM. We then investigate two members of the VPOS, Leo I and Leo II, both of which appear to be outliers of the dwarf galaxy population, and see what effect their inclusion has on the significance of the observed structure. Because the eleven classical dwarfs have been studied in detail over decades, their three dimensional velocities are known fairly accurately. Using this information, we integrate the orbits of the dwarfs, following their positions through time to see if the VPOS remains coherent or is just a current random alignment. We also perform an analysis on the effect of measurement errors in our orbit calculations and discuss limitations in our investigation.

In Chapter 3, previous work done by Chang & Chakrabarti (2011) is expanded and generalized. It has been found that through analyzing the observed H1 gas surface density of a spiral galaxy, the mass and current location of a galactic satellite can be found (Chakrabarti & Blitz, 2009, 2011; Chakrabarti et al., 2011; Chang & Chakrabarti, 2011). This novel method has been deemed the Tidal Analysis method. In Chang & Chakrabarti (2011), a simple scaling relation was found that related the density response of the gas disk and the mass of perturbing satellite. Relations like this are extremely useful since they can quickly provide information about something that is normally very hard to observe. While the relation that they found is useful, it is only applicable for interactions that occur when a satellite passes within 20 kpc of the host. Here, we extend this relation to include any pericenter passage. We also investigate multiple satellite interactions for cases when two satellites strike a disk galaxy within a dynamical time based on common interactions seen in dark matter simulations.
Chapter 1. Introduction

In the following chapter, we switch to observational studies of substructure. H\textsc{i} observations of the Milky Way discovered a large warp in the outer H\textsc{i} disk (Levine et al., 2006) that was not easily explained by the currently known dwarf satellites. By applying Tidal Analysis to the Milky Way, Chakrabarti & Blitz (2009) were able to explain the large warp through the presence of a large and as-of-yet undiscovered dwarf galaxy. The large dwarf was predicted to lie in the plane of the Milky Way towards the constellation of Norma at a distance of 90 kpc. Due to the presence of dust and extreme extinction of light through the galactic disk, observations in the direction of the dwarf were not available until a deep infrared survey of the disk was performed: VISTA Variables of the Via Lactea (Minniti et al., 2011). In the survey data, an overabundance of young variable stars were reported at the predicted location of the dwarf (Chakrabarti et al., 2015). This chapter describes a set of follow-up observations that were performed in an effort to characterize those variable stars to help confirm or deny the existence of the dwarf.

Going beyond the Milky Way, Chapter 5 describes an on-going H\textsc{i} study of spiral galaxies that also act as strong gravitational lenses. Because of this unique combination, both Tidal Analysis and gravitational lensing can be used to constrain the dark matter in these galaxies. Ultimately, high-resolution H\textsc{i} observations of these galaxies will be carried out so that Tidal Analysis can be performed. However, these observations are extremely time intensive and, as we will see, fraught with observational difficulties from terrestrial noise. Therefore, we must pre-observe our objects with large single-dish radio telescopes in order to constrain the total H\textsc{i} masses of these galaxies and ensure that mapping observations will be successful.

Finally, in Chapter 6, I conclude with a summary of the work that has been done and future work that remains.
CHAPTER 2

IS THE VAST POLAR STRUCTURE OF DWARF GALAXIES
A SERIOUS PROBLEM FOR $\Lambda$ COLD DARK MATTER?

Here we will investigate in detail one of the small scale problems with $\Lambda$CDM: the Planes of Dwarf Galaxies problem. The following is an adapted version of Lipnicky & Chakrabarti (2017) that includes more detail about our plane fitting algorithm and updated figures.

2.1 Abstract

The dwarf galaxies around the Milky Way are distributed in a so-called vast polar structure (VPOS) that may be in conflict with $\Lambda$ cold dark matter ($\Lambda$CDM) simulations. Here, we seek to determine if the VPOS poses a serious challenge to the $\Lambda$CDM paradigm on galactic scales. Specifically, we investigate if the VPOS remains coherent as a function of time. Using the measured Hubble Space Telescope (HST) proper motions and associated uncertainties, we integrate the orbits of the classical Milky Way satellites backwards in time and find that the structure disperses well before a dynamical time. We also examine in particular Leo I and Leo II using their most recent proper motion data, both of which have extreme kinematic properties but do not appear to drive the polar fit that is seen at the present day. We have studied the effect of the uncertainties on the
Chapter 2. Is the VPOS a serious problem for ΛCDM?

HST proper motions on the coherence of the VPOS as a function of time. We find that 8 of the 11 classical dwarfs have reliable proper motions; for these 8, the VPOS also loses significance in less than a dynamical time, indicating that the VPOS is not a dynamically stable structure. Obtaining more accurate proper motion measurements of Ursa Minor, Sculptor, and Carina would bolster these conclusions.

2.2 Introduction

A topic of recent interest and controversy is that concerning planes of dwarf galaxies in the Local Group. It has long been understood that an apparent plane of dwarf galaxies resides around the Milky Way very near the galactic poles, deemed the Vast Polar Structure (VPOS, Kunkel & Demers, 1976; Lynden-Bell, 1976; Kroupa et al., 2005; Zentner et al., 2005; Pawlowski et al., 2013), and recent works (Conn et al., 2013; Ibata et al., 2013) have also found a thin distribution of corotating galaxies around M31. Work by Shaya & Tully (2013) found that 43 of the 50 Local Group satellites within 1.1 Mpc are contained within four different planes. The observations of these planar structures appear to challenge the current Λ cold dark matter (ΛCDM) theory of hierarchical structure formation and call into question its validity (Kroupa et al., 2005; Pawlowski et al., 2015).

Following the initial impression of the VPOS as a challenge to ΛCDM, various authors have examined the effects of large-scale structure and baryonic physics on the VPOS, and have investigated its statistical significance relative to cosmological simulations that in fact do not manifest purely isotropic distributions, as assumed earlier by Kroupa et al. (2005). Zentner et al. (2005) showed first that an isotropic distribution of sub-haloes is not the correct null hypothesis for testing ΛCDM (even for dissipationless simulations), and showed that the origin of the flattening may be due to the preferential accretion of satellites along the major axis of the halo. Further insight into this problem was obtained by works such as Shaya & Tully (2013) and McCall (2014), which have examined how the cosmic web affects sub-galactic structures. Shaya & Tully (2013) found that
the planar structure of the Local Group dwarfs is consistent with large-scale structure and due to the evacuation of the Local Void. Similarly, Libeskind et al. (2015) showed that the alignment of the Local Group dwarfs along the velocity shear field agrees with the ΛCDM paradigm. Wang et al. (2013) have shown that in terms of spatial distribution, the Milky Way satellite plane is only in the 5–10 per cent tail of the distribution of planes found in simulations. Cautun et al. (2015) found a similar solution for both the Milky Way and M31 planes and state that the rarity of the observed planes is largely due to a posteriori defined tests and misinterpretation of results. The analysis of the VPOS in dissipationless cosmological simulations may be summarized as follows – simulations predict subhaloes to be distributed anisotropically (Wang et al., 2013; Cautun et al., 2015); however, the degree to which the VPOS is arranged seems to be at odds with ΛCDM (e.g., Pawlowski et al., 2014). It is of note that the degree of anisotropy is especially pronounced for the more massive satellites (Libeskind et al. 2014).

Various authors have also examined the effects of baryonic physics as a possible solution to this problem (Libeskind et al., 2007; Sawala et al., 2014, and others). Sawala et al. (2014, 2016) argued that many of the discrepancies between the ΛCDM paradigm and observations on sub-galactic scales, such as the Missing Satellites problem (Klypin et al., 1999; Moore et al., 1999; Kravtsov et al., 2004) and the Too Big To Fail problem (Boylan-Kolchin et al., 2011), can be resolved using hydrodynamical cosmological simulations that are designed to match the Local Group environment and may even play a part in the Planes of Satellites problem. However, Pawlowski et al. (2015) have argued that these resolutions may be problematic. In particular, they find that Sawala et al. (2014)’s resolution of the VPOS problem is due to ignoring the radial positions of the satellites. Moreover, although Sawala et al. performed a hydrodynamical simulation, they did not contrast their results with a dark matter-only simulation, as has been done recently by Ahmed et al. (2016), who find that the inclusion of baryons significantly changes the radial distribution of the satellites, thereby increasing the significance of planar structures.

It has also been suggested that these planes of dwarf galaxies are tidal dwarfs, having been pulled from the Milky Way during a past interaction with M31 (Kroupa et al., 2005; Hammer
et al., 2013; Pawlowski et al., 2013). Therefore, one might expect the planar dwarf galaxies to be distinct from off-plane dwarfs due to their different formation histories. However, Collins et al. (2015) found that there is no difference in the observed properties (sizes, luminosities, masses, velocities, metallicities and star formation histories) for the on and off plane dwarf galaxies in M31. Yet another class of solutions lies in the as yet unknown form of the dark matter particle. Solutions which use dissipative dark matter physics may be able to explain planar structures and solve other issuers such as the Missing Satellites problem but full simulations have yet to be performed (Randall & Scholtz, 2015; Foot & Vagnozzi, 2016).

Significant recent advances for near-field cosmology are the proper motions that have been obtained using HST for all of the classical Milky Way satellites (Kallivayalil et al., 2013; Massari et al., 2013; Sohn et al., 2013; Casetti-Dinescu & Girard, 2016; Piatek et al., 2016). These measurements now enable us to calculate realistic orbits for these satellites. Although there are errors associated with the proper motion measurements, several authors have been able to make substantive new inferences. For example, Kallivayalil et al. (2013) found using the third-epoch HST Magellanic Cloud proper motion measurements that periods less than 4 Gyr are ruled out, which is a challenge for traditional Magellanic Stream models. Furthermore, Kallivayalil et al. (2013) found that if one assumes that the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) have been a bound pair for a few Gyr, then first infall models are preferred. These proper motions can also inform our understanding of the VPOS – both its stability and the membership of the VPOS. When considering a possible plane of satellites, it is imperative to determine which satellites truly belong in such an analysis. In early studies of the VPOS, only position information was available to the authors (e.g. Kroupa et al., 2005; Zentner et al., 2005); however, we now have accurate three-dimensional (3D) space and velocity information, which enables one to look at the orbital elements (Pawlowski et al., 2013) and the past orbital history of each member. Much work has been done investigating the previous orbits of these satellites in order to constrain the mass of the Milky Way, the shape, and the extent of the Milky Way’s dark matter halo. For example, Sohn et al. (2013) and Boylan-Kolchin et al. (2013) used the motion of Leo I to constrain the virial mass
and extent of the Milky Way.

What we seek to do here is to investigate the stability of the VPOS and the membership of the VPOS using the recently obtained *Hubble Space Telescope (HST)* proper motions of the classical Milky Way satellites. If the VPOS is a serious problem for \( \Lambda \)CDM, one expects that it should persist over a dynamical time and should not be unique to the present day. Dynamical coherence over long time-scales would presumably occur for satellites with aligned angular momentum vectors, as has been claimed by prior work (Pawlowski & McGaugh, 2014), and thus it is critical to examine the long-term stability of this structure. Moreover, there may be certain satellites that drive the appearance of the planar structure at the present day. If so, it is critical to examine whether a subset excluding these satellites resembles cosmological simulations.

This Chapter is organized as follows. In Section 2.3, we discuss the dissipationless cosmological simulations that were used to compare to the Milky Way sample of dwarf galaxies, our method of plane fitting and the statistic measures used to compare our samples. We also discuss the orbit calculations we performed to analyze the longevity of the VPOS. In Section 2.4, we investigate individual members of the VPOS and explore the results of looking at subsets of the classical dwarfs. In Section 2.5, we discuss the results of the orbit calculations, the effects of the errors, and limitations of our analysis. Finally, in Section 2.6, we discuss the impact of these results, and conclude in Section 2.7.

### 2.3 Methods

The satellites that are used in our analysis are considered the ‘classical’ dwarf satellites and are the only satellites for which we have reliable proper motion measurements. The position and velocity vectors for the 11 classical satellites are given in the Appendix in Table A.1.
2.3.1 Dissipationless Cosmological Simulations

Following the work of earlier groups (Kroupa et al., 2005; Zentner et al., 2005), we compare the Milky Way distribution of satellites to current dark matter simulations of Milky Way-like haloes.

Our first comparison is to Via Lactea II (vlii; Diemand et al., 2007a), where an N-body code was used to model a Milky Way-sized halo to the present epoch ($z = 0$) using over 200 million particles. The simulations were performed with pdkgrav (Stadel, 2001; Wadsley et al., 2004) and adopted the best-fitting cosmological parameters from the Wilkinson Microwave Anisotropy Probe (WMAP) three year data release (Spergel et al., 2007): $\Omega_M = 0.238$, $\Omega_\Lambda = 0.762$, $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, $n = 0.951$, and $\sigma_8 = 0.74$. The host halo suffered no major mergers after $z = 1.7$ and had a host halo mass of $M_{\text{halo}} = 1.77 \times 10^{12}$ M$_\odot$ within a radius of $r_{\text{vir}} = 389$ kpc, making it a good candidate for a Milky Way-like disc galaxy at the present day. vlii has a sub-halo mass resolution limit of $M_{\text{sub}} = 4 \times 10^6$ M$_\odot$ and is therefore capable of resolving all the classical Milky Way dwarfs.

We also compare the Milky Way distribution to the simulations performed by Garrison-Kimmel et al. (2014): Exploring the Local Volume in Simulations (ELVIS). The ELVIS simulations were performed using GADGET-3 and GADGET-2 (Springel, 2005), both of which are tree-SPH codes that follow the dissipationless component with the N-body method. ELVIS is a dissipationless cosmological simulation with adopted $\Lambda$CDM parameters from WMAP-7 (Larson et al., 2011): $\Omega_M = 0.266$, $\Omega_\Lambda = 0.734$, $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $n = 0.963$, and $\sigma_8 = 0.801$. Simulations were chosen to be good analogues of the Local Group and had to meet a specific set of criteria based on host mass, total mass, separation, radial velocity, and isolation. In total, 12 pairs of galaxies were simulated to model the Milky Way – M31 system; these 24 haloes were then simulated again in isolation. The isolated simulations were shown to have similar subhalo counts and mass functions. However, subhaloes in paired simulations were shown to have substantially higher tangential velocities. For the comparisons made in this paper, we choose to compare the Milky Way dwarf population to the high resolution, isolated simulations referred to as iScylla and iHall. These two simulations have a subhalo mass resolution of $M_{\text{sub}} \sim 2 \times 10^5$ M$_\odot$, while all of the other ELVIS simulations have a mass resolution of $M_{\text{sub}} > 2 \times 10^7$ M$_\odot$ and therefore are not capable of resolving all the classical...
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Table 2.1: Summary of simulation values compared to the Milky Way. The last column refers to the number of subhaloes that have $V_{\text{peak}} > 10$ km s$^{-1}$ and are within 300 kpc of the host halo. The virial mass of the Milky Way is taken from Boylan-Kolchin et al. (2013), and the number of subhaloes of the Milky Way was gathered by McConnachie (2012).

<table>
<thead>
<tr>
<th>Halo</th>
<th>$M_{\text{vir}}(10^{12}M_\odot)$</th>
<th>$r_{\text{vir}}$ (kpc)</th>
<th>$V_{\text{vir}}$ (km s$^{-1}$)</th>
<th>$n_{\text{haloes}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Via Lactea II</td>
<td>1.77</td>
<td>389</td>
<td>140</td>
<td>874</td>
</tr>
<tr>
<td>iScylla HiRes</td>
<td>1.61</td>
<td>305</td>
<td>150</td>
<td>420</td>
</tr>
<tr>
<td>iHall HiRes</td>
<td>1.67</td>
<td>309</td>
<td>130</td>
<td>604</td>
</tr>
<tr>
<td>Milky Way</td>
<td>$1.6^{+0.8}_{-0.6}$</td>
<td>304</td>
<td>150</td>
<td>$\geq27$</td>
</tr>
</tbody>
</table>

Milky Way dwarfs. These haloes have similar properties to the Milky Way and are good analogues. The properties of the realized haloes from both simulations are given in Table 2.1.

2.3.2 Plane Fitting: The Dwarf Galaxies at the Present Day

Originally, we attempted to fit the distributions of dwarf galaxies using a least squares approach which works by minimizing the distance a dwarf lies from the plane in the $z$ direction. However, this approach yielded highly incorrect results in some important cases. When the dwarfs are aligned nearly vertically in $z$ (as is the case at the present time), least squares is unable to minimize the distance to the plane correctly since a dwarf lying off the plane in $x$ or $y$ would be infinitely far away in $z$ from a vertical plane. As a result, least squares instead returns a less inclined planar fit that does not accurately represent the distribution.

To avoid this problem, the method we chose to use to fit distributions of dwarf galaxies in both simulations and the Milky Way was the method of principal component analysis (PCA) which minimizes the perpendicular distance a dwarf lies from the best fitting plane. The best-fitting plane is defined by the equation $\hat{n} \cdot x = \hat{n}_x X + \hat{n}_y Y + \hat{n}_z Z = 0$, where $\hat{n}$ is the normal vector of the best-fitting plane and $X, Y, Z$ are the coordinate points for a satellite. Note that our solution forces a best-fitting plane to go through the center since an off-center solution would not be meaningful. To perform PCA, we evaluate the covariance matrix and perform an eigenvalue analysis. The resulting eigenvector associated with the smallest eigenvalue is the normal of the plane, $\hat{n}$, which
passes through the origin and ensures that the found plane is the best solution. In other words, a vector pointing along the direction of least variance will be perpendicular to the direction of greatest variance and therefore represents the normal vector of a best-fitting plane.

The distance that the $i$-th dwarf out of $N$ dwarfs lies above the plane is determined, and the total rms distance of the distribution is calculated as a measure of planarity:

$$D_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i} (\hat{n} \cdot x_i)^2}. \quad (2.1)$$

However, this comparison is not sufficient to give a full understanding of the distribution as it does not take into account the compactness of the distributions as a more compact distribution will naturally lead to a small $D_{\text{rms}}$ regardless of the actual distribution (Kang et al., 2005; Zentner et al., 2005; Metz et al., 2007). This effect can be nullified by normalizing $D_{\text{rms}}$ by the median radial distance, $R_{\text{med}}$, since the median is not influenced by distant outliers. We define this measure of compactness as Zentner et al. (2005) have defined:

$$\delta = \frac{D_{\text{rms}}}{R_{\text{med}}} \quad (2.2)$$

The Python code used to calculate the best-fitting planes, $D_{\text{rms}}$, and $\delta$ is given and described in Appendix A.2.

At the current time, the positions of every Milky Way dwarf (both confirmed and unconfirmed) and the best-fitting plane are shown in Fig. 2.1. The hypothetical plane is fitted only to the 11 classical dwarfs since these dwarfs are the only ones for which we have proper motion measurements. The data plotted in Fig. 2.1 are rotated by an angle of $\phi = 158.0^\circ$ about the $z$-axis so that the best-fitting plane is viewed edge-on. Using a clockwise rotation matrix, the rotated coordinates are found by $x_{\text{rot}} = x \cos \phi + y \sin \phi$ and $y_{\text{rot}} = -x \sin \phi + y \cos \phi$. 

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Figure 2.1: All known dwarf galaxies surrounding the Milky Way are displayed (including those that are not spectroscopically confirmed) and the VPOS is shown via the solid blue line. The solid horizontal line in the center represents the Milky Way galactic disc, and the dotted lines bordering the VPOS represent the rms distance, $D_{\text{rms}} = 21.3$ kpc, of the dwarfs from the fitted plane. The system is viewed from infinity and rotated by angle $\phi = 158.0^\circ$ so that the VPOS is viewed edge on.

The same plane-fitting analysis is also performed on the dark matter simulations described above. To make an accurate comparison to the Milky Way, we perform a series of cuts to the subhaloes found at the end of each simulation and limit our analysis only to those sub-haloes capable of holding baryonic matter. We limit the sample by selecting subhaloes that are within 300 kpc and have $V_{\text{peak}} > 10$ km s$^{-1}$, $V_{\text{peak}}$ being the maximum circular velocity at the point when the subhalo contained the most mass. This ensures that we consider all subhaloes that have enough mass to be considered a dwarf and are within the virial radius of the Milky Way. The resulting total
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![Figure 2.2: The Milky Way classical dwarfs are shown in red, while the sub-haloes remaining after our velocity and distance cuts from the ELVIS iHall simulation are shown in blue. The size of a point is related to its mass and has been normalized by the LMC, the most massive Milky Way dwarf. The black line shows the circular escape speed for the Milky Way at $M_{MW} = 1.1 \times 10^{12} M_\odot$, and the grey shaded region represents the circular escape speed for the Milky Way in the mass range $(0.7 - 2) \times 10^{12} M_\odot$.](image)

When considering the VPOS, Kroupa et al. (2005) looked at subsets of the dwarf population to see how plane-like the structure remained with fewer satellites. This was done by calculating the angle $|\cos(\omega)|$, which is calculated here by finding the angle between the normal of the best-fitting plane and the vector pointing to a sub-halo. It is a measurement of the ‘thinness’ of a
plane where a perfectly planar distribution would result in $|\cos(\omega)| = 0$ for every object. They ultimately found that the plane-like structure was extremely unlikely to have formed from an isotropic parent distribution. This analysis was revisited by Zentner et al. (2005), who showed that the null hypothesis posited by Kroupa et al. (2005) was incorrect. Kroupa et al. had used the $|\cos(\omega)|$ angle from $10^5$ satellites: a nearly uniform distribution and correct only in the limit of large sample size. Zentner et al. (2005) corrected this by taking a small subset of an isotropic distribution and then comparing $|\cos(\omega)|$ to that of the observed VPOS. With the correct null hypothesis, it was found that the Kolmogorov–Smirnov (KS) probability of drawing the Milky Way satellites from the sample of CDM subhaloes was $P_{KS} \simeq 0.15$ where, typically, numbers of $P_{KS} < 0.01$ indicate differing distributions. This was further improved by comparing to a more realistic triaxial halo where it was found that the KS probability was even higher. We repeat this analysis here using the two-sample KS test comparing the values of $|\cos(\omega)|$ between the observed dwarfs and CDM subhaloes.

2.3.3 Orbit Calculations: The VPOS as a Function of Time

We also perform orbit calculations using the observed proper motions of the classical satellites. We use the fourth-order Runge–Kutta orbit integrator code developed by Chang & Chakrabarti (2011) to calculate the orbital distribution over time. We employ a static, spherical, Hernquist (1990) potential that has the same mass and inner density slope within $r_{200}$ as an equivalent NFW (Navarro et al., 1997) profile. The host halo has a mass of $M = 1.1 \times 10^{12} \, M_\odot$ (Watkins et al., 2010; Deason et al., 2012; Wang et al., 2012) and a concentration parameter of $c = 9.39$ where $c$ defines the relationship between the virial and scale radii. These orbit calculations match well with the dark matter simulations described above, which use NFW halo solutions for their host galaxies. The ELVIS haloes have concentration values of $c_{Hall} = 5.8$ and $c_{Scylla} = 9.5$ (Garrison-Kimmel et al., 2014).
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The potential is described by

$$\Phi(r) = -\frac{GM_T}{r + a},$$

where $a$ is the scale-length of the Hernquist profile and $M_T$ is the normalization to the potential or the total mass. Dynamical friction is also modeled using the Chandrasekhar formula (Besla et al., 2007; Chang & Chakrabarti, 2011) and the equation of motion has the form

$$\ddot{r} = \frac{\partial}{\partial r} \Phi_M(|r|) + \frac{F_{DF}}{M_{sat}},$$

where $M_{sat}$ is the satellite mass, $\Phi_M(|r|)$ is the potential corresponding to equation 2.3 and $F_{DF}$ is the dynamical friction term. The dynamical friction term is given by:

$$F_{DF} = -\frac{4\pi G^2 M_{sat}^2 \ln(\Lambda) \rho(r)}{v^2} \left[ \text{erf}(X) - \frac{2X}{\sqrt{\pi}} \exp(-X^2) \right] \frac{v}{v}.$$  \hspace{1cm} (2.5)

Here, $\rho(r)$ is the density of the dark matter halo at a galactocentric distance, $r$, of a satellite of mass $M_{sat}$ traveling with velocity $v$; $X = v/\sqrt{2\sigma^2}$, where $\sigma$ is the 1D velocity dispersion of the dark matter halo, which is adopted from the analytic approximation of Zentner & Bullock (2003). The Coulomb logarithm is taken to be $\Lambda = r/(1.6k)$, where $k$ is the softening length if the satellite is modeled with a Plummer profile.

**Masses and Proper Motions**

For Carina, Draco, Fornax, Leo I, Leo II, Sculptor, Sextans, and Ursa Minor, we consider the total dynamical mass out to the maximum radius of the velocity dispersion data (an estimate of the total mass) from Walker et al. (2009). The Sagittarius dwarf galaxy is in the process of being
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tidally disrupted and equilibrium mass estimators are particularly ill-suited for this system. Cited progenitor masses have varied over two orders of magnitude for the Sagittarius dwarf (Johnston et al., 1999; Law & Majewski, 2010; Purcell et al., 2011). Chakrabarti et al. (2014) addressed this issue and showed that one may derive joint constraints on the progenitor masses of tidally disrupting satellites by employing the current position and velocity of the Sagittarius dwarf and its maximum radial excursion (estimated from observed tidal debris). The progenitor mass estimate we adopt from Chakrabarti et al. (2014) for the Sagittarius dwarf is $1 \times 10^{10} M_\odot$. For the LMC and SMC, we adopt mass estimates from van der Marel & Kallivayalil (2014), which are $3 \times 10^{10}$ and $3 \times 10^9 M_\odot$ respectively.

Proper motion data for Ursa Minor, Sculptor, Sextans, Carina, Fornax, and Leo I were gathered from Sohn et al. (2013). The proper motion measurements for Draco have been vastly improved since prior studies, and we have adopted the values reported in the recent work by Casetti-Dinescu & Girard (2016). This is also true of the motion of Leo II, which was recently reported by Piatek et al. (2016) to have a proper motion measurement of less than half of its previously reported value. Proper motion values of the LMC and SMC were taken from Kallivayalil et al. (2013). Finally, for Sagittarius, we adopt the values reported by Massari et al. (2013), which contain the best estimate of the mean center-of-mass motion. Their measurements correct for the fact that Sagittarius is large enough on the sky that there are perspective differences for the different fields that are measured and consider the most accurate proper motion measurements of other works as well. The errors of these measurements were obtained by sampling the error in the proper motion measurements directly in $10^4$ Monte Carlo realizations, assuming a Gaussian distribution (Sohn, private communication) and then converting to $V_x, V_y,$ and $V_z$. Some proper motion measurements (Draco, Leo II, and Sagittarius) had to be converted from galactic polar coordinates ($\Pi, \Theta, V_z$) into galactic cartesian coordinates ($V_x, V_y, V_z$) using the following equations,
\[ V_x = \Pi \cos(\phi) - \Theta \sin(\phi), \]  
\[ V_y = \Pi \sin(\phi) + \Theta \cos(\phi), \]  
\[ V_z = V_z, \]  

where

\[ \cos(\phi) = \frac{x}{\sqrt{x^2 + y^2}}, \]  
\[ \sin(\phi) = -\frac{y}{\sqrt{x^2 + y^2}}. \]  

Great care was taken to ensure that the coordinate systems of different studies were matched. For all our values, \( X \) points from the Sun to the Galactic Center, \( Y \) points in the direction of galactic rotation, and \( Z \) points towards the northern galactic pole. Errors were propagated using the standard error equation. Below is the error for \( V_x \) as an example

\[ \sigma_{V_x}^2 = \left( \sigma_{\Pi} \frac{\partial V_x}{\partial \Pi} \right)^2 + \left( \sigma_{\cos(\phi)} \frac{\partial V_x}{\partial \cos(\phi)} \right)^2 + \left( \sigma_{\Theta} \frac{\partial V_x}{\partial \Theta} \right)^2 + \left( \sigma_{\sin(\phi)} \frac{\partial V_x}{\partial \sin(\phi)} \right)^2. \]  

The velocity errors stated in Table A.1 for Draco, Leo II, and Sagittarius should be treated as lower limits since error propagation using the form of equation 2.3 does not take into account correlated errors.

### 2.4 Members of the VPOS

Performing the plane-fitting analysis to all the classical dwarfs results in \( D_{\text{rms}} = 21.3 \) kpc or \( \delta_{\text{Classical}} = 0.23 \). For \( 10^5 \) samples of plane fitting in dark matter simulations, the vl2 simulation
has $\delta_{\text{VLII}} = 0.41 \pm 0.13$, iHall has $\delta_{\text{iHall}} = 0.39 \pm 0.11$, and iScylla has $\delta_{\text{iScylla}} = 0.41 \pm 0.11$. These results are graphically shown in Fig. 2.3. Also shown in the figure is the distribution of dwarfs around M31 which is known as the Great Plane of Andromeda (GPoA; Pawlowski & McGaugh, 2014). This plane has a thickness of $D_{\text{GPoA}} = 12.34 \text{ kpc}$ and $\delta_{\text{GPoA}} = 0.12$. Thus, the VPOS and GPoA appear more constrained than the average cosmological simulation but are still well within all the distributions.

Figure 2.3: The probability density that a plane fitted to a random distribution of 11 haloes will have a certain thickness for the three dark matter simulations considered in this paper. Thinner distributions will appear to the left-hand side. The Milky Way and M31 distributions are shown as the vertical black and dashed lines respectively and both appear to be thinner than most random distributions from dark matter simulations.

The alignment of the VPOS is also more polar than most cosmological simulations predict. We define the angle between fitted planes and the host halo disc as $\theta$ and find that $\theta = 77.3^\circ$.
for the VPOS, in agreement with other works (e.g. Shao et al., 2016). Planar structures found in simulations tend to lie at shallow angles compared to their host halo, often at angles $\theta < 45^\circ$ (Zentner et al., 2005). It has been shown that there is often a misalignment between the dark matter halo and the stellar disk of the host galaxy (Shao et al., 2016). Because of this, a similar analysis cannot be made here since the simulations used in this analysis consist of only dark matter.

The KS test is a nonparametric statistical test that compares the cumulative distribution functions of two samples and reveals the likelihood that two distributions are drawn from the same parent distribution. In practice, it does this by calculating the maximum distance between the two cumulative distribution functions since two samples drawn from the same underlying distribution should have similarly shaped cumulative distribution functions. Here we compare the values of $|\cos(\omega)|$ obtained from the Milky Way distribution with the values of $|\cos(\omega)|$ from each of the $10^5$ distributions obtained from simulations and report the mean value. For VLII, we obtain a value of $P_{KS,VLII} = 0.50$, iHall has $P_{KS,iHall} = 0.59$, and iScylla has $P_{KS,iScylla} = 0.59$. This shows that it is very likely that the two distributions come from the same underlying distribution. The above results have been summarized in Table 2.2. The probability, $P$, of drawing a thinner distribution, $\eta$, from a simulation compared to the observed one is found by computing the total number of thinner distributions over the total. Fig. 2.3 shows that the Milky Way dwarfs are less planar than 4.2 per cent of CDM distributions, or, in other words, there is about a 1 in 24 chance of drawing a more planar distribution from a CDM simulation.

Previous work by Libeskind et al. (2014) has shown that the most massive sub-haloes have a much higher degree of anisotropy than smaller subhaloes due to a preferential infall with respect to large-scale structure. When we limit our samples to include only the 50 most massive dwarfs, we also find that our random distributions become more planar. For the classical dwarfs, this translates into a 1 in 10 chance of drawing a more planar distribution, more than doubling the probability when compared to the full sample. By limiting the distribution to contain only massive dwarfs, we find a leftward shift in the distributions of Fig. 2.3. For the analysis presented here, we choose to use the full sample of subhaloes described in Table 2.1.
Chapter 2. Is the VPOS a serious problem for $\Lambda$CDM?

![Figure 2.4: The measured velocities of the classical dwarf galaxies are shown as a function of their radial location. The black line shows the circular escape speed for the Milky Way at $M_{MW} = 1.1 \times 10^{12} M_\odot$, and the grey shaded region represents the circular escape speed for the Milky Way in the mass range of $(0.7-2) \times 10^{12} M_\odot$. Leo I and Leo II are traveling close to or in excess of the escape velocity and lie at a much greater distance than the other classical dwarfs.](image)

While it does appear that the VPOS is perhaps an uncommon structure, it does not appear to be unique within our results. To understand what drives the uncommon nature of the structure, we look at the population of classical dwarfs and consider a few individual members. Subsets of the VPOS have been considered by others; for example, Pawlowski et al. (2013) and Kroupa et al. (2005) considered subsets of the classical dwarf population based on orbital pole calculations. Here we will look at the positions and velocities of the dwarfs to analyze subsets. Fig. 2.4 shows the velocities of each dwarf and their radial distance.

It is clear from Fig. 2.4 that all the classical dwarfs, except Leo I and Leo II, lie close to the Milky Way center and are traveling within the escape velocity. Leo I and Leo II lie at distances
greater than 200 kpc and, therefore, may drive a tight planar solution. Therefore, Leo I and Leo II appear to be outliers in both position and velocity and each deserve a closer inspection. Also, depending on the choice of mass for the Milky Way, more dwarfs may be loosely bound.

2.4.1 Leo I

A number of authors have argued that Leo I’s extreme kinematic properties indicate that it is not a bound satellite of the Milky Way (Sales et al., 2007; Mateo et al., 2008; Rocha et al., 2012; Pawlowski et al., 2013; Sohn et al., 2013). Sohn et al. (2013) performed a proper motion study of Leo I based on two epochs of Hubble ACS/WFC images separated by ~5 yr time. In their study, they examined the proper motion error space, the star formation history, and the interaction history of Leo I. Sohn et al.’s analysis also showed that Leo I is most likely on first infall, having experienced only one pericenter passage within a Hubble time and appears to be on a parabolic or a nearly bound orbit. Orbit integrations of Leo I match up extremely well with epochs of star formation. A burst of star formation ~2 Gyr ago corresponds with the moment that Leo I entered the virial radius of the Milky Way. This is then followed by a quenching of star formation ~1 Gyr ago matching well with a pericenter passage. At the point of pericenter, Leo I would have experienced significant ram pressure stripping, removing the leftover gas from the halo. Pawlowski et al. (2013) further showed through orbital pole analysis that Leo I is not aligned with the other satellites of the VPOS and therefore should not be included in analysis.

2.4.2 Leo II

Until recently, the proper motion measurements of Leo II were poorly constrained. It was believed that Leo II had a large tangential velocity (265 ± 129 km s$^{-1}$; Lépine et al., 2011), which led to an overall velocity measurement of 266 ± 129 km s$^{-1}$. This measurement has been highly refined by Piatek et al. (2016), resulting in a new tangential velocity of 127 ± 42 km s$^{-1}$ and a total velocity of 129±39 km s$^{-1}$, less than half of the previous measurement but reasonably within the large error range of previous studies. Due to the previous large errors in velocity, Rocha et al.
(2012) ignored the velocity measurements and instead looked at the star formation history of Leo II and found that star formation occurred in Leo II up until \( \sim 2 \) Gyr ago. This led the authors to the conclusion that infall occurred between \( \sim 2 \) and \( 6 \) Gyr ago, indicating a fairly recent merger.

With this new velocity information, we investigate the inclusion of Leo II in a plane-fitting analysis by calculating its past orbital history. The Hernquist model was used in our calculations as described above; however, it was found that when a purely NFW profile or singular isothermal sphere (SIS) profile was used, it had little impact on results. This is due to the large distance at which Leo II interacts with the Milky Way; at such large distances, the different inner slopes of the profiles do not affect the motion of the satellite, which mostly sees the Milky Way as a point source. The inclusion of dynamical friction in our model also showed very little effect due to the large distance of Leo II and its small mass. Furthermore, for different Milky Way masses, the results remained nearly unchanged.

Using the new velocity data and errors from Piatek et al. (2016) for Leo II (Table A.1), we sampled the \( \pm 3\sigma \) velocity error space \( 10^3 \) times and integrated each realization backward in time. Only the velocity error space was investigated since the position measurement of Leo II is well known. Fig. 2.5 shows the galactocentric location of Leo II as a function of time, the \( 1\sigma \) and \( 3\sigma \) probability density contours, and the relative probability density contours. Due to errors in velocity, the results diverge at late times, but, in general, most realizations show that Leo II has spent most of its time at distances similar to its current position. At most, Leo II appears to have made only one pericenter passage within the last 2.5 Gyr. Therefore, it seems likely that Leo II is on first infall or has a similar orbital history to Leo I.

2.4.3 Other Dwarfs

From Fig. 2.4, it appears that there are five other dwarfs that may be close to the escape velocity if the Milky Way is very light \( (M_{MW} < 1 \times 10^{12} \ M_\odot) \). These galaxies include LMC, Sculptor, Draco, Sextans, and Fornax.

From an analysis of radial position, velocity information, star formation history, and compar-
Figure 2.5: Shown are the results of 10^3 realizations of the orbital history of Leo II sampling the proper motions and uncertainties thereof, from \( t = -2.6 \) Gyr to the present day \( (t = 0) \). The grey-scale contours show the relative probability density of an orbit being in a certain location at a given time, and the lines represent the \( 1 \sigma \) (blue, dashed) and \( 3 \sigma \) (red, dash–dotted) contours within which the orbit realizations are contained. The black line corresponds to the realization using the mean measured values.

Comparison to VLLI data, Rocha et al. (2012) were able to estimate the infall times for the classical dwarfs. Based on radial positions and velocities alone, Draco and Sextans likely fell on to the Milky Way more than 8 Gyr ago. From proper motion measurements, the small tangential velocity of Fornax and Sculptor disfavors a recent infall scenario and instead indicates an infall time of more than 5 and 8 Gyr ago, respectively. Furthermore, the presence of old stellar populations with no evidence of stars younger than \( \sim 10 \) Gyr indicates that Draco and Sculptor have been long-time satellites of the Milky Way having experienced ram pressure and tidal stripping long ago \( (t_{\text{infall}} > 8 \text{ Gyr}) \). These results indicate that Draco, Sextans, Fornax, and Sculptor are old satellites that may be...
part of a long lived structure if it exists.

When examining the proper motions and local environment of the LMC and SMC, studies have found that they are most likely a binary or active merger that is falling on to the Milky Way for the first time (Besla et al., 2007, 2010; Kallivayalil et al., 2013). Rocha et al. (2012) also found that the large 3D velocity and active star formation seen in the LMC demands a recent merger history of less than 4 Gyr ago. This indicates that the LMC and SMC may not be part of a long-lived structure.

2.4.4 Plane Fitting Revisited

When we perform the plane-fitting analysis again without including Leo I and Leo II, we find only a slightly different distribution (Table 2.2). The thickness of the plane decreases to $D_{\text{rms}} = 20.7$ kpc; however, it is now more compact, and therefore the normalized thickness grows to $\delta = 0.24$. This corresponds to a probability of randomly drawing a thinner distribution to about 1 in 19. Another interesting point to note is that the angle between the fitted plane and the Milky Way disc becomes steeper and is nearly perpendicular. Therefore, it appears that Leo I's and Leo II's distant radial locations do not influence a specific polar fit to the VPOS as a similar one is seen even without their inclusion.

If instead we look at only the dwarfs that have aligned angular momentum vectors as pointed out by Kroupa et al. (2005) and Pawlowski et al. (2013), we find almost the same solution as in the case of the classical dwarfs. All of the above distributions are pictured graphically in the lefthand column of Fig. 2.6.

The probabilities that are seen in this study are similar to $\sim 2\sigma$ of a normal distribution, which matches fairly well with the distributions in Fig. 2.3. This indicates that planar distributions do not appear to be rare in $\Lambda$CDM simulations. Pawlowski & McGaugh (2014) have also performed an analysis of ELVIS data, but found that the structures in that data set did not match the VPOS. However, their analysis did not consider the compact distribution of the Milky Way sample. Their subhalo selection also differed from this one as they chose only the largest 11 satellites remaining
Table 2.2: Plane-fitting results. Column 1 gives the distribution on which the analysis is done. Column 2 gives the $D_{\text{rms}}$ thickness of a theoretical plane fit to subhaloes. For the Milky Way, this is done to the classical or remaining dwarfs; for dark matter simulations, this is done to a random drawing of 11 subhaloes, as described in the text. Column 3 gives a measure of the thickness as normalized by the median distance of the distribution, as defined by equation 2.2. Column 4 shows the probability, $P$, of randomly drawing a distribution, $\eta$, from a simulation that is thinner than the observed distribution. Column 5 gives the KS probability that the Milky Way sample is from the same distribution as dark matter simulations. Column 6 gives the angle between the theoretical planar fit to the Milky Way dwarfs and the Milky Way stellar disk.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>$D_{\text{rms}}$ (kpc)</th>
<th>$\delta$</th>
<th>$P(\eta &lt; \delta)$</th>
<th>$P_{\text{KS}}$</th>
<th>$\theta(\degree)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLII</td>
<td>37±13</td>
<td>0.41±0.13</td>
<td>–</td>
<td>0.50</td>
<td>–</td>
</tr>
<tr>
<td>iHall</td>
<td>61±18</td>
<td>0.39±0.11</td>
<td>–</td>
<td>0.59</td>
<td>–</td>
</tr>
<tr>
<td>iScylla</td>
<td>64±17</td>
<td>0.41±0.11</td>
<td>–</td>
<td>0.59</td>
<td>–</td>
</tr>
<tr>
<td>Classical</td>
<td>21.3</td>
<td>0.23</td>
<td>1 in 24</td>
<td>–</td>
<td>77.3</td>
</tr>
<tr>
<td>No Leo I/II</td>
<td>20.7</td>
<td>0.24</td>
<td>1 in 19</td>
<td>–</td>
<td>85.3</td>
</tr>
<tr>
<td>Aligned (PK13)</td>
<td>22.6</td>
<td>0.23</td>
<td>1 in 24</td>
<td>–</td>
<td>79.8</td>
</tr>
<tr>
<td>Trusted PMs</td>
<td>20.1</td>
<td>0.21</td>
<td>1 in 40</td>
<td>–</td>
<td>79.2</td>
</tr>
</tbody>
</table>

after obscuring a region to correspond to a galactic disc, while the analysis in this paper is left open to a random sampling of the subhaloes remaining after imposing a cut on $V_{\text{peak}}$ and radial distance. Furthermore, the ELVIS simulations used by Pawlowski & McGaugh (2014) were not of a high enough resolution to resolve subhaloes that are comparable to the smaller classical dwarfs such as Leo II.

It is also worthwhile to discuss the other members of the VPOS as much work has been done investigating their inclusion. As mentioned earlier, the proper motions and local environment of the LMC and SMC indicate that they are most likely a binary or active merger that is falling on to the Milky Way for the first time. Other dwarfs appear to have orbits that carry them away from the VPOS, such as Ursa Minor (Piatek et al., 2005) and Fornax (Piatek et al., 2007). Orbital pole analysis has also shown that Sagittarius is on a polar orbit but lays at an approximate right angle to both the VPOS and the Milky Way disc (Palma et al., 2002), which may have been caused by it being scattered into it’s current position by an encounter with the LMC/SMC (Zhao, 1998).

Without including the above-mentioned dwarfs, there remain only four dwarfs not affected by
these results: Sculptor, Draco, Sextans, and Carina. Since the minimum number of objects needed
to perform a KS test is six and fitting a plane to four objects leads to little insight, we do not
perform further analysis on the reduced population.

2.5 Stability of the VPOS

Another important question to address is whether or not the VPOS is a long-lived structure or
a temporary alignment. For the 11 classical dwarfs, proper motion measurements have been made
and are listed in Table A.1. Using the test particle code developed by Chang & Chakrabarti (2011)
described above, we have simulated the orbits of the classical dwarfs backward in time (Fig. 2.6,
top row). Also shown in Fig. 2.6 are the orbit integrations when considering the classical dwarfs
minus Leo I and Leo II (second row) and the distribution of dwarfs that have aligned orbital poles
(third row).

The plane-fitting solution is essentially the same at the current time in all cases, with a nearly
polar fit to the distribution and similar probabilities for drawing a more planar distribution from
a simulation (Fig. 2.6, left-hand column). For every case, within 0.5 Gyr (half a dynamical
time, equation 2.12), the distribution becomes wider, and the likelihood of drawing a more planar
distribution increases by a factor of ~5. At 1 Gyr, all the distributions appear to grow slightly
thinner and tend towards a more coplanar solution.

2.5.1 The Influence of Observational Errors in Orbit Calculations

Since the errors in the proper motion measurements are quite large for some of the dwarfs we
investigate further to understand how much observational errors influence our results. To test this,
we set up a ring of 11 evenly spaced particles at radius $r = 150$ kpc with circular velocity. The
simulation was then run for 10 Gyr to ensure that stability was maintained. The dynamical time
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![Diagram of VPOS as a function of time and position](image)

**Figure 2.6:** (Caption displayed on next page.)
Figure 2.6: (Continued) Each row represents a different subset of the Milky Way classical dwarfs integrated backward in time. Due to errors in the proper motion measurements, these integrations cannot be trusted beyond 0.5 Gyr (see Section 2.5.1). First row: all 11 classical dwarfs. Second row: the classical dwarfs minus Leo I and Leo II. Third row: only the classical dwarfs that have aligned angular momentum vectors as defined in Pawlowski et al. (2013). Fourth row: only the classical dwarfs that have proper motion measurements accurate enough to be trusted in orbit integrations beyond 0.5 Gyr. This is the only distribution that does not show a dramatic increase in significance at $t = -1$ Gyr. In all panels: blue dots represent Milky Way dwarfs, the thick black line represents the Milky Way stellar disc, the thin black line represents the hypothetical best-fitting plane viewed edge on, the dashed lines represent the rms thickness of the best-fitting plane, and the probability of drawing a more planar distribution from a simulation is shown (see Section 2.4). The simulation time is shown at the top of each column.

for a ring of radius 150 kpc is:

$$
\tau_{\text{dyn}} \sim \tau_{\text{cross}} \sim \frac{R}{v} \sim 0.9 \text{ Gyr}
$$

(2.12)

We begin with a ring of particles and introduce simulated observational errors which inevitably causes our perfect ring of particles to disperse. As a result, the ring will grow in width and the amount by which the distribution is constrained to the shape of a ring is defined by Equation 2.2. Eventually, at very late times and with large errors the particles will disperse to the extent that their distribution is better described as a disc rather than a coherent ring. The moment when this transformation takes place is best described as when the 3σ thickness of the ring is comparable to the median radial extent of the particles. We therefore define the criteria that $\delta < 0.33$ describes a well-constrained ring.

Introduction of errors is done by percentages; we assume that there is a certain amount of error in each component of radius and velocity. We then randomly sample the ±3σ error space associated with a percentage of the true value for each component and repeat the simulation 100 times for each percentage, the results are given in Table 2.3. The HST proper motion measurements have larger errors in velocity than in the positions of the dwarfs. Therefore, we use the average error in
position and only vary the percentage error in velocity. To examine the impact of the measured position errors, we simulated the worst-case scenario based on Draco, which has a radial distance of \( 93 \pm 4 \) kpc corresponding to an error of 4.3 per cent. When this percentage was used for each component of position with no velocity errors, almost no impact on the ring structure was found. The median error of each position component for the classical dwarfs is \( \sim 3.5 \) per cent; we therefore used this for the position errors for all simulations.

It was found that even with 100 per cent error in each component of velocity, the ring maintained coherence past \( t = -0.5 \) Gyr. For velocity errors up to 50 per cent, the ring maintained coherence past \( t = -0.75 \) Gyr, and for errors up to 30 per cent, the ring maintained coherence longer than a dynamical time. Looking at the velocity measurements of the classical dwarfs, we see that 8 of the 11 have velocity errors that are under 100 per cent in each component. Ursa Minor, Sculptor, and Carina fail this criteria. Interestingly, Sextans has the largest error in velocity measurements but passes our criteria for being trustworthy up to 0.5 Gyr since none of its individual error components exceed 100 per cent. Only three dwarfs pass the criteria for integrations lasting up to 1 Gyr: Sagittarius, LMC, and Draco. All other dwarfs have large uncertainties in general or have at least one small velocity component that is very uncertain.

These results indicate that 8 of the 11 classical dwarfs have errors that can be trusted in integrations beyond 0.5 Gyr: Sagittarius, LMC, SMC, Draco, Sextans, Fornax, Leo II, and Leo I. To reduce the amount of error entering our orbit calculations and to test whether the plane loses significance due to a few high-error dwarfs, we restrict ourselves to the dwarfs mentioned above and integrate the orbits again to see if coherence is maintained (Fig. 2.6, bottom row). We find that they too more or less follow the same trends as the other distributions. Interestingly, however, at \( t = -1 \) Gyr, we find that the significance of the plane remains the same rather than increasing as the other populations do.

These results also indicate that our integrations cannot be fully trusted up to 1 Gyr, especially those that contain the high-error dwarfs, Ursa Minor, Sculptor, and Carina, but can be trusted up to 0.5 Gyr. Therefore, the trends that are seen at \( t = -0.5 \) Gyr are indicative of the true solution.
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Table 2.3: The first column indicates the amount of error given to each component of velocity of our test particles, while position errors were held at the median position component error of the Milky Way dwarfs: 3.5 per cent. Columns 2–4 give the normalized thickness of the ring at $t = -0.5, -0.75, \text{ and } -1 \text{ Gyr}$ respectively. Those values shown in bold fail our criteria for coherence.

<table>
<thead>
<tr>
<th>Per cent error in each velocity component</th>
<th>$\delta_{t=-0.5\text{Gyr}}$</th>
<th>$\delta_{t=-0.75\text{Gyr}}$</th>
<th>$\delta_{t=-1\text{Gyr}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.05</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>20</td>
<td>0.08</td>
<td>0.14</td>
<td>0.20</td>
</tr>
<tr>
<td>30</td>
<td>0.11</td>
<td>0.19</td>
<td>0.30</td>
</tr>
<tr>
<td>40</td>
<td>0.14</td>
<td>0.26</td>
<td>0.38</td>
</tr>
<tr>
<td>50</td>
<td>0.18</td>
<td>0.31</td>
<td>0.42</td>
</tr>
<tr>
<td>60</td>
<td>0.20</td>
<td>0.35</td>
<td>0.52</td>
</tr>
<tr>
<td>70</td>
<td>0.23</td>
<td>0.40</td>
<td>0.56</td>
</tr>
<tr>
<td>80</td>
<td>0.26</td>
<td>0.43</td>
<td>0.59</td>
</tr>
<tr>
<td>90</td>
<td>0.28</td>
<td>0.47</td>
<td>0.64</td>
</tr>
<tr>
<td>100</td>
<td>0.31</td>
<td>0.50</td>
<td>0.69</td>
</tr>
</tbody>
</table>

2.5.2 Limitations

There are many factors that may influence the outcome of our orbit integrations. First, the shape of the Milky Way halo is currently very uncertain. It is almost certainly non-spherical, but the extent and the orientation of the halo has varied significantly in studies (e.g. Law & Majewski, 2010; Loebman et al., 2012; Debattista et al., 2013; Deg & Widrow, 2014; Bovy et al., 2016). There are also observed differences between the shapes of haloes in simulations compared to observations since simulations mainly find triaxial haloes and observations mainly find spherical haloes (Debattista et al., 2008). It appears that the presence of baryons condensing within haloes works to make haloes rounder, at least in their central regions (Debattista et al., 2013). It may be the case that haloes have spherical cores that become triaxial at large distances, in which case, a non-spherical halo may work to shepherd sub-haloes into a preferred axis. Shao et al. (2016) studied how likely it was to have satellite systems nearly perpendicular to the disc of their central galaxies, and found that it occurred $\sim20$ per cent of the time in simulations. Here we have assumed spherical haloes; however, the plethora of proper motion data that Gaia will deliver should serve to
constrain the true shape of the Milky Way potential in the near future (Price-Whelan & Johnston, 2013; Price-Whelan et al., 2014; Bovy et al., 2016).

Another factor that influences our simulations is our choice of Milky Way halo mass, which is also very poorly constrained. Through a multitude of methods, the Milky Way mass has been estimated to be $\sim (0.7 - 2) \times 10^{12} M_\odot$ (Watkins et al., 2010; Deason et al., 2012; Wang et al., 2012; Boylan-Kolchin et al., 2013), although measurements can vary quite dramatically (see fig. 1 of Wang et al., 2015). Many of these estimates use measurements of the mass from the inner 10–50 kpc and extrapolate to the full halo and are therefore highly affected by the choice of the Milky Way halo shape. To investigate the impact of our choice of halo mass, we varied the mass in the range of $\sim (0.7 - 2) \times 10^{12} M_\odot$. At $t = -0.5$ Gyr, almost no effect between simulations was seen; however, by $t = -1$ Gyr, the effect was visible. For lower halo mass simulations, the distribution was significantly more dispersed than higher halo mass simulations. With a lower Milky Way mass, satellites experience longer orbits as more dwarfs are traveling closer to the escape velocity. Therefore, it seems that between the limitations imposed by observational errors in proper motion measurements and the uncertainty in halo mass, orbit integrations can be trusted only up to $\sim 500$ Myr.

2.6 Discussion

It is interesting to note that relatively few subhaloes in simulations are traveling in excess of the escape velocity, while it appears that perhaps two dwarfs of the Milky Way do. VII, for example, has almost none (~1 per cent) and Fig. 2.2 shows that the ELVIS simulations form relatively few; furthermore, recent work by Boylan-Kolchin et al. (2013) found almost none in the simulations that they analyzed. It is important to consider if high-velocity dwarfs near the escape velocity of their hosts contribute to plane-like structures due to their large radial extents. When the high-velocity, distant dwarfs of the Milky Way were removed (Leo I and Leo II), we found almost no difference in our plane-fitting solution. Also, when we limit our analysis to include only random selections
that include at least one high-velocity dwarf, we find that structures become only marginally more planar. Although, this may be connected to another underlying discrepancy between simulations and observations: Milky Way dwarfs are more centrally located. Simulations tend to have most subhaloes at large distances, while the Milky Way dwarfs are tightly clustered near the center, nine within 150 kpc (Kravtsov et al., 2004). This effect can be seen in Fig. 2.2 where the largest concentration of subhaloes is at a large radial distance, this is especially evident with massive subhaloes. In this study, we have limited our subhalo selection to choose only those haloes that have \( V_{\text{peak}} > 10 \text{ km s}^{-1} \), which helps to remove a radial bias from our sample that would be present if we limited our sample by \( V_{\text{max}} \), the maximum circular velocity of a subhalo at the current time. However, this still leads to a slightly radially extended solution because of resolution issues near the centers of massive haloes. Although, Kravtsov et al. (2004) were able to match the Milky Way distribution well with their model, which found that only the largest sub-haloes were able to accrete enough matter to form successful galaxies before being tidal stripped to the smaller masses we observe today.

It must be realized that there exists some observation bias to preferentially detect only those dwarfs above and below the plane of the Milky Way (Mateo, 1998), although these areas are now starting to be explored (Minniti et al., 2011; Chakrabarti et al., 2015, 2016; Chambers et al., 2016). The current dearth of Milky Way satellites close to the plane (Mateo, 1998) and the lack of observational surveys probing Galactic substructure at low latitudes may mean that we have missed some massive Milky Way dwarfs close to the Galactic plane (Chakrabarti & Blitz, 2009, 2011). Furthermore, there is evidence that the Milky Way sample is far from complete. Yniguez et al. (2014) looked at the distribution of satellites around the Milky Way and M31, and found that within 100 kpc, the two distributions were remarkably similar but differed greatly at larger radii, indicating that our census of the bright Milky Way dwarfs is significantly incomplete beyond \( \sim 100 \text{ kpc} \). Willman et al. (2004) also argue that the Milky Way sample is incomplete due to obscuration and insufficient survey depth; therefore, the true number of dwarfs could be as much as three times larger than the current count. Recently, Homma et al. (2016) reported the detection of an ultra-
faint dwarf galaxy at a heliocentric distance of 87 kpc with the Subaru Hyper-Suprime Camera. They also point out that at the magnitude it was detected, SDSS has a completeness depth of only 28 kpc, meaning that even for dedicated surveys, dwarf galaxy detection is still incredibly difficult and far from complete.

However, if deeper surveys do not uncover a similarly large number of bright satellites at large Galactocentric distances as we see in cosmological simulations, then we have to conclude that this is a real discrepancy. Kroupa et al. (2010) have argued that this discrepancy suggests that a new solution using modified Newtonian dynamics (MOND) is needed on galactic scales to explain the distribution and number of satellites. Another solution is that torques from the baryonic components cause the satellites to lose angular momentum and spiral inwards. The majority of hydrodynamical, cosmological simulations do not produce sufficiently extended H I discs as observed in the Local Volume, so the lack of extended baryonic components in simulations (or the so-called angular momentum problem) may well be responsible for this problem (Guedes et al., 2011). If this is the cause, then one would expect to see a similarly compact structure in high-resolution hydrodynamical cosmological simulations that do have extended baryonic components, and it may be the case that spiral galaxies with extended H I discs have more compact satellite distributions. Therefore, an interesting simulation to consider is ILLUSTRIS (Genel et al., 2014), which includes both baryonic and dark matter. However, the resolution of ILLUSTRIS allows only the detection of dwarfs down to a mass of $\sim 2 \times 10^7$ M$_{\odot}$ (Haider et al., 2016). At this resolution, only galaxies larger than Ursa Minor would be detected. Simulations do not yet realistically represent physical processes that could make dwarfs spiral in more quickly or completely disrupt faster than expected.

Planes of satellites similar to the observed Milky Way and M31 planes have been studied in detail in dark matter-only simulations by Buck et al. (2015, 2016). Similar to this study, they found that these planes are not uncommon but are unstable and quickly disrupt. However, it has also been argued that the distributions of satellites found between dark matter-only and baryonic+dark matter simulations are inherently different (Ahmed et al., 2016). Although the results in this paper contest those found by Pawlowski & McGaugh (2014), it is agreed that there is a need for
high-resolution simulations that include both dark and baryonic matter.

The eight classical dwarfs that were found to have reliable proper motion measurements were shown to lose significance within 0.5 Gyr, which is within the time that their orbit integrations were found to be trustworthy. Beyond that, those dwarfs continued to show a low significance even up to 1 Gyr unlike the other distributions that were studied (Fig. 2.6). In order to more definitively say that the structure is not coherent, more accurate proper motions of all the dwarfs are needed, especially those dwarfs that have poorly constrained velocity components such as Ursa Minor, Sculptor, and Carina. However, in order to analyze the orbits of all the dwarfs beyond 0.5 Gyr, accurate proper motions of SMC, Sextans, Fornax, Leo II, and Leo I will also have to be achieved. All of these dwarfs have at least one velocity component that has an uncertainty nearly equal to or greater than its magnitude. It appears that directionality is very important since the direction of a velocity component with a large uncertainty can flip, which will lead to very different solutions.

Truly understanding the orbital history of a dwarf like Leo II is especially complicated. Because of its great distance from the Milky Way, large errors in velocity result in a large volume of error space unlike Sextans, for example, which is the least constrained dwarf in velocity but lies within 100 kpc of the Milky Way and will therefore lie closer to any planar solution due to its proximity to the center. Previous work has shown that possibly only four dwarfs truly belong to a planar structure: Sculptor, Draco, Sextans, and Carina, three of which have proper motions that are the most poorly constrained. While an alignment of four dwarfs would be unique, it would not threaten to falsify $\Lambda$CDM as an entire VPOS may but maybe instead indicate a large merger event in the past.

The era of large scale surveys and accurate proper motion studies like the Large Synoptic Survey Telescope (LSST; LSST Science Collaboration et al., 2009) and Gaia (Gaia Collaboration et al., 2016) will inevitably help solve this problem as well as add more VPOS dwarfs to the list of satellites for which we have accurate proper motions. Proper motions of dwarf galaxies are exceedingly difficult to obtain. Without these measurements, it is difficult to distinguish between dwarf
galaxies located in a coherent structure and dwarfs that happen to align momentarily. However, as surveys and observations continue to improve we will be able to detect more dwarf galaxies around neighboring hosts and may begin to infer the presence of more dwarf planar structures.

We have compared the Milky Way distribution of massive dwarf galaxies to distributions of subhaloes in CDM simulations. We have also seen how the GPoA around M31 compares with CDM simulations and see that it too is thinner than most predicted distributions but is still contained within them (Fig. 2.3). It is important to note that when comparing one or two observations against a full theoretical distribution, it is not entirely unlikely to see outliers from the true distribution. When observing multiple systems for the same phenomenon, one must consider the “look elsewhere effect” which explains that expanding your search area includes increasing your chances of seeing more statistical fluctuations (e.g. Way et al., 2012). In other words, observing multiple significant events is not as unlikely as seeing just one significant event when you continue to broaden your search. This effect can be quantified through the use of the trials factor which defines the probability of falsely defining a distribution as significant by the sum of the probabilities.

\[
\text{Prob(false +)} = 1 - (1 - p)^N,
\]

where \( p \) is the probability of falsely judging a distribution as significant and \( N \) is the number of trials. For our case, the VPOS is located 2.03\( \sigma \) away from the mean of Fig. 2.3 (or \( p = 0.0424 \)). Ibata et al. (2013) and Conn et al. (2013) showed that 15 of the 27 known dwarfs around M31 are aligned in a plane of thickness, \( D_{\text{rms}} = 12.34 \text{ kpc} \) or \( \delta = 0.12 \). This means that the plane around M31 is located 3.43\( \sigma \) away from the mean (or \( p = 0.0006 \)). Here, \( p \) represents the number of simulated planes thinner than the observed distribution over the total number of simulated planes. Therefore, if we were to judge these results as significant alignments then the probability that one or both of them are actually false positives is \( \text{Prob(false +)} = 0.043 = 4.3 \text{ per cent.} \)
Chapter 2. *Is the VPOS a serious problem for $\Lambda$CDM?*

### 2.7 Conclusions

Our main results and conclusions are as follows:

- We have analysed the Milky Way distribution of classical dwarf galaxies and compared it to distributions of subhaloes in CDM simulations. Plane fitting was performed using PCA. We compared the Milky Way distribution to the *vlii* (Diemand et al., 2007a) and ELVIS (Garrison-Kimmel et al., 2014) dark matter-only simulations. Fig. 2.3 shows that most solutions from simulations form relatively poor planar structures with a normalized thickness of $\delta \sim 0.40$. However, the Milky Way alignment is in rough agreement with this value, lying less than $2\sigma$ away from the mean, leading to a probability of drawing a more planar distribution from a simulation to about 1 in 24. When only the 50 largest subhaloes are considered, the probability of drawing a more planar distribution from a simulation increases to about 1 in 10.

- New proper motion data from Piatek et al. (2016) have significantly improved the accuracy of the proper motion measurements for Leo II. We have presented an orbital analysis of Leo II and find that it has spent much of its time at large distances, making, at most, one pericenter passage within the last 2.5 Gyr. When this knowledge is combined with information about its star formation history, it appears that Leo II may be on first infall onto the Milky Way. Therefore, we argue that Leo II should be excluded from VPOS analyses.

- Due to the distant radial location, high velocity, and star formation history of Leo I, it appears that it too is not part of a long-lived structure.

- When plane-fitting analysis was performed on the remaining classical dwarfs after Leo I and Leo II were removed, a very similar plane was found. This indicates that although Leo I and Leo II are located distantly compared to the other dwarfs, they alone do not drive the polar fit of the VPOS.
• Through the use of the test particle code developed by Chang & Chakrabarti (2011), we integrated the orbits of the dwarfs backward in time to analyze the stability of the VPOS. We found that the structure became less significant over time. This result was seen for all the subsets considered: all 11 classical dwarfs, Leo I and Leo II removed, and dwarfs with aligned orbital angular momentum vectors.

• We found that adding errors to the components of velocity and radius inevitably led to a loss of coherent structure. For errors up to 100 per cent in each velocity component, coherence was maintained after 0.5 Gyr; for errors greater than 50 per cent, coherence was lost after 0.75 Gyr; and for errors greater than 30 per cent, coherence was lost after 1 Gyr. This shows that eight dwarfs have errors that are constrained enough that orbit integrations can be trusted for up to 0.5 Gyr. Those dwarfs are Sagittarius, LMC, SMC, Draco, Sextans, Fornax, Leo II, and Leo I. When the orbits of these dwarfs are integrated backward in time, they also display a loss of significance well within 1 Gyr. Thus, we find that the VPOS is not a stable structure that maintains coherence or significance.\(^1\)

• The three remaining dwarfs that have error estimates too large to be trustworthy include Ursa Minor, Sculptor, and Carina. Only three dwarfs have proper motion measurements that are accurate enough to be trusted in orbit integrations beyond 1 Gyr: Sagittarius, LMC, and Draco. The other remaining dwarfs (SMC, Sextans, Fornax, Leo II, and Leo I) suffer from at least one very uncertain velocity component. If the errors on the proper motions of the dwarfs were constrained to a level of \(\leq 30\) per cent, our conclusion on the stability of the VPOS would be further bolstered.

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\(^1\)The authors would like to recognize the work of Fernando et al. (2017) who found that Milky Way/M31 planes are unstable in general; this paper was submitted while our paper was in the review process.
SCALING RELATIONS FOR H\textsubscript{I} STUDIES OF SPIRAL GALAXIES: RELATING DENSITY STRUCTURE TO PASSING SATELLITES

In the current structure formation paradigm of ΛCDM, large, Milky Way-sized spiral galaxies grow by the merger of thousands of smaller galaxies and, thus, should be surrounded by hundreds of subhaloes. However, observations have so far failed to find more than the ~50 dwarf galaxies that are currently known. This discrepancy has been deemed the Missing Satellites problem. We have already seen that there may be many reasons for some subhaloes to not form successful galaxies through either suppressed star formation during the epoch of reionization (Bullock et al., 2000), feedback from the first stars expelling any unused gas from the shallow potential well (Wise & Abel, 2008), ram pressure stripping of gas (Simpson et al., 2013), tidal stripping of gas and dark matter (Kravtsov et al., 2004), changes to the observed power spectrum of the cosmic microwave background at small scales through warm dark matter (Bode et al., 2001; Zentner & Bullock, 2003; Lovell et al., 2012), or, more likely, a combination of some or all those factors. However, if these dark or nearly dark subhaloes do exist, how could we ever expect to observe them?
3.1 The Tidal Analysis Method

Spiral galaxies are surrounded by diffuse neutral hydrogen ($\text{H}^i$) gas that extends far outside the stellar disk of galaxies. This extended $\text{H}^i$ gas disk is susceptible to perturbations from passing substructure due to its kinematically cold and diffuse nature. Furthermore, the location of the $\text{H}^i$ disk, far outside the optical disk, places it where theoretical models expect substructure to be (Bigiel et al., 2010) making it an ideal “detector” of substructure. This massive reservoir of cold gas is observable through the “forbidden” 21 cm emission line caused by electron spin flip and observations of the Milky Way have shown large perturbations well outside the optical disk of the Galaxy (Levine et al., 2006). The strength and scale of these perturbations cannot be explained by differential rotation or propagating density waves induced by the stellar spiral arms (Chakrabarti & Blitz, 2009). Through the analysis of disturbances in the extended $\text{H}^i$ disks of spiral galaxies using hydrodynamical simulations and $\text{H}^i$ observations, constraints on the subhalo distribution and variations in halo shapes can be obtained.

The work done by Chakrabarti & Blitz (2009, 2011); Chakrabarti et al. (2011) and Chang & Chakrabarti (2011) has shown that one can constrain the mass, current radial distance, and azimuth of a galactic satellite by finding the best-fit to the low-order Fourier modes of the projected gas surface density of an observed galaxy. Then by performing and searching a set of hydrodynamical simulations, a best-fit to the observed data can be obtained. This process is called the Tidal Analysis method (Chakrabarti & Blitz, 2009, 2011). In Chakrabarti et al. (2011) this process was applied to M51 and NGC 1512, both of which have known optical companions about 1/3 and 1/100 the mass of their hosts, respectively. When Tidal Analysis was performed on these galaxies the masses and relative positions of the satellites in both systems were accurately recovered. Moreover, the fits to the data were found to be insensitive to reasonable variations in choice of initial conditions of the primary galaxy or orbital inclination and velocity of the satellite. The advantage of this method is that it can be used to find dark matter dominated satellites, as long as they are at least 0.1 percent the mass of the primary.
There are many methods for detecting the dark matter distribution within galaxies. One method is via gravitational lensing analysis which has the ability to constrain substructure within an individual galaxy lens (Vegetti et al., 2012); however, single galaxy strong lenses are very rare systems. The analysis of stellar streams of tidal debris can yield information about past encounters of dwarf galaxies with the host as well as simultaneously provide a tracer of the gravitational potential over a wide range of radii (Johnston et al., 1999); however, it is can only be used on very nearby galaxies where tidal streams can be mapped in three dimensions. Studying velocity asymmetries in the stellar disk can also provide evidence of past interactions (Widrow et al., 2012; Xu et al., 2015). However, Tidal Analysis has many advantages over these other methods. Firstly, it is not subject to uncertainties in the projected mass distribution like gravitational lensing. Unlike the other methods, Tidal Analysis is not restricted to the stellar disk which has a much smaller cross section for interactions and only the largest interactions can create disturbances. Instead, Tidal Analysis takes advantage of the large surface area covered by the H\textsc{i} gas that is easily disturbed by passing substructure. Tidal Analysis also provides an indirect detection method for dark matter dominated objects but it does not make any assumptions about the nature of the dark matter particle like gamma ray (Strigari et al., 2008; Hooper et al., 2008) or direct detection experiments (e.g. Angle et al., 2008; Bernabei et al., 2008).

### 3.2 Introduction

It has been shown that obtaining an H\textsc{i} map of a galaxy and searching a set of hydrodynamical simulations can allow observers to constrain substructure and through the work of Chang & Chakrabarti (2011) it was further shown that a simple relation exists between the density response of the gas disk (specifically the low-order Fourier amplitudes of the projected surface gas density)
Chapter 3. Scaling Relations for H I Studies of Spiral Galaxies

and the mass of a perturbing satellite,

\[ a_{t,\text{eff}} = 0.5 \left( \frac{m_{\text{sat}}}{M_{\text{host}}} \right)^{0.5}, \]  

(3.1)

where \( a_{t,\text{eff}} \) is the total effective amplitude of the projected gas surface density response, \( m_{\text{sat}} \) is the mass of a perturbing satellite, and \( M_{\text{host}} \) is the mass of the host galaxy.

Simple scaling relations such as these between observable quantities and unobservable quantities are extremely useful for astronomers. One of the more famous examples being the \( M - \sigma \) relation (Ferrarese & Merritt, 2000; Gebhardt et al., 2000), which relates the easily observable velocity dispersion of a galaxy to the much harder to constrain mass of the central massive object. This type of relation is extremely useful as it gives astronomers a way of immediately obtaining useful knowledge of substructure without having to perform time-intensive hydrodynamical simulations. However, the above relation, equation 3.1, is true only for interactions that occur when a satellite interacts with a halo at a specific pericenter distance (20 kpc).

The purpose of this work is to extend the previous results of Chang & Chakrabarti (2011) to find simple scaling relations for the density response of the H I disk of a galaxy for any interaction that occurs at any pericenter distance. Here, we simulate satellite interactions with a steady state disk and vary the pericenter approach distance, the mass ratio of the satellite to the host, and the inclination of approach for an impacting satellite. We then follow the evolution of the disk and record the total effective density response after the interaction has occurred. We also study the effects of multiple satellites interacting with a gas disk. Disturbances in the H I gas disk dissipate on the order of a dynamical time or \( \sim 1 \) Gyr (Chakrabarti et al., 2011); however, interactions also occur about every \( \lesssim 1 \) Gyr. Therefore, signatures of multiple previous encounters may still be present and it is important to study their effects.
3.3 Methods: Test Particle Simulations

3.3.1 Halo Potentials

This work uses the code developed by Chang & Chakrabarti (2011) as was described previously in Section 2.3.3. We employ a static, spherical, Hernquist (1990) potential that has the same mass and inner density slope within $r_{200}$ as an equivalent NFW (Navarro et al., 1997) profile. The host halo has a mass of $M = 1.1 \times 10^{12} \, M_\odot$ (Watkins et al., 2010; Deason et al., 2012; Wang et al., 2012) and a concentration parameter of $c = 9.39$. For convenience, the potential and equations of motion are stated again here.

The potential is described by

$$\Phi(r) = -\frac{GM_T}{r + a},$$

where $a$ is the scale-length of the Hernquist profile and $M_T$ is the normalization to the potential or the total mass. Dynamical friction is also modelled using the Chandrasekhar formula (Besla et al., 2007; Chang & Chakrabarti, 2011) and the equation of motion has the form

$$\ddot{r} = \frac{\partial}{\partial r} \Phi_{MW}(|r|) + \frac{F_{DF}}{M_{sat}},$$

where $M_{sat}$ is the satellite mass, $\Phi_{MW}(|r|)$ is the potential corresponding to equation 2.3 and $F_{DF}$ is the dynamical friction term. The dynamical friction term is given by:

$$F_{DF} = -\frac{4\pi G^2 M_{sat}^2 \ln(\Lambda) \rho(r)}{v^2} \left[ \text{erf}(X) - \frac{2X}{\sqrt{\pi}} \exp(-X^2) \right] \frac{v}{v}.$$

Here, $\rho(r)$ is the density of the dark matter halo at a galactocentric distance, $r$, of a satellite of
mass $M_{\text{sat}}$ travelling with velocity $v$; $\text{erf}(X)$ is the error function and $X = v/\sqrt{2\sigma^2}$, where $\sigma$ is the 1D velocity dispersion of the dark matter halo which is adopted from the analytic approximation of Zentner & Bullock (2003). The Coulomb logarithm is taken to be $\Lambda = r/(1.6k)$, where $k$ is the softening length.

Perturbing subhaloes are modeled as simple, spherical Plummer spheres with a potential described by

$$\Phi_P(r) = -\frac{GM}{\sqrt{r^2 + a^2}}. \quad (3.2)$$

### 3.3.2 Test Particle H\text{I} Disk

The host halo “H\text{I} gas” disk is represented by massless test particles that follow the potential in circular orbits unless perturbed. To fully capture the response of the disk, $10^5$ test particles are used for the host galaxy disk. This was shown to give the best trade off between resolution and computation time. The disk extends to 60 kpc in radius, motivated by observations of the Milky Way’s H\text{I} disk (Wong & Blitz, 2002; Levine et al., 2006; Kalberla & Kerp, 2009; Bigiel et al., 2010). The type of halo used was also checked to see the impact on observations. Besla et al. (2007) showed that an isothermal sphere model for a dark matter halo was too simple and yielded unphysical results due to excessive dynamical friction. Therefore, both NFW and Hernquist profiles were investigated. The host galaxy used in the simulations was chosen to be Milky Way-like and NFW halos were tested with values obtained from Kallivayalil et al. (2013). Those simulations all yielded similar results to a Hernquist profile with a matched inner density slope and mass (as was used in Chang & Chakrabarti 2011).

In order to obtain initial conditions of the perturbing satellites, the perturber was placed in the plane of the galaxy at the location of periapsis traveling at escape velocity. The simulation was then run backward in time to ascertain the position and velocity components of a point in time at which the perturber was well outside the range of influence; this distance was chosen to be $\sim 150$
kpc away. Once the initial conditions were found, the simulations were then run forward in time \( \sim 2.5 \) Gyr.

There are several ways in which a test particle code simplifies the computation of the disk response. Firstly, unlike N-body codes, gravitational forces between the particles in the disk are not computed self-consistently. The particles in the disk are massless tracers that feel the perturbing effects of the satellites and the gravitational potential, but they do not contribute to the overall potential, which is pre-specified (either Hernquist or NFW). Secondly, the dissipational effects of a gaseous component are not modeled (as is done in smoothed particle hydrodynamic (SPH) codes), so the response of the disk is long-lived and settles to a relatively constant value about 1 Gyr after the initial perturbation. These effects can be captured by full SPH simulations which we will carry out in the future. As shown by Chang & Chakrabarti (2011) by comparison to SPH simulations, neglecting these effects allows for a very fast and relatively accurate computation of the disk response in the regime where the self-gravity of the disk and dissipationless effects are not significant.

### 3.3.3 Density Response

In addition to modeling the response of the disk as test particles, Chang & Chakrabarti (2011) showed that the response of the disk could be calculated perturbatively in the regime where the self-gravity of the particles and dissipation is not significant. This allows for a simplification of the equations of motion for the particles in the disk into separate wave equations. Solving these perturbed equations for a finite number of modes, \( m \), allows for the estimate of the linear response of a circular ring of orbiting particles. This greatly simplifies the orbit of a particle into a sum of \( m \) simple harmonic oscillators, whose natural frequency only depends on radial position (Chang & Chakrabarti, 2011). This method of breaking the disk into rings has been used before in the context of ring galaxies (Struck-Marcell, 1990; Struck-Marcell & Lotan, 1990; Struck-Marcell & Higdon, 1993); however, in ring galaxies only the \( m = 0 \) mode is relevant. Here, the relevant modes are the lower but \( m \neq 0 \) modes since the low order modes include information on spiral structure.
induced by interactions.

The individual Fourier modes of the gas surface density are calculated at every radius as a function of time and are integrated over azimuth, $\phi$, via

$$a_m(r, t) = \frac{1}{2\pi} \int_0^{2\pi} \Sigma(r, \phi, t) \exp(-im\phi) d\phi,$$  \hspace{1cm} (3.3)

where $\Sigma(r, \phi, t)$ denotes the projected gas surface density on a cylindrical grid. The range of radii values where the individual Fourier modes are calculated are taken to be between $r_{in} = 10$ kpc and $r_{out} = 40$ kpc, motivated by H\textsc{i} observations of the Milky Way (Levine et al., 2006). The Milky Way disk appears to have well developed spiral structure out to $\sim 40$ kpc, beyond that the H\textsc{i} disk appears to be patchy and highly turbulent out to $\sim 60$ kpc (Kalberla & Kerp, 2009), which is the extent of the disk in our simulations. As pointed out in Chang & Chakrabarti (2011), the individual density modes display localized peaks at the location of pericenter passage (Fig. 3.1).

We also plot in Fig. 3.1, $a_{tot}$, which is a synthetic measure of the power in all the modes defined as

$$a_{tot}(r, t) = \sqrt{\sum_{m=1}^{4} \frac{|a_m(r, t)|^2}{4}}.$$ \hspace{1cm} (3.4)

The power of this synthetic measure is that it is less susceptible to changes in the orbits of the perturbing satellite since the response in the individual modes will vary with orbital parameters (Figure 3.2). For higher inclinations, the response from the disk gets smeared into two nearby peaks around the impact location but still shows the largest response around the pericenter location. This is because some of the force of impact goes into creating horizontal disturbances in this disk and some of the force creates vertical disturbances in the disk, thus splitting the density response between the two directions while we only measure the projected density structure. This analysis
Figure 3.1: The density response of each mode versus radius for a perturbing satellite with a mass ratio of 1:100 and an pericenter of $R_p = 20$ kpc on a coplanar orbit ($i = 0$). Each panel displays the density response of modes $m = 1 - 4$ normalized by the complete $m = 0$ mode. The time is displayed in the top left of each panel relative to the point of impact of a perturbing satellite, impact occurs in the second panel labeled “Impact”.

shows that it is possible for us to find the pericenter location of a perturber if that perturber passes through the H\textsc{i} disk of the host galaxy.

Now that we have a method for finding the pericenter of a perturbing satellite, we must define a global measure of the density response that is averaged over both radius and azimuth in an effort to find the mass of the perturbing satellite. The effective amplitude of the disk for an individual mode is defined as

$$a_{m,\text{eff}}(t) = \frac{1}{r_{\text{out}} - r_{\text{in}}} \int_{r_{\text{in}}}^{r_{\text{out}}} |a_m(r, t)| \, dr.$$  \hfill (3.5)

The total effective disk response is thus calculated by summing the effective response of each
Figure 3.2: For each panel, the disk has experienced an interaction with a satellite of mass 1/100 the mass of the host at a pericenter of 20 kpc for varying inclinations. The inclination is stated in the upper left of each panel. The response for each frame is shown 100 Myr after pericenter passage.

\[
a_{t,\text{eff}}(t) = \sqrt{\frac{1}{4} \sum_{m=1}^{4} |a_{m,\text{eff}}(t)|^2}. \tag{3.6}
\]

Although this quantity varies with time, it settles to a nearly constant value \(\sim 1\ \text{Gyr}\) after the initial interaction in the absence of dissipation and is dependent on the mass ratio and pericenter of a perturbing satellite (see Fig. 9 of Chang & Chakrabarti, 2011).

3.3.4 Parameter Space

Simulations were run with varying initial conditions to try and constrain the parameters which impact the Fourier response the most and also to find a relation between observed disk response and the parameters that we are trying to infer: satellite mass and pericenter distance. Simulations
were run with subhalo masses ranging from $1/10$th to $1/1000$th the mass of the host halo which was set as $M_{\text{host}} = 1.1 \times 10^{12} \, M_\odot$; although, the outcome of the simulations was found to be consistent with reasonable changes to host halo mass. The angle of inclination was also varied from coplanar to nearly perpendicular where $i = 0^\circ$ indicates a coplanar orbit. Finally, pericenter distance was varied from 20 to 100 kpc in steps of 10 kpc. Simulation data is listed in Table 3.1.

### 3.4 Results

#### 3.4.1 One Satellite

The results of our parameter search can be seen in Figure 3.3. When investigating the disk response with respect to varying pericenter, we see that in the 1:10 and 1:15 mass ratio simulations the response actually decreases or flattens out when pericenter decreases, clearly an unphysical result. Also, there seems to be a heavy dependence on inclination for these mass ratios that is not seen in the other cases. For these reasons the 1:10 and 1:15 mass ratio results are not included in further analysis. For relatively massive satellites, the test particle code is unable to capture the full impact of the dynamics, as tidal stripping of the satellite is not included nor is the self-gravity of the disk and its backreaction on the satellite. The other mass ratios show the expected result that the pericenter distance is inversely related to the density response of the disk.

Table 3.1: Simulation parameters, host galaxy parameters are given in the upper part of the table and the parameter space for interacting satellites is in the lower half.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ($M_\odot$)</td>
<td>$1.1 \times 10^{12}$</td>
</tr>
<tr>
<td>a (kpc)</td>
<td>50</td>
</tr>
<tr>
<td>$v_0$</td>
<td>9.39</td>
</tr>
<tr>
<td>$v_{200}$ (km s$^{-1}$)</td>
<td>180</td>
</tr>
<tr>
<td>$R_{\text{peri}}$ (kpc)</td>
<td>20, 30, 40, 50, 60, 70, 80, 90, 100</td>
</tr>
<tr>
<td>Inclination ($^\circ$)</td>
<td>0, 10, 20, 30, 40, 50, 60, 70, 80</td>
</tr>
<tr>
<td>Mass Ratio</td>
<td>1:10, 1:15, 1:30, 1:50, 1:100, 1:500, 1:1000</td>
</tr>
</tbody>
</table>
Figure 3.3: The results of our parameter search varying pericenter, inclination, and mass ratio of the perturber to host (See Table 3.1). $a_{t,\text{eff}}$ is the global measure of the density response of the gas disk to the perturber and is defined by Equation 3.6. The title of each panel lists the mass ratio of the perturbing satellite to the host. Each data point represents an individual run, the vertical spread at each pericenter, $R_p$, represents the change in response with inclination. The red line is the found scaling relation represented by Equation 3.7.

In Chang & Chakrabarti (2011), for a single pericenter, a simple power law scaling relation was found (equation 3.1) that showed that the effective density response increased as the square root of the mass ratio. Now that we are investigating multiple pericenters, we see that the pericenter of the perturbing satellite affects the slope of the scaling relation. To find the correct form of the fitting equation, a linear fit was made to each pericenter data set on a log$_{10} (a_{t,\text{eff}})$ versus log$_{10} (m_{\text{sat}}/M_{\text{host}})$ plot. Since linear fits performed very well, the fitting equation was of the form $a_{t,\text{eff}} = A (m_{\text{sat}}/M_{\text{host}})^B (R_p/50 \text{ kpc})^C$ where $A$, $B$, and $C$ are constants. Ultimately, the final form of the equation was found to be

$$a_{t,\text{eff}} = 0.88 \left( \frac{m_{\text{sat}}}{M_{\text{host}}} \right)^{0.6 \sqrt{R_p/50 \text{ kpc}}} ,$$

and is shown as the red line in Fig. 3.3.
3.4.2 Multiple Satellites

In these simulations it is important to note that gas dissipation has not been taken into account. In the presence of gas dissipation, the Fourier amplitudes will decrease as a function of time and disturbances in the gas will damp out in approximately a dynamical time or $\sim 1 \text{ Gyr}$ (Chakrabarti et al., 2011). While it is more likely that satellites will interact with larger halos on the timescale of once per $\sim \text{Gyr}$ (Kazantzidis et al., 2008), there is also evidence that multiple satellites may fall onto large halos simultaneously. In fact, there is evidence to suggest that the Large and Small Magellanic Clouds are falling onto the Milky Way as a binary system (Besla et al., 2010). Therefore, it is important to study the effects of multiple satellite interactions on our results. For these interactions, the tidal force is a good indication for which interactions produce the largest response and is given in approximate form by

$$F_T \propto \frac{M_{\text{sat}}}{R^3},$$  \hspace{1cm} (3.8)

where $F_T$ is the tidal force, $M_{\text{sat}}$ is the satellite mass, and $R$ is the radial location. With this knowledge, we searched two dark matter-only cosmological simulations, Exploring the Local Volume In Simulations (ELVIS; Garrison-Kimmel et al., 2014) and VIA LACTEA II (VLI; Diemand et al., 2007b, 2008), for large interactions that occurred.\footnotemark For both simulations, we used the full evolutionary tracks which follows the position of every dark matter halo in the simulation from the start of the simulation until present day.

To find which subhaloes had the greatest effect on the host galaxy, we found the pericenter for each halo and calculated the tidal force at pericenter using equation 3.8. We then sorted the results by tidal force and looked at the top ten interactions that occurred. Because we know that our analysis is only sensitive to subhaloes with masses greater than $1/1000$ the mass of the host halo, we limited our analysis to only those haloes which were above that mass. This also eliminated

\footnotetext{For a full description of both dark matter simulations, see Section 2.3.1.}
Table 3.2: The top ten interactions seen dark matter simulations, shown in order of occurrence. Column 1 displays the name of the simulation. Column 2 displays the time of interaction with Time = 0 being present day. Column 3 shows the ratio between the mass of the subhalo to the mass of the host halo. Column 4 displays the pericenter distance. Column 5 shows the total effective amplitude of the density response calculated via equation 3.7. Column 6 shows the rank of the interaction in terms of the tidal force calculated via equation 3.8. Finally, Column 7 displays notes on interesting encounters.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Time (Gyr)</th>
<th>Mass ratio</th>
<th>$R_p$ (kpc)</th>
<th>$a_{t,e}$</th>
<th>Rank</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELVIS: iHall</td>
<td>0</td>
<td>1:71</td>
<td>50</td>
<td>0.068</td>
<td>2</td>
<td>$R_p$ at same location</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1:759</td>
<td>35</td>
<td>0.032</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.1</td>
<td>1:487</td>
<td>34</td>
<td>0.041</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.5</td>
<td>1:502</td>
<td>38</td>
<td>0.034</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.1</td>
<td>1:17</td>
<td>44</td>
<td>0.179</td>
<td>1</td>
<td>First two, $90^\circ$ separated, next at same location,</td>
</tr>
<tr>
<td></td>
<td>-2.1</td>
<td>1:668</td>
<td>35</td>
<td>0.034</td>
<td>7</td>
<td>twice the distance</td>
</tr>
<tr>
<td></td>
<td>-2.3</td>
<td>1:11</td>
<td>100</td>
<td>0.115</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.7</td>
<td>1:56</td>
<td>60</td>
<td>0.062</td>
<td>4</td>
<td>$R_p$ at same location</td>
</tr>
<tr>
<td></td>
<td>-2.7</td>
<td>1:477</td>
<td>57</td>
<td>0.017</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-8.0</td>
<td>1:626</td>
<td>51</td>
<td>0.018</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>ELVIS: iScylla</td>
<td>0</td>
<td>1:86</td>
<td>133</td>
<td>0.011</td>
<td>9</td>
<td>Same location, three times the distance</td>
</tr>
<tr>
<td></td>
<td>-0.3</td>
<td>1:31</td>
<td>29</td>
<td>0.183</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.0</td>
<td>1:956</td>
<td>53</td>
<td>0.013</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.4</td>
<td>1:124</td>
<td>75</td>
<td>0.025</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-3.0</td>
<td>1:87</td>
<td>179</td>
<td>0.006</td>
<td>10</td>
<td>Same location, twice the distance</td>
</tr>
<tr>
<td></td>
<td>-3.2</td>
<td>1:9</td>
<td>100</td>
<td>0.136</td>
<td>3</td>
<td>Mirrored orbits</td>
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<td></td>
<td>-4.7</td>
<td>1:608</td>
<td>59</td>
<td>0.013</td>
<td>5</td>
<td>Mirrored orbits</td>
</tr>
<tr>
<td></td>
<td>-4.7</td>
<td>1:441</td>
<td>67</td>
<td>0.013</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-5.9</td>
<td>1:62</td>
<td>23</td>
<td>0.164</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-7.4</td>
<td>1:863</td>
<td>56</td>
<td>0.012</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>VLII</td>
<td>0</td>
<td>1:557</td>
<td>54</td>
<td>0.017</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.8</td>
<td>1:305</td>
<td>114</td>
<td>0.005</td>
<td>10</td>
<td>Mirrored orbits</td>
</tr>
<tr>
<td></td>
<td>-4.2</td>
<td>1:741</td>
<td>48</td>
<td>0.018</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-4.2</td>
<td>1:697</td>
<td>85</td>
<td>0.005</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-5.6</td>
<td>1:588</td>
<td>63</td>
<td>0.012</td>
<td>6</td>
<td>90° separated</td>
</tr>
<tr>
<td></td>
<td>-7.0</td>
<td>1:130</td>
<td>132</td>
<td>0.008</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-7.6</td>
<td>1:310</td>
<td>49</td>
<td>0.029</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-7.6</td>
<td>1:110</td>
<td>89</td>
<td>0.020</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-8.3</td>
<td>1:482</td>
<td>69</td>
<td>0.011</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-11.0</td>
<td>1:210</td>
<td>23</td>
<td>0.100</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
spuriously large tidal force values for extremely small subhaloes that passed very close to the center of the host halo. The results of that investigation are shown in Table 3.2.

A few things are immediately clear from this comparison. Firstly, it appears that large interactions do indeed occur on a timescale of every $\sim 1$ Gyr in agreement with other studies (Kazantzidis et al., 2008); both the iScylla and vlHI runs show greater separations between large encounters but iHall shows more rapid large encounters. It is also clear that large encounters occur at distances greater than 20 kpc with the average pericenter distance being $\langle R_p \rangle = 67$ kpc. Masses of the perturbers seem to span the whole range that was studied above, with almost all interactions occurring with subhaloes that were within the mass range where our analysis is valid i.e. $m_{\text{sat}}/M_{\text{host}} > 1/30$. It also appears that every simulation shows the occurrence of multiple subhaloes interacting with the host halo simultaneously. Furthermore, they appear to fall into only a few categories: 1) interactions occur in roughly the same azimuthal location but are either delayed, 1/10 the mass of the other perturber, or occur further in radius, 2) interactions are on roughly “mirrored” orbits where two nearly identical satellites strike the disk at roughly the same radius but opposite sides of the disk or 3) interactions occur $90^\circ$ separated. Here we investigate the first two categories of interactions in sets we refer to as “delayed” or “mirrored” orbits. For the mirrored cases, the disk was impacted by two identical satellites at the same time with one having the inverse parameters of the other: $\mathbf{X}_2, \mathbf{V}_2 = ((X_1, Y_1, Z_1), (V_{x1}, V_{y1}, V_{z1})) * (-1)$. The delayed cases were defined as an identical satellite with an identical orbit trailing $< 0.5$ Gyr behind the initial satellite. Results of our simulations are shown in Fig. 3.4. Also displayed in Fig. 3.4 are the results from Table 3.2 for each simulation. Each interaction is plotted in the bottom row, and multiple interactions are plotted in the corresponding row where appropriate.

### 3.5 Discussion

Since $a_{t,\text{eff}}$ is a global parameter dependent on two unknowns, there is obviously a degeneracy between a higher mass perturber with a large pericenter and a low mass perturber with a small
Figure 3.4: (Caption displayed on next page.)
Figure 3.4: (Continued) The title of each panel displays the mass ratio of each satellite, \( a_{t,\text{eff}} \) is calculated by equation 3.6, and \( R_p \) represents the pericenter of the satellite. Each blue data point represents an individual run, the vertical spread at each pericenter represents the change in response with inclination. Green circles, cyan triangles, and magenta squares represent the density response from the interactions shown in Table 3.2 which were seen in the dark matter simulations ELVIS and vLH. The first row indicates the response for a disk that is impacted in the same location by two identical satellites in quick succession. The second row indicates the density response for a disk that is impacted by two identical satellites at the same time having mirrored orbits. The third row shows the density response for a disk that is impacted by two satellites on mirrored orbits but one satellite is 1/10 the mass of the other. The fourth row is identical to Figure 3.3 except that the mass ratios 1:10 and 1:15 have been excluded. The red line is the found scaling relation represented by equation 3.7 and the cyan line is the quadrature addition of two impacts (equation 3.9).

pericenter. However, in order to calculate \( a_{t,\text{eff}} \) we must sum the low order Fourier modes of the response which means that we have information about the individual modes. If we look at the modes individually and plot their amplitude against radius we can clearly see the difference between these two cases since there is a long lived peak in the response at the site of contact (Fig. 3.1). If the perturber never penetrates the disk (passes outside of 40 kpc for these simulations) then we observe no peaks in the response and must therefore look at the sum of the individual modes. However, even here we are not completely burdened by degeneracy since visually, the two cases will appear very different. For high mass perturbers that pass outside of the disk, gas gets stripped from the outer parts of the galaxy into long tidal tails whereas, for a less massive galaxy passing closer to the center, features such as long tidal tails are not seen (see Fig. 3 of Chakrabarti & Blitz, 2009).

For interactions with multiple satellites, we can see that, unsurprisingly, the impact of another satellite increases the response seen in the disk (top two panels of Fig. 3.4). Since each interaction is independent and creates an independent response in the disk, the response from each interaction should add in quadrature. The cyan line shows the quadrature addition of the two interactions which does appear to fit the data fairly well, essentially this is equation 3.7 multiplied by a factor
of $\sqrt{2}$.

$$a_{t,\text{eff}} = \sqrt{\sum_{1}^{k} \left[ 0.88 \left( \frac{m_{\text{sat}}}{M_{\text{host}}} \right)_{k} \frac{0.6}{\sqrt{R_{p,k}/50 \text{ kpc}}} \right]^{2}}, \tag{3.9}$$

where $(m_{\text{sat}}/M_{\text{host}})_{k}$ and $R_{p,k}$ are the mass ratio and pericenter of the $k$-th satellite.

Because of this behavior, only secondary satellites of equal mass will make substantial contributions to the total effective density response, otherwise the response is nearly equal to that of a single body interaction. To illustrate this point, row three of Figure 3.4 shows the total effective density response when two satellites interact with the disk simultaneously but one satellite is $1/10$ the mass of the other satellite. It can be clearly seen that the total effective density response from this type of interaction is very nearly identical to that of a single body interaction. Therefore, our analysis is only sensitive to the largest perturbing satellites, even in the presence of multiple interactions.

Interestingly, it appears that there may be an increased dependence on inclination for the mirrored cases that were studied. This increased dependence on inclination is an odd result that does not match the results from our one body or delayed simulations. In order to investigate this effect more, the individual Fourier modes were analyzed and are plotted in Fig. 3.5.

As you can see, there is larger response than that seen from one-body interactions (Fig. 3.1); however, the response is only seen in the $m = \text{even}$ modes. This occurs because of the perfect symmetry of the disk response that occurs for mirrored interactions and causes less power in $a_{t,\text{eff}}$ than would be expected. Although such perfect symmetry would not be expected to occur in physical systems, it raises a key point. Some physical systems may have some degree of symmetry that will make certain modes have less power, thus the effective total density response will not accurately represent those systems. However, all our simulations fall within the range of $a_{t,\text{eff}} - \sqrt{2} \ast a_{t,\text{eff}}$ with those systems with some degree of symmetry filling the volume in between those bounds. Therefore, the effects of multiple perturbers on the determination of $R_{p}$ and mass ratio
somewhat increases the degeneracy between results but not in an unbounded way and only for interactions with equal mass, multiple perturbers.

With the knowledge that the response from multiple satellite encounters adds in quadrature, we now know the results of any other combination of orbits through the quadrature addition of the one-body case. One concern is that, in the presence of symmetry, degeneracy may exist between one-body cases and two-body cases that are symmetric, if our scaling relation is used alone. In these cases, it is important to include the visual information that would be obtained from observations as this would help distinguish between single body cases and symmetric two body interactions.

In order to validate the results obtained here (equation 3.7), full SPH simulations will have to be performed. These simulations will incorporate the effects of gas dissipation and will represent more realistic systems. Also, because the disk of the host halo will be modeled as actual gas particles with mass and gravity, the mass ratios that could not be studied here will be able to be studied in detail (i.e. $m_{\text{sat}}/M_{\text{host}} > 1/30$).
3.6 Conclusions

Astronomers use scaling relations in many situations in order to gain information of a quantity which is otherwise unobservable. A well known example is the $M - \sigma$ relation relating the velocity dispersion of a galaxy (an easily observable quantity) to the mass of the central massive object (an incredibly hard observable quantity). Here, we have found a scaling relation between the projected gas surface density and the presence of passing substructure. We have also seen the effects of multiple perturbers on our results and found that the results are not completely degenerate. Since the observed density response in the gas disk from each interaction adds in quadrature, only equal mass satellites make substantial contributions to the total effective response seen.

The power of Tidal Analysis is that it is not necessary to be able to resolve the substructure itself and, in fact, the substructure need not contain baryonic matter. The scaling relation found here can easily be applied to galaxies that have already been mapped in $H\alpha$, such as The $H\alpha$ Nearby Galaxies Survey (THINGS, Walter et al., 2008), to constrain substructure. A further benefit of this study is that it limits the degeneracy between different interactions and thus limits the number of hydrodynamical simulations one needs to perform to recreate an observed system. This will greatly reduce the amount of time that it takes to perform Tidal Analysis.
4.1 Introduction

Now we switch gears from theoretical studies of substructure to observational studies. As discussed previously, there is a clear discrepancy between the expected number of dwarfs from simulations and the number of dwarfs seen around the Milky Way (i.e. the Missing Satellites problem; Klypin et al., 1999, see Section 1.4.1). This discrepancy may be a significant problem for $\Lambda$CDM; however, there is a lot of uncertainty that clouds our analysis. We have discussed the uncertain mass of the Milky Way (Section 2.5.2), which could highly influence the expected number of subhaloes since a less massive Milky Way leads to a lower number of expected subhaloes. Another uncertainty lies in our ability to detect dwarfs around the Milky Way due to obscuration from the dust and gas located in the plane (Section 2.6). Finally, we are also not sure if all subhaloes form successful galaxies as there are many processes that can inhibit mass accretion and star formation in the shallow potential wells of dwarf galaxies (Section 1.4.2).

This final point raises an interesting question: if nearly baryon-free, dark subhaloes do exist around galaxies, how would we expect to find and observe them? One method is gravitational lensing which has been used to derive constraints on substructure for redshift $z \sim 1$ ellipticals. In fact,
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One study found no controversy with the Missing Satellites problem when investigating the light distribution of a strong elliptical galaxy gravitational lens (Vegetti et al., 2012). However, gravitational lensing cannot be used in the Local Volume nor can it be guaranteed that the population of dwarf galaxies around elliptical and spiral galaxies are similar (Nierenberg et al., 2012). Another method to detect massive but nearly dark satellites is through the use of Tidal Analysis (Section 3.1). These galaxies could be detectable from the tidal imprints on the gas disks of their host galaxies since the neutral hydrogen (H\textsubscript{i}) disks of spiral galaxies extend several times their optical radius and extend to distances where theoretical models expect dwarf galaxies to be (Bigiel et al., 2010). Also, H\textsubscript{i} disks are colder than stellar disks and thus more responsive to tidal interactions; thus, H\textsubscript{i} disks of spiral galaxies make perfect “detectors” of substructure. Through the analysis of disturbances in the extended H\textsubscript{i} disks of spiral galaxies using hydrodynamical simulations and H\textsubscript{i} observations, constraints on the subhalo distribution and variations in halo shapes can be obtained.

Using Tidal Analysis, Chakrabarti & Blitz (2009) predicted the existence of a massive dwarf one-hundredth the mass of the Milky Way located 90 kpc from the galactic center based on SPH simulations of the warp in the Milky Way’s H\textsubscript{i} disk (Levine et al., 2006). Since the proposed dwarf is along the line of sight where the galactic disk is located, the search for the dwarf was significantly hindered by obscuration due to dust. This problem has since been alleviated by the advent of the VISTA Variables of the Via Lactea (VVV) survey (Minniti et al., 2011): a near-infrared survey along the Milky Way’s disk that specifically searches for variable stars. A group of clustered potential Cepheid variables was reported by Chakrabarti et al. (2015) located at a distance of ~90 kpc in the direction of the constellation Norma.

Cepheid variables are supergiant stars of luminosity class Ib and therefore have very short lifetimes (≤100 Myr). Thus, they are always found in young, gas rich systems where there are enough raw materials present to form these massive stars. When these stars were initially discovered by Henrietta Swan Leavitt, she studied the pulsating stars in the SMC and found a clear correlation between their apparent magnitudes and pulsation periods with brighter stars taking longer to complete a full period (Leavitt & Pickering, 1912). Because all the stars in her study were located
at roughly the same distance, the differences in apparent magnitude must be the same as the
differences in their absolute magnitudes because of the form of the distance modulus.

\[ m - M = 5 \log_{10} d_{\text{pc}} - 5, \tag{4.1} \]

where \( m \) is the apparent magnitude, \( M \) is the absolute magnitude, and \( d_{\text{pc}} \) is the distance in parsecs. Therefore, the observed differences in the apparent brightness of the stars reflected intrinsic differences in their luminosities or absolute magnitudes. Because of this amazing work, one can calculate the distance to a Cepheid simply by timing the pulsation, and because these stars are extremely bright, they can be measured over intergalactic scales. Once the relation was found and the distance to a nearby Cepheid was independently found, the period-luminosity relation was formed. Originally, it was found for optical wavelengths; however, it suffers from uncertainty due to dust extinction. To reduce the impact of dust absorption, infrared measurements can be made. Even further improvement can be done by including a color term since it will correct for the impact of dust absorption. The relation is slightly different depending on wavelength but as an example, below is the relation for the Johnson \( I \)-band (Ngeow et al., 2015).

\[ M_{(I)} = -2.918 \log_{10} P_d + 17.127. \tag{4.2} \]

Thus, with the observed period, \( P_d \), the average absolute magnitude, \( M_{(I)} \), can be obtained and the distance can be found using the distance modulus. For an excellent discussion of Cepheid variables see Carroll & Ostlie (2007).

If the objects reported by Chakrabarti et al. (2015) are indeed Cepheids, they would have no way of forming at a distance of \( \sim 90 \) kpc unless they are part of a comoving system, such as a gas rich dwarf galaxy, since this distance is far outside the galactic disk which extends to \( \sim 15 \) kpc. However, Cepheids are not the only variable stars nor is there only one type. Type II Cepheids
pulsate on similar timescales of 1-50 days but are much older (~10 Gyr) and have masses smaller than the sun. Another possibility are spotted stars and close contact eclipsing binaries which show similar sinusoidal light curves that may resemble short period Cepheids; however, their light curves are unstable and change noticeably from cycle to cycle.

Chakrabarti et al. (2015) identified an excess of variable stars toward the constellation of Norma using the VVV survey light curves. They then made an effort to examine the different mechanisms for creating the observed light curves and ultimately found that they best matched the profiles of Type I classical Cepheids. However, Pietrukowicz et al. (2015) presented a followup analysis of the four objects presented in Chakrabarti et al. (2015). They argued that two of the sources were not variable, one was not observed, and the last source was variable but possibly a spotted star. Chakrabarti et al. (2016) performed a followup to this analysis using a more strict source selection criteria that did not allow objects with poor photometry to be flagged as variable. This new criteria excluded two of the previously identified sources presented in Chakrabarti et al. (2015); however, it was found that one of their previous sources and two new sources appear to be intrinsically variable stars and very likely Cepheids variables of unknown type, either Type I or Type II.

Without fully sampled light curves, it is not possible to robustly determine the distances to these variable stars and without spectroscopic observations, it is not possible to determine if they represent a coherent structure. With high resolution spectra it would also be possible to determine which type of Cepheid these variables are. In order to further study these sources, follow up observations and spectroscopy were performed and reported in Chakrabarti et al. (2016). As a part of that study, I performed observations using the Swope telescope at Las Campanas Observatory in the Johnson I-band for ten nights to further characterize the light curves of the three Cepheids. Of the three objects, one target was the one shown to be variable in both Chakrabarti et al. (2015) and Pietrukowicz et al. (2015) and the two others were unreported variables found in the VVV data.

In the next section, I will describe the observations and difficulties experienced. Next, I will discuss the data reduction process including error estimation. Finally, I will discuss the results and
Chapter 4. *Searching for a Dwarf Galaxy in Norma*

![Finder charts for our three targets.](image)

(a) 4.902 days  
(b) 4.923 days  
(c) 5.695 days

Figure 4.1: Finder charts for our three targets. In each panel, North is up and West is to the right and the field of view is about $4' \times 4'$. The target is in the exact center of each panel.

conclude.

4.2 Observations

The observations were taken with the Henrietta Swope 1-meter telescope at Las Campanas Observatory using the E2V CCD with the Johnson $I$-band filter over the ten nights of 2015 August 18–27. Due to the time of year, our objects were only visible during the first half of the night. Observations were ceased each night once seeing better than $\sim 2''$ was no longer possible which typically occurred around an airmass of $\sim 1.8$. Clouds and high winds impacted some of our observations causing two lost nights, 2015 August 19 and 20, and a few lost epochs. Also, I was temporarily hospitalized due to a severe upper respiratory infection which caused a loss of one night’s worth of data on 2015 August 22. The observations on the nights of 2015 August 23 and 24 were carried out by collaborator Nidia Morrell; however, observations on the night of 2015 August 23 were impacted by an earthquake that caused the observations for that night to end early.

The three targets observed will be referred to by their respective periods, their information is given in Table 4.1. Due to many nearby bright stars in each field, over exposure and bleeding into neighboring pixels was an issue. This was dealt with by increasing the number of exposures per
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Table 4.1: Position and observation results from Swope observations. Column 4 lists the average Johnson $I$-band magnitude that was observed for each source with estimated error. Column 5 lists the number of epochs each object was observed for which the data is of a good enough quality to obtain a secure magnitude.

<table>
<thead>
<tr>
<th>Period (days)</th>
<th>RA</th>
<th>Dec</th>
<th>$\langle I \rangle$</th>
<th>No. Epochs</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.902</td>
<td>243.140542</td>
<td>-54.022122</td>
<td>18.7±0.15</td>
<td>8</td>
</tr>
<tr>
<td>4.923</td>
<td>244.968946</td>
<td>-50.176306</td>
<td>19.1±0.16</td>
<td>7</td>
</tr>
<tr>
<td>5.695</td>
<td>245.330825</td>
<td>-52.042578</td>
<td>19.0±0.12</td>
<td>25</td>
</tr>
</tbody>
</table>

observing epoch. Both the 4.902 day and 5.695 day targets were observed in epochs corresponding to 3 images of 300 seconds each. The 4.923 day target was located very close to a magnitude $\sim$6 star; we therefore used a shorter integration time with a higher cadence so that each epoch consists of 30 images of 30 seconds each. Finder charts for each target are shown in Figure 4.1.

To increase readout speed, the CCD is read out in four quadrants. Previous characterization studies of the Swope instruments have found the third quadrant (lower right) to have the greatest linearity and quantum efficiency; therefore, our targets were always placed in the third quadrant.\(^1\) Sky flats and bias images were taken every night for reduction purposes. Pointing and focusing were also performed at the start of every observation and in the event that seeing became worse than $\sim$2″ the telescope was refocused.

4.3 Data Reduction

The image reduction process was performed using Philip Massey’s e2v IRAF routine\(^2\) specifically designed for Swope data which performs linearity corrections, merges the four fields from readout into one final image, and then flattens and bias subtracts the image. All further reduction was performed using IRAF (Tody, 1986, 1993).

The field of view of the Swope telescope is 29.7′ × 29.8′ and since the targets were located in the

\(^1\)Carnegie Supernova Project: \url{http://csp2.lco.cl/manuals/swo_nc_linearity.php}

\(^2\)\url{http://www2.lowell.edu/users/massey/e2vred.html}
galactic plane, timely data reduction and target finding was an issue (each image contained up to \( \sim 10^{5-6} \) stars!). To reduce calculation time, the final images were trimmed to include a small area around each target \( 4' \times 4' \). None of our targets overlapped any nearby stars so source confusion was not an issue. After trimming, reference stars were found using the IRAF task, DAOFIND. The images were then aligned using IMALIGN, and finally each epoch was median combined using IMCOMBINE.

Photometry was then performed on these combined images. DAOEDIT was used to calculate the background flux, average deviation, and FWHM of stars in the image. DAOFIND was then used again with a lower threshold of \( 3\sigma \) to ensure that the target was included. If the target was not found by the program at this level then the data for that epoch was not used. Next, PHOT was used to perform aperture photometry, in almost all cases the default values were used. It was then necessary to create the point-spread-function (PSF) for the stars in the image. This was done using PSTSELECT in interactive mode. No less than ten stars were selected from each image which showed a good PSF with minimal to no outer disturbances from nearby stars. PSF was then run to generate the PSF for the image. Finally, ALLSTAR was run with default parameters to fit the PSF to every star in the image and generate a final magnitude for the stars in the image.

These magnitudes were compared to the catalogue values of known stars in the image. The reference catalogue that was used was the Deep Near Infrared Survey of the Southern Sky (DENIS; Paturel et al., 2003) which includes the optical \( I \)-band at 0.8 \( \mu \)m which matches well with the Johnson \( I \)-band used at Swope. No less than six stars were used to find the average offset between the calculated magnitudes and the catalogue values. Stars of different colors ranging from red to blue were chosen for comparison and no significant difference in offset was seen between stars indicating that the two passbands are nearly identical. Once the average offset was obtained, this was applied to the target to obtain the actual magnitude.

Bright stars were used to calibrate the images to find the true magnitudes but this type of analysis was also performed with stars that had catalogue values which were near the magnitude of the target star. We found the difference in the catalogue and observed values of these stars and calculated the deviation from epoch to epoch. As expected, for bright stars the deviations
from epoch to epoch were small but grew larger for dimmer stars. As an example of this analysis, Figure 4.2 shows the standard deviation versus magnitude for background stars in the images of our period 5.695 day target. This allowed us to calculate a modest uncertainty of $\sim 0.2$ magnitudes per epoch. In order to increase the significance of our observations, all the epochs from each night were averaged together. This reduced the uncertainty by $N_{\text{epochs}}^{1/2}$.

### 4.4 Results

The resultant light curves are shown in Figure 4.3. In the figure, both the near infrared $K_s$-band and optical $I$-band data are displayed, the $K_s$-band data was obtained from the VVV survey (Minniti et al., 2011). The $I$-band data is the averaged data from each night and has been subtracted by a constant in order to better show the phase matching between the $K_s$- and $I$-bands. Phase matching was performed using equation 4.3 assuming that the first data point was at Phase $= 0.0$.
and that the correct period is known.

\[ \text{Phase} = \frac{(\text{MJD}_i - \text{MJD}_0) \mod p}{p}, \]  

(4.3)

where MJD is the modified Julian date of the observation and \( p \) is the period. Since each epoch is the combination of many images, the MJD is defined as the central time between the start and finish of each epoch.

Figure 4.3: Near infrared \( K_s \)-band (blue) and optical \( I \)-band (red) data are displayed for each target. Each \( I \)-band data point represents the averaged value from all the epochs over an entire night and, in order to see the phase matching, has been shifted by the amount displayed in the legend of each panel.

Figure 4.3 shows that there is some variation from night to night in our targets that appear to match the phase of the \( K_s \)-band; however, the amount of variation is about equal to the extent of the error in the measurements. Also, for the \( I \)-band measurements the light curves are very sparsely sampled and incomplete. At this time, the only definitive result we can state is the mean \( I \)-band magnitude which is displayed in Table 4.1 and was reported in Chakrabarti et al. (2016).
4.5 Discussion

A separate analysis was performed in Chakrabarti et al. (2016) that measured the radial velocities of these sources using the Flamingos-2 instrument on Gemini-South. That analysis showed the objects were moving \( \sim 169 \text{ km s}^{-1} \), which is distinct from galactic rotation, typically \( \sim \text{few km s}^{-1} \) in that part of the sky. Therefore, it appears that these stars are halo stars and not part of the Galactic disk. However, the spectra obtained in that study do not have high enough S/N for a determination of metallicity; therefore, it is still unknown if they are Type I or Type II Cepheids. If these stars are Type II Cepheids, they would lie at \( \sim 40 \text{ kpc} \) from the Galactic center and may be part of a disrupted stellar tidal stream (Chakrabarti et al., 2016). If these stars are Type I Cepheids, they would lie at twice the distance, around \( \sim 80 \text{ kpc} \).

In the future, obtaining spectra of more Cepheids candidates in this location of the sky will enable the determination of a velocity dispersion which would shed light on whether or not these stars are part of a coherent object such as a disrupting stellar stream or dwarf galaxy. Also, future large-scale surveys, such as the Large Synoptic Sky Survey (LSST Science Collaboration et al., 2009) and OGLE (Optical Gravitational Lensing Experiment; Udalski et al., 1992) will be able to provide more accurate and complete light curves for these targets as well as other Cepheids in the same region of sky.
CHAPTER 5

THE FIRST DETECTION OF NEUTRAL HYDROGEN IN EMISSION IN A STRONG SPIRAL LENS

Now moving beyond the Milky Way, we look to apply Tidal Analysis (Section 3.1) to spiral galaxies outside the Local Group. We specifically look at a unique set of spiral galaxies that also act as strong gravitational lenses seeking to combine the two methods for the first time. The following Chapter is an adapted version of Lipnicky et al. (submitted) that includes more detail throughout.

5.1 Abstract

We report H\textsubscript{i} observations of eight spiral galaxies that are strongly lensing background sources. Our targets were selected from the Sloan WFC (Wide Field Camera) Edge-on Late-type Lens Survey (SWELLS) using the Arecibo, Karl G. Jansky Very Large Array, and Green Bank telescopes. We securely detect J1703+2451 at $z = 0.063$ with a signal-to-noise of 6.7, obtaining the first detection of H\textsubscript{i} emission in a strong spiral lens. We measure a mass of $M_{\text{H}\textsubscript{i}} = (1.77 \pm 0.06^{+0.35}_{-0.75}) \times 10^9 \, M_{\odot}$ for this source, consistent with other spiral galaxies of similar stellar mass. For six other sources we did not secure a detection; however, we are able to place strong constraints on the H\textsubscript{i} masses of those galaxies. The observations for one of our sources were rendered unusable due to strong
radio frequency interference. We also compute the expected H\(_i\) masses and signal strengths for all the “Grade A” SWELLS sources using the linear relation between the gas fraction of a galaxy, log(M\(_{\text{H}i}/M_\star\)), and its NUV — r color.

5.2 Introduction

Gravitational lensing has been used extensively as a tool for constraining the amount of dark matter contained within galaxy clusters. With the advent of large scale surveys, it has now been found that many individual galaxies are also strong gravitational lenses and can be used to provide constraints on their dark matter haloes. At these small scales, the agreement between cosmological simulations and observations is not yet as secure as on large scales (Klypin et al., 1999; Dutton et al., 2007; Weinberg et al., 2015). For example, with the SWELLS sample (Sloan WFC (Wide Field Camera) Edge-on Late-type Lens Survey, Treu et al., 2011; Brewer et al., 2012), a set of strong-lens spiral galaxies selected in the same manner as the larger SLACS lens survey (Sloan Lens ACS (Advanced Camera for Surveys); Bolton et al., 2008) from within the spectroscopic data set of the Sloan Digital Sky Survey (SDSS; York et al., 2000), studies attempts to break the “Disk-Halo Degeneracy” (Section 1.4.5), a problem that arises from the fact that rotation curves can be fit equally well by having either a high mass halo and low mass disk or vice-versa. The problem can be alleviated by identifying strong spiral lenses and combining gravitational lensing analysis with stellar kinematics (Treu et al., 2011). Through sampling the various distributions and combining both lensing and kinematic data Dutton et al. (2011) were able to highly constrain the model for the disk and halo and lessen the impact of the disk-halo degeneracy.

Other work has shown the possibility that the Missing Satellites problem, the discrepancy between the number of observed and simulated subhaloes, only applies to the Local Group. Vegetti et al. (2012) analyzed surface brightness anomalies in gravitationally lensed images of an elliptical deflector at z = 0.8 and argued that their derived constraints on cold dark matter (CDM) substructure are consistent with simulations. However, gravitational lensing analyses have con-
Chapter 5. *First Detection of H\textsc{i} Emission in a Strong Spiral Lens*

centrated mainly on deflectors that are ellipticals and there are indications that the distribution of substructure may be intrinsically different in ellipticals than in spirals of the same mass due to their different formation histories (Nierenberg et al., 2012). These discrepancies, along with other deficiencies of gravitational lensing, call for an independent measurement of dark matter distribution.

Alternate probes of the dark matter distribution, whether of the potential or dark matter substructure, can be obtained by analyzing stellar tidal debris (Johnston et al., 1999), velocity asymmetries in the stellar disk (Widrow et al., 2012; Xu et al., 2015), or disturbances in outer H\textsc{i} disks (Chakrabarti & Blitz, 2009, 2011; Chakrabarti et al., 2011; Chang & Chakrabarti, 2011; Chakrabarti, 2013). The gas disk is a particularly sensitive probe of the dark matter distribution as it is kinematically colder than the stars, and extends out to several times the optical radius (Wong & Blitz, 2002). Recent extragalactic H\textsc{i} surveys (Giovanelli et al., 2005; Catinella et al., 2010; Fernández et al., 2016) and future prospects with the Square Kilometer Array (SKA; Giovanelli & Haynes, 2016) open a new window for H\textsc{i} studies beyond the Local Volume.

We have already seen that Tidal Analysis is a powerful tool for constraining substructure and determining the location and interaction history of substructure in spiral galaxies (Chapter 3). Tidal Analysis can be used to independently constrain the dark matter distribution of spiral galaxies and can, therefore, provide accurate priors for more precise strong lensing models. Also, lensing and Tidal Analysis look at different regions of galaxies as gravitational lensing is sensitive to the inner regions and Tidal Analysis is sensitive to the outer regions where the gas disk is most easily disturbed by passing substructure. Therefore, the combination of methods provides a more complete picture of substructure in a galaxy.

Traditionally, strong gravitational lensing has been largely a high redshift probe of dark matter due to the requisite optical depth needed to achieve strong lensing. On the other hand, Tidal Analysis requires that galaxies be located at low redshift in order to successfully obtain detailed H\textsc{i} maps and has therefore been generally restricted to the Local Volume. Until recently, gravitational lensing and Tidal Analysis could not be combined due to the difference in requisite redshifts. The
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SWELLS sample, however, is a sufficiently low redshift sample of strong spiral lenses ($z_{\text{avg}} \sim 0.1$) that enables these two methods to be combined for the first time. The galaxies in this sample also show visible signs of interaction with satellite galaxies and therefore probable substructure.

The goal of this project is to ultimately obtain H\textsubscript{I} maps of $z \sim 0.1$, strong spiral lenses for which the individual Fourier modes of the projected gas surface density can be calculated. With these observations, information of past interactions and substructure can be found using Tidal Analysis. At the same time, lensing analysis can be used to also constrain substructure which will allow us to compare and contrast two independent methods of observing substructure. As a first step in this project, we must ensure that our target galaxies have sufficient H\textsubscript{I} masses so that follow-up, high resolution H\textsubscript{I} mapping will be successful. We have thus employed the use of the large single-dish radio telescopes at Arecibo and Green Bank. Here we discuss those observations and the obtained spectra.

This Chapter is organized as follows: In Section 5.3, we discuss our sample selection. In Section 5.4, we discuss the observations and data reduction. In Section 5.5, we discuss our results. In Section 5.6 we discuss the possibility of background source confusion and how our observations compare to the work of others. Finally, we conclude in Section 5.7.

All distance-dependent quantities in this work are computed assuming $\Omega = 0.3, \Lambda = 0.7,$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

### 5.3 Sample Selection

The galaxies we observed lie at low redshift (the average redshift of the SWELLS sample is $z_{\text{avg}} \sim 0.1$) but still at the very edge of what is currently possible for H\textsubscript{I} mapping observations. Recently, Fernández et al. (2016) presented an H\textsubscript{I} map of a massive spiral ($M_{\text{H\textsubscript{I}}} = 2.9 \times 10^{10} M_\odot$) at $z = 0.376$ observed with the Karl G. Jansky Very Large Array (VLA) for 178 hours and obtained a signal-to-noise of $S/N = 7$ for their integrated spectrum, although the structure in the outskirts is uncertain. This is the highest redshift H\textsubscript{I} emission map obtained to date. Previously, that record...
was held by Donley et al. (2006), who observed HIZOAJ0836-43 with the ATCA for \( \sim 2 \times 12 \) hours which is a large disk galaxy at \( z = 0.036 \) with \( M_{\text{HI}} \sim 7 \times 10^{10} \, M_{\odot} \) and a H\( \text{I} \) diameter of \( \sim 130 \) kpc.

Treu et al. (2011) have derived stellar masses for the SWELLS sources based on multiband photometry and stellar population synthesis models. Two common initial mass functions (IMFs) were used, the Chabrier (2003) and Salpeter (1955) IMFs. Brewer et al. (2012) carried out a gravitational lensing analysis of the SWELLS sources. By fitting a singular isothermal ellipsoid (SIE) mass model for the deflector, they were able to use the Einstein angle and axis ratio to measure a velocity dispersion. Thus, they have provided velocity dispersions and stellar masses for the SWELLS sample; however, the H\( \text{I} \) masses were not measured. Unfortunately, the neutral hydrogen gas fraction, \( M_{\text{HI}}/M_{\star} \), is not tightly correlated with stellar mass (Catinella et al., 2010); therefore, we must pre-observe objects of interest with large single dish telescopes in order to ascertain their total mass in H\( \text{I} \). In order to narrow our search, we estimate the expected H\( \text{I} \) mass of each galaxy. From the GALEX-Arecibo-SDSS survey (GASS) of \( \sim 1000 \) galaxies studied between redshifts \( 0.025 < z < 0.05 \) with \( M_{\star} > 10^{10} \, M_{\odot} \), Catinella et al. (2010) found that \( M_{\text{HI}}/M_{\star} \) was most clearly correlated with the NUV — r color since gas-rich galaxies will be have more star formation and appear bluer (or vice-versa), although even here there is a large dispersion (Fig. 5.1).

In an effort to combine gravitational lensing with Tidal Analysis, we chose a set of galaxies that were most likely to have visible substructure. We chose “Grade A” (unambiguous multiple images reproduced by a relatively simple lens model) strong spiral lenses from the SWELLS Survey (Treu et al., 2011; Brewer et al., 2012). All galaxies in our sample are star-forming spirals with strong H\( \alpha \) emission with high surface brightness lensed features. They have varying inclinations, redshifts, disk-to-bulge ratios, masses, and clarity of lensing features (from partial to complete Einstein rings). These sources have been observed in NUV by the Galaxy Evolution Explorer (GALEX; Martin et al., 2005) and in r by SDSS (Alam et al., 2015). Other factors which contributed to our sample selection included the ability to observe them with the Arecibo and/or Green Bank telescopes, the expected H\( \text{I} \) mass, expected signal, the probability of substructure, and the Ra-
Chapter 5. First Detection of H\textsc{i} Emission in a Strong Spiral Lens

Table 5.1: Data for the SWELLS targets which are grade “A” lenses (secure) as well as grade “B” lenses (probable) J0329-0055 (Bolton private communication) and J1228+3743. Column 1 gives the source ID for each object which corresponds to the deflector or nearby object that we are interested in mapping. Those sources marked with an asterisks (*) were observed in this study and are presented here. Column 2 gives the approximate SDSS redshift of the deflector object which we are interested in observing. Column 3 gives the stellar velocity dispersion as measured from fits to the stellar continuum (Bruzual & Charlot, 2003). Column 4 gives the velocity dispersion as measured from the gravitational lensing analysis presented in Brewer et al. (2012). Column 5 gives the stellar masses of each galaxy, compiled from Treu et al. (2011) and Brewer et al. (2012) and are the averaged disk masses given Chabrier and Salpeter IMFs. Column 6 gives the NUV — r color of each source based on data from GALEX and SDSS observations. Column 7 gives the gas fraction of each source, log($M_{\text{H} \text{i}}/M_\odot$), and is calculated from a fit to the gas fraction versus NUV — r color from Catinella et al. (2010) as displayed in Fig. 5.1. Column 8 gives the predicted H\textsc{i} mass of each source based on the fit to the Catinella et al. (2010) data. Column 9 gives the expected signal in mJy of each source, calculated via equation 5.3 assuming a velocity width of 300 km s\textsuperscript{-1}.

<table>
<thead>
<tr>
<th>Source ID</th>
<th>$z_d$</th>
<th>$\sigma_{\text{SDSS}}$ (km s\textsuperscript{-1})</th>
<th>$\sigma_{\text{SIE}}$ (km s\textsuperscript{-1})</th>
<th>log($M_\star$) (M_\odot)</th>
<th>NUV-r</th>
<th>log($M_{\text{H} \text{i}}/M_\odot$)</th>
<th>log($M_{\text{H} \text{i}}$)exp (M_\odot)</th>
<th>$S_{\text{exp}}$ (mJy)</th>
</tr>
</thead>
<tbody>
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<td>J0329-0055*</td>
<td>0.1062</td>
<td>94±25</td>
<td>...</td>
<td>10.30</td>
<td>2.90</td>
<td>-0.688</td>
<td>9.612</td>
<td>0.28</td>
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<tr>
<td>J0820+4847</td>
<td>0.1310</td>
<td>188±26</td>
<td>191.9±10.7</td>
<td>10.56</td>
<td>4.89</td>
<td>-1.326</td>
<td>9.234</td>
<td>0.08</td>
</tr>
<tr>
<td>J0822+1828</td>
<td>0.1153</td>
<td>174±24</td>
<td>185.1±4.0</td>
<td>10.22</td>
<td>4.73</td>
<td>-1.274</td>
<td>8.946</td>
<td>0.05</td>
</tr>
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<td>J0841-3824*</td>
<td>0.1160</td>
<td>217±18</td>
<td>251.2±4.4</td>
<td>11.35</td>
<td>3.59</td>
<td>-0.911</td>
<td>10.439</td>
<td>1.57</td>
</tr>
<tr>
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<td>0.0780</td>
<td>219±54</td>
<td>195.2±2.2</td>
<td>10.55</td>
<td>5.50</td>
<td>-1.522</td>
<td>9.028</td>
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<td>238.4±7.3</td>
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<td>3.92</td>
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<td>9.294</td>
<td>0.12</td>
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<td>162.8±8.1</td>
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<td>3.78</td>
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<td>5.38</td>
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<td>...</td>
<td>...</td>
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<td>227.9±1.5</td>
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<td>9.890</td>
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</tr>
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<td>3.62</td>
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<td>9.516</td>
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<td>203.0±2.6</td>
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<td>-0.751</td>
<td>10.339</td>
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<td>3.43</td>
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<td>9.732</td>
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<td>198±33</td>
<td>189.7±2.2</td>
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<td>10.85</td>
<td>5.75</td>
<td>-1.601</td>
<td>9.249</td>
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Figure 5.1: A clear correlation exists between gas fraction, \( \log(M_{\text{HI}}/M_\ast) \), and the NUV — r color of a galaxy. From a linear fit to this data (black line), we get a broad indication of the expected H\( \text{I} \) mass for our galaxies. Data from Data Release 1 of Catinella et al. (2010).

Radio Frequency Interference (RFI) environment at the redshifted frequency. Due to redshift, the frequency location of the 21 cm emission is a particularly hostile portion of the radio spectrum. Beyond redshift of \( z \sim 0.05 \), 1100 \( \lesssim \nu(\text{MHz}) \lesssim 1300 \), the spectrum is heavily populated by: satellite communications; airplane navigation; airport, military, and defense radar; cellular communications; and other unknown sources of noise. Shown in Table 5.1 is information on all the Grade “A” lenses as well as Grade “B” (probable gravitational lensing structure) lenses J0329-0055 (Bolton private communication) and J1228+3743 from the SWELLS survey and their predicted H\( \text{I} \) masses and signals. Our predictions for H\( \text{I} \) masses are based off the linear fit seen in Figure 5.1.
5.4 Observations and Data Reduction

Some of our sources were initially observed by collaborator, Carl Heiles, using the Arecibo Telescope with the L-wide receiver on 2014 April 23 and 2014 May 14 for a total of 5.25 hours. Targets were observed with with a narrow bandwidth of 3.125 MHz to avoid RFI. This was separated into 2048 channels, two linear polarizations, and had a velocity resolution of $\sim394$ m s$^{-1}$ with a beam size of $\sim3.5\arcmin$. Observations were then carried out by myself using the Green Bank Telescope (GBT) over the Fall semesters (August through January) of 2014 and 2016 for a total of 127.75 hours. The observations used the L-band receiver with the Versatile GBT Astronomical Spectrometer (VEGAS) backend in mode 15 which has a bandwidth of 11.72 MHz separated into 32,768 channels, 9$\arcmin$ beam size, and two linear polarizations. This yielded a velocity resolution of $\sim87$ m s$^{-1}$. We used short, four minute scans with one second integration times to minimize the effect of RFI. This allowed us to flag transient RFI signals caused by pulsed radar without losing large amounts of data.

For both the Arecibo and GBT observations, we used the observing method of position switching. This method involved observing our source for a duration of four minutes (the “ON” observation) and then moving the telescope along the same hour angle to a location on the sky that did not include our source and observing for another four minutes (the “OFF” observation). Afterwards, the two spectra were combined using the standard (ON-OFF)/OFF calculation. This method has been proven to maximize the likelihood of observing good spectral baselines. A more thorough description of the observing method is provided in Appendix B.1. All of our GBT observations were performed with the notch filter removed since they were located in the frequency region covered by the filter. Therefore, intermittent Federal Aviation Administration (FAA) signals were present in much of our data.

All data reduction of the GBT observations was performed using gbtidl v2.10 (Marganian et al., 2013). Due to the presence of significant RFI in all spectra, detailed data editing was necessary. This was done both automatically and by hand. Each one second integration was inspected automatically for the presence of wideband RFI (e.g. radar) and flagged if a signal...
stronger than five times the theoretical rms was present. The theoretical rms was computed using the radiometer equation

$$T_{\text{rms}} = \frac{\sqrt{2} T_{\text{sys}}}{\sqrt{N_{\text{pol}} \Delta f_{\text{ch}} t_s}},$$

(5.1)

where $T_{\text{sys}}$ is the system temperature, $N_{\text{pol}}$ is the number of polarizations, $\Delta f_{\text{ch}}$ is the channel bandwidth in hertz, and $t_s$ is the integration time in seconds. The extra factor of $\sqrt{2}$ comes from the combination of both the ON and OFF spectra, assuming that both spectra have the same noise.

Once this was performed, each observing session was combined into a single spectrum per polarization. Polynomial baselines of order three were subtracted from each spectrum. Then each source was combined into two master polarized spectra. This allowed us to check the spectra for RFI that mimicked H\textsc{i} signals as RFI is typically highly polarized. Finally, the two polarizations were combined into a final spectrum. This spectrum was then inspected by hand for narrowband RFI which was flagged. Narrowband RFI typically only affected a few channels, it was therefore blanked and interpolated over. The flux density scale was determined via online system temperature measurements with a blinking noise diode.

For those spectra that were affected by noisy baselines, the measured rms across the spectrum was compared to the theoretical rms. Integrations that showed $\text{rms}_{\text{obs}} > 3\text{rms}_{\text{theo}}$ were discarded. If the baseline noise was non-stationary, baseline noise decreased as $(N_{\text{scans}})^{1/2}$. However, stationary baseline noise would add when combined with other spectra. To avoid this, we imposed a final measured versus theoretical rms check on each scan and discarded those scans that showed $\text{rms}_{\text{obs}} > 3\text{rms}_{\text{theo}}$. More details on how data reduction was performed for the GBT data, including an example reduction code, can be found in Appendix B.2.

Observations of J0329-0055 were performed during August 2013 with the VLA in “C” configuration for a total of 15.2 hours. The target was observed using 2048 channels with a beam size of $44'' \times 28''$ and a resolution of 31.25 kHz centered on velocity 31,826 km s$^{-1}$. Calibration and RFI
excision of the VLA observations was performed using the standard Obit calibration pipeline (Cotton, 2008). The standard calibrator, 3C138, was used for flux density, group delay, and bandpass calibrations and J0323+0534 was used for phase calibrations. The data were Hanning smoothed to 62.5 kHz or \( \sim 16.5 \) km s\(^{-1}\) resolution before RFI excision. Then flagging was performed in both time and frequency domains at the 5\( \sigma \) level by using a running mean. Calibration of the data was then repeated with the flagged data to further reduce the impact of RFI.

### 5.5 Results

Of the six objects observed using the GBT, we have obtained one detection, four non-detection upper limits, and the data for one object was completely lost due to RFI. We also report an upper limit non-detection from the VLA and another upper limit non-detection from Arecibo. The detection we obtained of source J1703+2451 is shown in Fig. 5.2(a), the six non-detection upper limit spectra are shown in Fig. 5.2(b) – (g), all our current mass estimates are displayed in Table 5.1, and our observational results are displayed in Table 5.2.

The H\( \text{i} \) mass of a galaxy can be obtained using the following relation:

\[
M_{\text{H}\text{i}}(M_{\odot}) = \frac{2.356 \times 10^5}{1 + z} D_L^2 \int Sdv, \tag{5.2}
\]

where \( z \) is the redshift to the source, \( D_L \) is the luminosity distance to the galaxy in Mpc, and \( \int Sdv \) is the integrated flux of the H\( \text{i} \) signal in units of Jy km s\(^{-1}\) (Wild, 1952; Roberts, 1962).

For spectra that do not display a clear signal, we use an approximate form of equation 5.2:

\[
M_{\text{H}\text{i}}(M_{\odot}) \approx \frac{2.4 \times 10^5}{1 + z} D_L^2 S_{\text{peak}} W, \tag{5.3}
\]

where \( S_{\text{peak}} \) is the peak of the signal in Jy and \( W \) is the width of the signal in km s\(^{-1}\). In the case
Table 5.2: Column 1 gives the Source ID. Column 2 displays the total usable time on source. Column 3 shows the total time spent observing the object including reference observations. Column 4 shows the percentage of the time on source that was lost due to RFI. Column 5 shows the theoretical rms in mJy computed using equation 5.1 in order to compare to Column 6 which displays the measured rms in mJy of the observed spectrum. Column 7 gives the mass that was determined from observations. Upper limits have an extra term defined as \( C = \log(v/300 \text{ km s}^{-1}) \) which comes from our choice of \( \Delta v=300 \text{ km s}^{-1} \). Column 8 shows the telescope on which observations for that object were performed.

<table>
<thead>
<tr>
<th>Source ID</th>
<th>( t_s ) (hrs)</th>
<th>( t_{tot} ) (hrs)</th>
<th>RFI lost (%)</th>
<th>rms_{theo} (mJy)</th>
<th>rms_{obs} (mJy)</th>
<th>( \log(M_{\text{H}I})<em>{\text{obs}} ) (M(</em>\odot))</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0329-0055</td>
<td>–</td>
<td>15.2</td>
<td>&gt;50</td>
<td>0.31</td>
<td>0.38</td>
<td>(&lt; 10.47 + C )</td>
<td>VLA</td>
</tr>
<tr>
<td>J0841+3824</td>
<td>0.873</td>
<td>11.6</td>
<td>85.0</td>
<td>0.52</td>
<td>0.77</td>
<td>(&lt; 10.84 + C )</td>
<td>GBT</td>
</tr>
<tr>
<td>J1037+3517</td>
<td>10.139</td>
<td>39.733</td>
<td>49.0</td>
<td>0.20</td>
<td>0.32</td>
<td>(&lt; 10.52 + C )</td>
<td>Arecibo/GBT</td>
</tr>
<tr>
<td>J1103+5322</td>
<td>11.6</td>
<td>100.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>(&lt; 11.02 + C )</td>
<td>GBT</td>
</tr>
<tr>
<td>J1111+2234</td>
<td>0.733</td>
<td>2.067</td>
<td>64.5</td>
<td>0.28</td>
<td>0.29</td>
<td>(&lt; 11.102 + C )</td>
<td>Arecibo</td>
</tr>
<tr>
<td>J1117+4704</td>
<td>1.343</td>
<td>2.933</td>
<td>8.5</td>
<td>0.64</td>
<td>1.52</td>
<td>(&lt; 11.49 + C )</td>
<td>GBT</td>
</tr>
<tr>
<td>J1135+3720</td>
<td>5.350</td>
<td>17.867</td>
<td>40.1</td>
<td>0.27</td>
<td>1.03</td>
<td>(&lt; 11.28 + C )</td>
<td>GBT</td>
</tr>
<tr>
<td>J1703+2451</td>
<td>4.948</td>
<td>10.8</td>
<td>8.4</td>
<td>0.31</td>
<td>0.27</td>
<td>( 9.25 \pm 0.01^{+0.08}_{-0.24} )</td>
<td>VLA/GBT</td>
</tr>
</tbody>
</table>

of an upper mass limit, \( S_{\text{peak}} \) is represented by five times the measured rms of the spectrum when smoothed to \( 20 \text{ km s}^{-1} \) and \( W \) is assumed to be \( 300 \text{ km s}^{-1} \). This assumption is stated explicitly in all our mass estimates with an added \( (\Delta v/300 \text{ km s}^{-1})^{1/2} \) term, defined as \( C \) in Table 5.2.

### 5.5.1 Notes on Each Source

Below is a discussion about each individual galaxy, all stated observation times are total observation time including reference (“OFF”) observations.

**J0329-0055:** Observations of this object were performed using the VLA in L-band with the telescope in the C configuration for a total of 15.2 hours. Due to RFI interference, more than 50 per cent of the data were flagged. After smoothing to a velocity resolution of \( \sim 16.5 \text{ km s}^{-1} \), no signal was present at the expected source location (Fig 5.2(b)). A wide feature is seen at \( \sim 1282.8 \text{ MHz} \); however, this does not correspond to any known source within the field of view. This
Figure 5.2: (Caption displayed on next page.)
Figure 5.2: (Continued) In all panels: solid black vertical lines indicate parts of the spectrum that were blanked due to narrowband RFI; red regions with central dot–dashed lines indicate interloper galaxies that lie in the field of view and their $3\sigma$ redshift error, see Section 5.6 for discussion. Panel (a): $S/N = 6.7$ detection of J1703+2451. The black, dashed line and shaded region indicate the measured center of the line and error which corresponds to redshift $z = 0.06289 \pm 0.00004$. The green region and center dotted line indicate the expected location of the 21 cm emission for this frequency from SDSS with $3\sigma$ redshift error. For panels (b) – (g): the black, dashed line indicates the expected location of the 21 cm emission for this redshift from SDSS and the shaded region indicates the error in redshift. Panel (b): this source was observed with the VLA and has been smoothed to a velocity resolution of $\sim 16.5$ km s$^{-1}$. Panel (e): this source was observed with Arecibo, it has been boxcar smoothed to a velocity resolution of 20 km s$^{-1}$ and fit with a third order polynomial. Panels (c), (d), (f), and (g): each spectrum has been Hanning smoothed and resampled, then boxcar smoothed to a velocity resolution of 20 km s$^{-1}$. After smoothing, a third order polynomial baseline was subtracted.

frequency location also contains a known source of RFI corresponding to tethered aerostat radar system (TARS) pulsed radar from Ft. Huachuca, Arizona. The measured rms of the spectrum around the expected signal location is $S_{\text{rms}} = 0.38$ mJy which yields an upper mass limit of $M_{\text{HI}} < 2.95 \times 10^{10} \times (\Delta v/300$ km s$^{-1})^{1/2} M_\odot$.

**J0841+3824:** This object was observed for a total of 11.6 hours; however, due to intermittent RFI and stationary baseline ringing, 85 per cent of the data for this source were lost. At the expected source location there is no discernible signal (Fig. 5.2(c)). The features seen to the left of the expected source location are highly polarized and are therefore RFI. We estimate an upper mass limit from the measured rms of the spectrum where white noise dominates and find $S_{\text{rms}} = 0.77$ mJy. This yields an upper mass limit of $M_{\text{HI}} < 6.92 \times 10^{10} \times (\Delta v/300$ km s$^{-1})^{1/2} M_\odot$.

**J1037+3517:** This object was originally observed with Arecibo for 72 minutes where a tentative $2\sigma$ signal was present at the expected source location. However, due to the presence of strong RFI nearby, the source of the signal at the source location was not clear. We then observed this object for a total of 39.7 hours with GBT; however, 49 per cent of the data was lost due to RFI. The final spectrum is shown in Fig. 5.2(d). The background RFI environment at this frequency location is higher than expected but does not cause baseline ripples. From the smoothed spectrum, we observe
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no discernible signal at the expected source location and therefore estimate an upper mass limit using $S_{\text{rms}} = 0.32 \text{ mJy}$ which yields $M_{\text{H}_1} < 3.31 \times 10^{10} \times (\Delta v/300 \text{ km s}^{-1})^{1/2} \text{ M}_\odot$. Due to the RFI environment and the sensitivity of the GBT, it is likely that this object cannot be observed at GBT as this spectrum is at the limit of the telescope.

**J1103+5322**: This object was observed for a total of 11.6 hours; however, the data for this source were rendered completely unusable due to a strong constant source of RFI $\sim$1.5 MHz wide, centered at 1227.5 MHz that caused significant baseline ripples and could not be removed.

**J1111+2234**: Observations of this source were performed using the Arecibo telescope with the L-wide receiver. It was observed for a total of 2.067 hours over two days; however, RFI strongly affected much of the observing time leading to a total usable observation time of 0.733 hours. The final spectrum shown in Fig. 5.2(e) has a measured rms of $S_{\text{rms}} = 0.29 \text{ mJy}$, yielding an upper mass limit of $M_{\text{H}_1} < 1.05 \times 10^{11} \times (\Delta v/300 \text{ km s}^{-1})^{1/2} \text{ M}_\odot$.

**J1117+4704**: This source was observed for a total of 2.93 hours, of which, 8.5 per cent was lost to intermittent RFI. However, Fig. 5.2(f) shows the presence of baseline ripples that are much wider than our smoothing. The observed rms of $S_{\text{rms}} = 1.52 \text{ mJy}$ yields an upper mass limit of $M_{\text{H}_1} < 3.09 \times 10^{11} \times (\Delta v/300 \text{ km s}^{-1})^{1/2} \text{ M}_\odot$.

**J1135+3720**: This source was observed for a total of 17.9 hours, of which, 40 per cent was lost to RFI. Observations of this source were affected by noisy baselines. Fig. 5.2(g) shows that large variations still exist in the baseline, even after our baseline flagging algorithm was applied. The observed rms of $S_{\text{rms}} = 1.03 \text{ mJy}$ yields an upper mass limit of $M_{\text{H}_1} < 1.91 \times 10^{11} \times (\Delta v/100 \text{ km s}^{-1})^{1/2} \text{ M}_\odot$.

**J1703+2451**: This source was originally observed at the VLA in 2013 July; however, due to RFI the data were unusable. It was revisited at the GBT where we obtained a very clean spectrum (Fig. 5.2(a)), only 8.4 per cent of the data was lost to RFI (see Table 5.2). An intermittent, strong RFI signal was present at 1336.7 MHz with a width of 0.2 MHz and a period of 12 s which affected
some of our data but was easily identified and removed. Narrowband RFI was also present but was likewise easily removed and only affected single channels.

A clear signal of width $W_{50} = 79 \pm 13$ km s\(^{-1}\) and $W_{20} = 93 \pm 12$ km s\(^{-1}\) is seen at $\nu = 1336.37 \pm 0.05$ MHz where $W_{50}$ is the width of the line at 50 per cent flux and $W_{20}$ is the width at 20 per cent flux. J1703+2451 is highly inclined with inclination $i = 53 \pm 5$ degrees (Treu et al., 2011; Brewer et al., 2012; Alam et al., 2015) yielding a corrected velocity width of $W_{20,\text{cor}} = 116 \pm 15$ km s\(^{-1}\). We fitted the feature using different velocity resolutions and different baselines. Because the baselines for this object were good, changing the region where the baseline was fitted did not influence the measurement noticeably (differences of $\sim 1$ km s\(^{-1}\)). By choosing reasonable different edges of the signal and locations for the horns, the output only changed by $\sim 1$ km s\(^{-1}\) between fits. The main factor was the change in the number of channels used to smooth. We varied the smoothing in steps from 10 - 30 km s\(^{-1}\) and found that the width varied from $76 < \Delta v < 91$ [km s\(^{-1}\)] and the error varied from $13 < \sigma_{\Delta v} < 32$ [km s\(^{-1}\)]. The largest velocity width occurred with the largest velocity smoothing (as expected) which also had the largest error in width. With a smoothing of $\sim 20$ km s\(^{-1}\), the error in velocity width minimized at 13 km s\(^{-1}\). We used this as an estimate of the systematic error.

The location of the line corresponds to redshift $z = 0.06289 \pm 0.00004$. This matches extremely well with the stated SDSS redshift of $z_{\text{SDSS}} = 0.06287 \pm 0.00001$ (green shaded region of Fig. 5.2(a)). The signal-to-noise, S/N, was measured to be S/N = 6.7 following the convention of Saintonge (2007) and adapting to a velocity resolution of 20 km s\(^{-1}\). The measured flux across the line is $\int S \Delta v = 0.10$ Jy km s\(^{-1}\) which yields a mass of $M_{\text{HI}} = (1.77 \pm 0.06^{+0.35}_{-0.75}) \times 10^9$ M\(_\odot\). Statistical errors came from error in the measurements of velocity width, redshift, and flux, with the error in velocity width dominating. Systematic errors came from unaccounted for deficiencies in the reduction process in GBTIDL which leads to a mass measurement accurate to about 20 per cent on the high end and the presence of nearby galaxies creates uncertainty on the low end.
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5.6 Discussion

Comparing the width of the J1703+2451 line to the velocity dispersions measured via gravitational lensing and stellar kinematics (Table 5.1), our detection appears anomalously narrow. However, the three measurements consider very different regions of the galaxy. For an undisturbed spiral galaxy, we would expect the circular velocity to be constant out to large radius i.e. a flat rotation curve (Rubin et al., 1978). However, J1703+2451 exhibits a warp in the outer edges of the stellar disk (Brewer et al., 2012) that may indicate an interaction with a large perturber in the past. Due to this interaction, the extended $H\text{I}$ disk may be distributed into long tidal tails while the stellar disk remains intact. It is also worth noting that the lensing models used in Brewer
et al. (2012) to measure the velocity dispersion assumed a singular isothermal ellipsoid model which is known to be overly simplistic for spiral galaxies which have multiple components (disk, bulge, and halo) unlike elliptical galaxies (see, for example, Barnabè et al. (2012), which have a much better treatment for a spiral galaxy lens model). Furthermore, comparing our measurement of J1703+2451 to galaxies in The HI Nearby Galaxy Survey (THINGS; Walter et al., 2008) and the GASS sample, there are multiple galaxies of similar stellar mass in both surveys that exhibit HI emission lines on the order of 100 km s$^{-1}$ in width.

As one observes at deeper redshifts, the density of sources increases due to the increased observation volume. Since the field of view for the GBT in the L-band is quite large ($9^\circ$) we must ensure that the only object in our field of view is the target of interest. We therefore checked the SDSS Data Release 12 (Alam et al., 2015) database to ensure that the our spectra were not contaminated by background sources and the signal seen in the spectrum of J1703+2451 is indeed our target. Two of our observations were affected by background sources, J0329-0055 and J1703+2451.

Within the field of view of J1703+2451, there are three sources that lie at similar redshift. One is our target and two others are the nearby galaxies SDSS J170334.39+245233.7 (spiral) and SDSS J170332.91+245412.3 (galaxy type uncertain). These two galaxies lie at redshifts nearly equal to our target and are shown as vertical red, dotted lines in Fig. 5.2(a). Good optical spectra exist for both background galaxies which show very strong H$\alpha$ and [O$\text{II}$] lines, indicating that they are star forming galaxies. The red shaded region of Fig. 5.2(a) represents the $3\sigma$ error on the redshift measurements of these background galaxies. Because of their strong emission lines, their redshifts are determined very accurately. Both background galaxies lie more than 26$\sigma$ away from the center of the feature, which indicates that the feature is not a detection of the background galaxies. However, since they do lie near the edge of the feature, we estimate their contribution to the signal.

The spectra for both galaxies have been fit using the Portsmouth Spectral Energy Distribution (SED)-fit pipeline developed by Maraston et al. (2013) which measures the stellar mass using a passive or active star-forming SED template. The measured stellar masses using the star-forming
template for the contaminant galaxies are \(\log(M_*) = 9.24 \, M_\odot\) and \(\log(M_*) = 9.27 \, M_\odot\) for SDSS J170334.39+245233.7 and SDSS J170332.91+245412.3 respectively. These measurements show that the stellar masses of both galaxies are more than an order of magnitude smaller than the stellar mass of our target.

Both galaxies have been observed with GALEX so we can estimate the expected H\(_i\) mass contribution from each galaxy using the linear relationship shown in Fig. 5.1. The NUV — \(r\) color is 3.12 and 2.95 for SDSS J170334.39+245233.7 and SDSS J170332.91+245412.3, respectively. This translates to a signal of \(S_{\text{peak}} \sim 0.17 \, \text{mJy}\) and \(S_{\text{peak}} \sim 0.21 \, \text{mJy}\) for SDSS J170334.39+245233.7 and SDSS J170332.91+245412.3, respectively. Individually, both signals are less than the measured rms in the spectrum. If the signals were additive, the resultant would be \(S_{\text{peak}} \sim 0.38 \, \text{mJy}\) which is a S/N = 1.4 signal. Thus, the contribution of both background galaxies is indistinguishable from the noise as there are baseline variations of this magnitude and greater already present in the spectrum where there are no known sources. However, we reflect the estimated contribution of these background galaxies in the systematic error. Since the spectrum represents the total power within the field of view, the presence of the two background galaxies would work to lower the mass measurement and therefore only affects the low end of our systematic error. We add in quadrature the estimated mass of the background galaxies with the other systematic errors from reduction.

J0329-0055 was observed with the VLA with a beam size of 44"×28". Within the field of view lies one other galaxy, SDSS J032957.19-005544.7, which is located at 1282.1 MHz. No NUV data exists for this object so a mass estimate cannot be made and no signal is seen at that location. However, this serendipitous observation allows us to place an upper limit on this galaxy as well. The measured rms in the channels surrounding the source location is \(S_{\text{rms}} = 0.48 \, \text{mJy}\) which corresponds to an upper mass limit of \(M_{\text{H}_i} < 1.24 \times 10^{10} \times (\Delta \nu/100 \, \text{km s}^{-1})^{1/2} \, M_\odot\). Within a 4.5' radius (i.e. the field of view of the GBT in the L–band) nine galaxies lie at similar redshift, one of which lies at nearly the same redshift as our source. Therefore, this object would not benefit from observations with a single dish radio telescope as all these sources would be observed simultaneously and could not be disentangled.
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Figure 5.4: Our measured sources versus other published results. The black dots correspond to Catinella et al. (2010) DR1 data, cyan squares correspond to our upper limit measurements, the red dot is our detection of J1703+2451, the blue triangle is the the Fernández et al. (2016) detection and the solid line is the Donley et al. (2006) detection.

Fig. 5.3 shows the relationship between stellar mass and gas fraction for the Catinella et al. (2010) data set and our measurements. Comparing the gas fraction of J1703+2451 to the GASS sample and other galaxies in the Virgo group (Cortese et al., 2011), it appears to lie well within the distribution as an “H\text{I} Normal” galaxy (see Fig. 2 of Huang et al., 2012), meaning that both the measured NUV–r color and gas fraction of J1703+2451 appear to lie along the mean of the GASS distribution of galaxies. The uncorrected star formation rate (SFR) of J1703+2451 measured from the strength of the \( H_\alpha \) emission line (Kennicutt, 1998) is SFR = 0.36 M\(_\odot\) yr\(^{-1}\). Although this value appears low, the Balmer decrement, which measures the flux ratio of the first two Balmer emission lines and should be equal to 2.85, is measured to be \( H_\alpha/H_\beta = 6.28 \). This indicates a large
amount of visual extinction caused by dust. Comparing the uncorrected SFR of J1703+2451 to the uncorrected SFRs of the GASS sample, it appears to lie well within the distribution (see Fig. 4 of Huang et al., 2012). The depletion time for this galaxy is $t_{\text{dep}} = M_{\text{H}}/\text{SFR} = 4.9 \, \text{Gyr}$, which also aligns well with the GASS sample.

The characteristics of J1703+2451 fit well along the mean of the GASS sample but it is by far our lowest redshift object and lies at the far redshift edge of the GASS sample ($z_{\text{GASS}} \leq 0.05$). The remainder of our sample lies a factor $\sim 2$ further in redshift. Due to continuous star formation throughout the lifetime of galaxies, the low redshift sample of galaxies from Catinella et al. (2010) should have a smaller gas reservoir than our target galaxies. On average, $M_{\text{H}_1}/M_*$ for THINGS galaxies is 20% (Leroy et al., 2008), while gas mass fractions in BzK $z \sim 1$ galaxies are 57% (Daddi et al., 2008), which may be more representative of this sample, as gas fractions are higher at higher redshift (Daddi et al., 2008; Tacconi et al., 2010). With this in mind, our mass predictions stated in Table 5.1 should be lower than the actual mass of these galaxies. However, both the Fernández et al. (2016) source and our detection fit along the relation shown in Fig. 5.1. The relations that are shown are quite wide due to the complicated nature of galaxy evolution and star formation rates, which are affected by galaxy environment, merger timescales, and supernova rates among other things. Therefore, it should be noted that our mass predictions should be used with caution.

In Fig. 5.4 we see how our results compare to the works of Donley et al. (2006), Catinella et al. (2010), and Fernández et al. (2016). Due to its location behind the Milky Way, the NUV — $r$ color for the Donley et al. (2006) source is unknown. The SFR for the Donley et al. (2006) source is measured to be 35 $M_\odot$ yr$^{-1}$, which indicates that it should have strong NUV emission. Although it appears to be very massive compared with the rest of the distribution, it is likely to lie along the general trend and have a low, blueward value for NUV — $r$. Furthermore, the Fernández et al. (2016) detection also appears to fit well within the distribution as do a few of our upper limit measurements, notably that of J0329-0055, J1037+3517, and our detection of J1703+2451.

Currently, H$\text{I}$ observations of galaxies at redshifts beyond $z \sim 0.1$ are fraught with challenges. For example, the frequency range below 1350 MHz is so filled with RFI signals at Arecibo that it has
inhibited our knowledge of the H\textsubscript{i} mass of galaxies beyond redshift $z > 0.05$ (Catinella et al., 2010; Catinella & Cortese, 2015; Giovanelli & Haynes, 2016). Arecibo’s superior dish size and sensitivity is negated by the presence of harsh interference signals that are impossible to remove. National Radio Quiet Zones such as the one around GBT help but still do not completely alleviate RFI issues that come from such sources as global positioning satellites and current technology requires many hours of observations for the detection of single galaxies even without interference. Arecibo has been able to detect galaxies at redshifts of $z \sim 0.2$; however, due to the large field of view, targets must be selected carefully to lie in low density environments. Next generation H\textsubscript{i} surveys with the SKA and its pathfinders ASKAP (Australian Square Kilometer Array Pathfinder) and MeerKAT (Expanded Karoo Array Telescope) will be able to detect H\textsubscript{i} at much higher redshifts than ever before due to superior spatial resolution and RFI handling (Carilli & Rawlings, 2004; Johnston et al., 2008; Booth et al., 2009; Catinella & Cortese, 2015; Giovanelli & Haynes, 2016). These interferometric surveys will be able to study H\textsubscript{i} morphology and kinematics of thousands of galaxies across a much wider redshift, shedding light on the H\textsubscript{i} mass function and how the gas supply of spiral galaxies evolves through cosmic time.

5.7 Conclusions

In summary, based on the relation between NUV — $r$ color and the $M_{\text{H\textsubscript{i}}}/M_*$ gas fraction, we computed the expected total H\textsubscript{i} masses of the SWELLS sources. We then carried out an observing campaign to secure the H\textsubscript{i} masses of these galaxies. We successfully detected one of our sources, J1703+2451, with a $S/N = 6.7$ detection, which is the first detection of H\textsubscript{i} emission in a strong spiral lens. We found a mass of $M_{\text{H\textsubscript{i}}} = (1.77 \pm 0.06^{+0.35}_{-0.75}) \times 10^9$ M$_\odot$ with our systematic error reflecting the possible influence of nearby background galaxies that were in the field of view of our observations. The width of the detected H\textsubscript{i} emission line was found to be unusually narrow ($W_{50} = 79 \pm 13$ km s$^{-1}$); however, the SFR, color, depletion timescale, and gas fraction of J1703+2451 are all typical for galaxies of its size and redshift. We found significant upper limit H\textsubscript{i} mass constraints
of three other galaxies, J0329-0055, J0841+4847, and J1037+3517 and also report a significant upper limit for background galaxy SDSS J032957.19-005544.7 which was serendipitously observed with J0329-0055. For three other sources, J1111+2234, J1117+4704, and J1135+3720, we were burdened by RFI and therefore can only place loose upper limit constraints for them. Finally, due to RFI, our observations of J1103+5322 were completely unusable.

For all our observations, RFI was a significant issue that had to be dealt with carefully. One of the lessons learned through these observations is that the expected H\textsc{i} mass and signal of a galaxy is not necessarily the best factor when prioritizing observations, nor does a large H\textsc{i} mass make a target ideal for future follow-up observations. The RFI environment of both single dish and interferometric telescopes must be considered carefully since the RFI environment around each telescope is unique. Unfortunately, future observations will likewise be burdened by ever increasing RFI issues. Mitigation in the form of nighttime observing can help with FAA radar and cellular RFI signals; however, many RFI issues come from unknown sources and likely from the instrument itself. Future observatories, such as the SKA, will have better understood systematics and may also employ real-time RFI flagging which will give a more accurate and thorough treatment for RFI affected data (Dumez-Viou et al., 2016; van Nieuwpoort, 2017). Furthermore, like the GBT, the SKA will be located in a radio quiet zone and therefore mainly affected only by satellite and airplane interference. As long as RFI is properly accounted for, these galaxies should be detectable in future high resolution H\textsc{i} mapping studies.
CHAPTER 6

SUMMARY AND FUTURE WORK

The observational evidence for the existence of dark matter is overwhelming. With cutting-edge computer simulations, we have been able to recreate the large-scale structure of the Universe to an exceptionally high degree of accuracy. However, on small scales there are many, many structure problems such as: the Missing Satellites problem, which describes the lack of observed substructure compared to what simulations predict (Section 1.4.1); the Too Big To Fail problem, which describes the fact that the largest satellites in simulations are incompatible with the largest observed dwarfs and are “too big” to have failed to become successful galaxies (Section 1.4.2); the Planes of Dwarf Galaxies problem, which describes the fact that dwarf galaxies appear to preferentially line up into thin planes around host galaxies (Section 1.4.3, Chapter 2); and more (Section 1.4). Because of all these small scales issues, some have called into question the validity of our currently accepted structure formation paradigm and have offered alternative solutions (Section 1.5).

The purpose of the work presented in this Dissertation has been to address some of the issues surrounding the small scale crisis of the ΛCDM paradigm and to further develop some tools for investigating small scale structure. In Chapter 2, we studied the Vast Polar Structure of dwarf galaxies around the Milky Way in detail to investigate whether or not it truly poses a significant threat to ΛCDM. In Chapter 3, we developed a scaling relation to help us quickly find information
about substructure around spiral galaxies using the concept of Tidal Analysis. By applying Tidal Analysis to the Milky Way, we have found evidence of a possible undiscovered dark matter dominated dwarf galaxy in line with the disk of the Milky Way. Observations attempting to observe variable stars in that putative dwarf were described in Chapter 4. Finally, in Chapter 5, we carried out an observing campaign utilizing three radio telescopes in an attempt to observe neutral hydrogen (H\textsubscript{i}) gas in spiral galaxies that are also strong lenses so that Tidal Analysis may one day be performed on those galaxies.

The following is a summary of the major results of each Chapter along with ideas of how to improve each project and any future work that remains to be done.

### 6.1 Investigating the Vast Polar Structure

One of the more controversial issues with CDM at small scales is the Planes of Dwarf Galaxies problem. Since the discovery of the odd alignment of the Milky Way’s brightest dwarf galaxies in the mid-1970’s (Kunkel & Demers, 1976; Lynden-Bell, 1976), there has yet to be a satisfactory solution or explanation of the phenomenon. Additionally, as more dwarfs were discovered they also appeared to line up with the previously known dwarfs until the entire collection of dwarfs was eventually deemed, the “Vast Polar Structure” (VPOS; Pawlowski et al., 2012). Because the brightest dwarfs around the Milky Way, known as the “classical” dwarfs, have been studied for so long, we now have accurate proper motion data for each of them. This enables us to follow their positions through time burdened only by the amount of observational error in their measurements.

To understand the significance of the VPOS compared with the CDM paradigm, we compared the degree of alignment seen in the Milky Way with planes fitted to distributions of subhaloes in dark matter-only cosmological simulations. By fitting to 11 random subhaloes in cosmological simulations $10^5$ times, we were able to produce a distribution of planes to compare with the Milky Way (Fig. 2.3). We found that the Milky Way distribution of satellites fit comfortably within the distribution of planes found in cosmological simulations and did not appear to be an outlier.
Because we have the proper motion data for the classical dwarfs, we integrated their orbits through time to investigate the longevity of the VPOS (Fig. 2.6). We found that the structure dispersed faster than a dynamical time, becoming less significant over time. We also investigated different distributions of the classical dwarfs. Leo I and Leo II were specifically singled out since their distant location and velocity makes them outliers in the classical dwarf galaxy distribution (Fig. 2.4). However, the results were consistent with the full distribution: the structure appears to disperse in less than a dynamical time. Furthermore, we integrated the orbits of just those dwarfs that appear to have aligned angular momentum vectors and found that they too became less significant over time. To ensure that our results were meaningful, we performed an error analysis and found that they could be trusted for up to 0.5 Gyr which was longer than the time it took for the observed structures to become significantly less aligned. When analyzing only those dwarfs whose proper motion data could be trusted beyond 0.5 Gyr, the structure dispersed quickly and remained a less significant alignment.

This analysis could be improved several ways. For our orbit integration calculations, a static, spherical Hernquist potential was chosen to represent the Milky Way. Observations have shown that the shape of the Milky Way’s halo is almost certainly not spherical (Section 1.4.6). Furthermore, we know that galaxies accrete material and grow in mass, deepening their potential wells over time. This will therefore affect orbital calculations which follow the potential of the host galaxy. To some degree, increased dynamical friction and tidal stripping of baryons and dark matter also affects the orbits of dwarf galaxies. In our simulations tidal stripping and baryons are ignored. Lastly, the mass of the Milky Way is also currently very uncertain (Section 2.5.2) and although we found our results to be independent of our choice of halo mass, if integrations are to be trusted over 0.5 Gyr, the mass of the Milky Way must be much more well constrained.
6.2 Scaling Relations for H\textsubscript{I} Studies

Spiral galaxies are surrounded by diffuse, extended H\textsubscript{I} gas disks that are susceptible to tidal perturbations by passing subhaloes. By modeling the observed disturbances in the H\textsubscript{I} disks of spiral galaxies with hydrodynamic simulations, it is possible to infer the current radius, azimuth, and pericenter of a perturbing satellite. This process is called Tidal Analysis. Although extremely useful, performing large sets of hydrodynamic simulations is computationally expensive; therefore, a simple, test particle code was developed by Chang \& Chakrabarti (2011). Through this code, a simple scaling relation was found between the total effective density response and the mass of a perturbing satellite. In that study; however, the found scaling relation was only valid for a single pericenter.

Through the work presented in Chapter 3, we extended the previous work of Chang \& Chakrabarti (2011) and found that the density response from a gas disk due to a perturbing satellite is a function of both satellite mass and pericenter distance in the following way (equation 3.7):

\[ a_{t,\text{eff}} = 0.88 \left( \frac{m_{\text{sat}}}{M_{\text{host}}} \right)^{0.6} \sqrt{R_{p}/50 \, \text{kpc}}, \]

where \(a_{t,\text{eff}}\) is the total effective density response, \(m_{\text{sat}}\) is the perturbing satellite mass, \(M_{\text{host}}\) is the mass of the host galaxy, and \(R_{p}\) is the pericenter radius. The degeneracy issues faced by this single equation with two unknowns is solved by analyzing the individual modes which will show a large density response near the location of pericenter (Fig. 3.1). Furthermore, the difference between different interactions can be seen visually since a large interaction that occurs far away will pull gas away from the galaxy into long tidal tails that would not be present from a less massive perturber interacting at a smaller pericenter.

We also studied how multiple satellites affected this result and found that interactions were independent and thus added in quadrature (equation 3.9, Fig. 3.4). Because of this fact, every multiple perturber case (included those not explicitly studied here) has a known result through the
Summary and Future Work

quadration addition of results from the one satellite case:

\[ a_{t,\text{eff}} = \sqrt{\sum_{k}^{k} \left[ 0.88 \left( \frac{m_{\text{sat}}}{M_{\text{host}}} \right)_{k}^{0.6} \frac{R_{p,k}}{50 \text{ kpc}} \right]^{2}} \]

where \((m_{\text{sat}}/M_{\text{host}})_{k}\) and \(R_{p,k}\) are the mass ratio and pericenter of the \(k\)-th satellite. Furthermore, only the largest satellite interactions will produce the largest density response since, as we saw in Fig. 3.4, a second satellite with 1/10 the mass of the other satellite will produce a negligible addition to the total effective density response.

In systems where there is symmetry in the density structure of the disk, we found that some modes held less power (Fig. 3.5), which may lead to degeneracy between one- and two-body interactions; although, here too, degeneracy can be avoiding by including visual information and identifying symmetry in the system. Even with degeneracy, the number of cases that need to be studied through detailed hydrodynamical simulations with Tidal Analysis is now greatly reduced through the use of the above relation.

The scaling relation found in this study can be applied to any current or future H I mapping observations of spiral galaxies. The H I Nearby Galaxy Survery (THINGS; Walter et al., 2008) is a perfect sample of extremely detailed H I maps for Tidal Analysis to be performed. However, for THINGS, large perturbers consist of companion galaxies that can be optically resolved. In fact, as a proof of concept for Tidal Analysis, Chakrabarti et al. (2011) used two galaxies from THINGS to see if they could find the largest perturber for M51 and NGC 1512 without using any prior knowledge of the optical companions. In both cases, they successfully found the known, large optical companion. It will therefore be most beneficial to apply this scaling relation to galaxies which do not have known optical companions but for which H I studies can still be done. For this reason, we investigated the galaxies of the Sloan WFC (Wide Field Camera) Edge-on Late-type Lens Survey (SWELLS; Treu et al., 2011; Brewer et al., 2012) which was described in Chapter 5.

There still remains work to be done for this project. Most importantly, the found scaling relation
must be verified using smoothed particle hydrodynamic (SPH) codes. Doing this will model the
effects of gas dissipation and a self-gravitating disk capable of providing fully realistic models of
interactions. These simulations will also be able to model the mass ratios where the test particle
code was not valid, mainly $m_{\text{sat}}/M_{\text{host}} < 1/30$. Once the scaling relation is verified, it will then be
important to check it against sources with known optical companions (such as M51 or NGC 1512).
Eventually, this work will become a future publication.

In an effort to model these simulations as observations, it would also be interesting to look at the
velocity information in the simulations since observations would yield this information. With the
velocity information, it may be possible to more clearly distinguish between individual interactions
due to the presence of large moving groups of material near the pericenter location.

### 6.3 Searching for a Dwarf Galaxy in Norma

Observations of the Milky Way’s extended H$\text{I}$ disk have shown a substantial warp (Levine et al.,
2006). By applying Tidal Analysis to the Milky Way, Chakrabarti & Blitz (2009) attempted to
recreate the observed structure with the known dwarfs but were unable. This led them to the
conclusion that a large, dark matter dominated dwarf galaxy must have sculpted the Milky Way’s
H$\text{I}$ disk into its current shape and must reside at 90 kpc in line with the Milky Way’s galactic
stellar disk. Because of extreme extinction along the line of sight towards the predicted location, it
was not until the infrared VISTA Variables in the Via Lactea survey (VVV; Minniti et al., 2011)
was complete that any progress could be made in identifying the dwarf. Using the VVV survey,
Chakrabarti et al. (2015) reported an overabundance of variable stars towards the predicted location
of the dwarf. Furthermore, they appeared to match the profile of being Type I classical Cepheids. If
these variable stars were Cepheid variables (short lived, standard candle stars), then their presence
would simultaneously allow very accurate distance measurements and indicate that there is a large
reservoir of gas for star formation. Due to an error in the source selection criteria, follow-up studies
by others (Pietrukowicz et al., 2015) found that the stars were either non-variables or spotted stars
that were well within the stellar disk of the Milky Way. The error has now been fixed and two new Cepheid candidates were identified and presented in Chakrabarti et al. (2016).

The work presented here are the results of a follow-up study of three Cepheid variable sources in an attempt to add more epochs to the light curves for these sources and thus make a more accurate distance measurement. Observations were carried out over ten nights using the Henrietta Swope optical telescope at Las Campanas Observatory in the Johnson $I$-band. Due to many difficulties associated with the observations (targets up only half the night, faint targets in crowded fields, high winds, earthquakes, etc.) the number of recorded epochs for all three sources was small (Table 4.1). The data that was obtained was compared with infrared data from the VVV survey (Fig. 4.3). The general shape of the light curves obtained from optical data appears to match the general shape of the infrared data; however, there are far too few epochs to make a meaningful comparison. Ultimately, the average $I$-band magnitudes were reported in Chakrabarti et al. (2016).

For these sources, there is a need for either a dedicated observing campaign to increase the number of epochs so that the light curves are complete or more survey data from a survey capable of making repeated measurements at the depth and resolution necessary to resolve these sources in the crowded field. A further observation that would help to resolve the issues associated with determining the identity of these variable stars would be accurate measurements of their spectra. Spectra for these stars were presented in Chakrabarti et al. (2016), which show that radial velocities for the three targets are $\sim 169$ km s$^{-1}$, indicating that they are part of the Milky Way’s stellar halo and unassociated with the stellar disk. However, the signal-to-noise of those spectra are not high enough to determine metallicities and, therefore, we are currently unable to determine if these are Type I or Type II Cepheids.

### 6.4 H$_1$ Studies of Strongly Lensed Spiral Galaxies

There are many methods to constrain the structure of dark matter halos and to constrain the amount of substructure around galaxies. One method is gravitational lensing, which takes
advantage of the fact that the amount of bending of light from a background source is directly proportional to the mass contained with the lens (Section 1.2, equation 1.1). As discussed in the previous two chapters, Tidal Analysis is another method that can provide information about substructure around spiral galaxies. Treu et al. (2011) and Brewer et al. (2012) attempted to use strong gravitational lensing to help break the Disk-Halo Degeneracy (Section 1.4.5) and well constrain the halo shapes of galaxies. By using the Sloan Digital Sky Survey (SDSS; York et al., 2000), they spectroscopically selected spiral galaxies that were also strong gravitational lenses and performed high-resolution followup observations as part of the SWELLS survey. This collection of strongly lensed spiral galaxies at redshift, $z \sim 0.1$, offers a unique set of galaxies for which both Tidal Analysis and gravitational lensing could be performed. Because of the different mechanisms these two methods use, gravitational lensing is sensitive to the inner regions of the galaxy while Tidal Analysis is sensitive to the outer parts of the halo.

H i mapping observations of spiral galaxies at $z \sim 0.1$ are very time intensive and extremely prone to interference issues. Because of this, it is important to know the total H i mass of the galaxy to ensure that mapping observations will be successful. However, the SWELLS did not measure the H i masses and because the neutral hydrogen gas fraction is not well correlated with stellar mass (Fig. 5.3) we are unable to accurately estimate it with current observations. We therefore carried out an observing campaign using the large single dish radio telescopes in Arecibo, Puerto Rico and Green Bank, West Virginia as well at the Karl G. Jansky Very Large Array radio interferometer in Socorro, New Mexico to securely obtain the H i masses of our sample.

The spectra we obtained are shown in Fig. 5.2. Unfortunately, radio frequency interference (RFI) was a significant issue for all our observations and resulted in us making only one secure detection and six significant upper limits (Table 5.2). We learned that the predicted H i mass of a spiral galaxy is not the only limiting factor to performing radio observations since RFI is such a significant problem. Without properly accounting for RFI issues, it is easy to lose an entire dataset to noise. Unfortunately, it is impossible to avoid all RFI signals as some may come from the instrument itself, but future telescopes will have a better understanding of their systematics.
and live RFI flagging software that will prevent the loss of large amounts of data. In the future, we will continue our observing campaign of these interesting sources and will attempt to map two of these sources in the Fall of 2017 using the VLA. Once a high-resolution map is successfully obtained of one of these objects, work can begin performing Tidal Analysis to recreate the observed disturbances that we will certainly see in the disk structure.
A.1 Milky Way Dwarf Galaxy Data

On the following page are all the position and velocity data for the classical Milky Way dwarf galaxies.
Table A.1: Information of each of the 11 classical dwarf galaxies ranked by distance. Those dwarfs listed in bold have errors that are not accurate enough to be trusted in orbit integrations up to 0.5 Gyr (see Section 2.5.1). In this coordinate system, X points from the Sun to the Galactic Center, Y points in the direction of galactic rotation, and Z points towards the northern galactic pole. References: (1) Casetti-Dinescu & Girard (2016) (2) Chakrabarti et al. (2014) (3) Kallivayalil et al. (2013) (4) Majewski et al. (2003) (5) Massari et al. (2013) (6) Piatek et al. (2016) (7) Pryor priv. comm. (8) Sohn et al. (2013) (9) van der Marel & Kallivayalil (2014) (10) Walker et al. (2009). All errors from Sohn private communication, except the velocity errors for Sagittarius (Pryor, private communication), Leo II (Piatek et al., 2016), Draco (Casetti-Dinescu & Girard, 2016), and LMC and SMC (Kallivayalil et al., 2013).

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass ((10^8 , M_\odot))</th>
<th>D (kpc)</th>
<th>X (kpc)</th>
<th>Y (kpc)</th>
<th>Z (kpc)</th>
<th>V (km s(^{-1}))</th>
<th>(V_x) (km s(^{-1}))</th>
<th>(V_y) (km s(^{-1}))</th>
<th>(V_z) (km s(^{-1}))</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittarius</td>
<td>100</td>
<td>20.6±0.5</td>
<td>19.2±0.5</td>
<td>2.70±0.05</td>
<td>-6.9±0.1</td>
<td>318±10</td>
<td>235±4</td>
<td>-49±15</td>
<td>208±14</td>
<td>2, 4, 5, 7</td>
</tr>
<tr>
<td>LMC</td>
<td>300</td>
<td>50±2</td>
<td>-1.1±0.4</td>
<td>-41±2</td>
<td>-28±1</td>
<td>321±24</td>
<td>-57±13</td>
<td>-226±15</td>
<td>221±19</td>
<td>3, 8, 9</td>
</tr>
<tr>
<td>SMC</td>
<td>30</td>
<td>59±2</td>
<td>15.3±0.9</td>
<td>-37±2</td>
<td>-43±2</td>
<td>217±26</td>
<td>19 ±18</td>
<td>-153±21</td>
<td>153±17</td>
<td>3, 8, 9</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>0.77</td>
<td>78±3</td>
<td>-22.2±0.8</td>
<td>52±3</td>
<td>54±3</td>
<td>159±43</td>
<td>-108±51</td>
<td>-15±34</td>
<td>-116±34</td>
<td>8, 10</td>
</tr>
<tr>
<td>Sculptor</td>
<td>1.35</td>
<td>85±1</td>
<td>-5.3±0.2</td>
<td>-9.6±0.2</td>
<td>-84±1</td>
<td>248±39</td>
<td>-19±42</td>
<td>225±43</td>
<td>-102±5</td>
<td>8, 10</td>
</tr>
<tr>
<td>Draco</td>
<td>3.9</td>
<td>93±4</td>
<td>-3.5±0.4</td>
<td>76±5</td>
<td>53±3</td>
<td>136±16</td>
<td>95±18</td>
<td>-73±11</td>
<td>-63±17</td>
<td>1, 8, 10</td>
</tr>
<tr>
<td>Sextans</td>
<td>0.29</td>
<td>100±2</td>
<td>-40.0±0.9</td>
<td>-64±2</td>
<td>65±2</td>
<td>242±106</td>
<td>-181±116</td>
<td>114±98</td>
<td>114±85</td>
<td>8, 10</td>
</tr>
<tr>
<td>Carina</td>
<td>0.57</td>
<td>106±1</td>
<td>-24.8±0.3</td>
<td>-95±1</td>
<td>-39.3±0.5</td>
<td>83±36</td>
<td>-73±38</td>
<td>7 ±14</td>
<td>38 ±30</td>
<td>8, 10</td>
</tr>
<tr>
<td>Fornax</td>
<td>1.45</td>
<td>144±1</td>
<td>-40.0±0.4</td>
<td>-49.2±0.5</td>
<td>-129±1</td>
<td>178±20</td>
<td>-25±23</td>
<td>-141±23</td>
<td>106±11</td>
<td>8, 10</td>
</tr>
<tr>
<td>Leo II</td>
<td>0.64</td>
<td>236±7</td>
<td>-77±3</td>
<td>-58±2</td>
<td>215±8</td>
<td>129±39</td>
<td>-41±40</td>
<td>116±41</td>
<td>41±16</td>
<td>6, 8, 10</td>
</tr>
<tr>
<td>Leo I</td>
<td>1.3</td>
<td>261±8</td>
<td>-125±6</td>
<td>-121±6</td>
<td>194±10</td>
<td>196±30</td>
<td>-168±32</td>
<td>-37±33</td>
<td>94 ±24</td>
<td>8, 10</td>
</tr>
</tbody>
</table>
A.2 Plane-fitting

Below is the Python function that was used to perform plane-fitting to the Milky Way dwarfs and subhaloes in simulations. It uses Principle Component Analysis as described in Section 2.3.2 and makes use of equations 2.1 and 2.2.

```python
import numpy as np

def best_fitting_plane(data):
    """Computes the best fitting plane from a given set of points using Principal Component Analysis (PCA).

    Input Parameters:
    data: [n, 3] array
    The x, y, z coordinates corresponding to the points from which we want to find the best-fitting plane.
    Expected format:
    np.array([[
        [x1, y1, z1],
        ...
        [xn, yn, zn]])

    Returns:
    normal: [1,3] array
    The coefficients of the best fitting plane which corresponds to the normal vector. The equation of the plane is given by
    a*X + b*Y + c*Z + d = 0
    We set d = 0 so that the best-fitting plane goes through the center.
    D_rms: float
    The point-plane distance is calculated for each data point.
    """
```
point via the dot product of the normal vector and each
data point. This information is then used to calculate
the rms thickness of the plane as a measurement of the fit.

delta : float
The normalized thickness of the plane is given by dividing
the rms thickness of the plane, \( D_{\text{rms}} \), by the median radial
distance each point lies from the center.

"""
# Find the covariance matrix.
matrix = np.cov(data.T)

# Calculate the eigenvalues and eigenvectors.
eigenvalues, eigenvectors = np.linalg.eig(matrix)

# Sort the eigenvalues and eigenvectors from greatest to least.
sort = eigenvalues.argsort()[:,::-1]
eigenvalues = eigenvalues[sort]
eigenvectors = eigenvectors[:,sort]

# The normal of the plane is the last eigenvector which
# corresponds to the smallest eigenvalues. This is the vector
# which points along the direction of least variance and is
# therefore perpendicular to the fitted plane.
normal = eigenvectors[:,2]
a, b, c = normal

# Calculate the rms thickness of the fitted plane.
point_plane_distance = abs(a*data[:,0] + b*data[:,1] + c*data[:,2])
D_rms = (np.sum(point_plane_distance**2)/len(data))**0.5

# Calculate the normalized thickness of the plane.
delta = D_rms/np.median(np.sqrt(np.sum(data**2, axis=1)))

return normal, D_rms, delta

# Import data.
XYZ = np.genfromtxt('/Users/andy/XYZData.txt')

# Find the best-fitting plane and statistics.
normal, D_rms, delta = best_fitting_plane(XYZ)
In this appendix, I will describe the observing method used for the observations described in Chapter 5, the methodology behind data reduction and radio frequency interference (RFI) flagging, and give an example code in GBTIDL for how to process H\textsc{i} spectral line data. I will discuss some of the tools of GBTIDL but will not go into all the details of how to use it. For more information, please find the wonderful GBTIDL User’s Manual (Thomas et al., 2012). Any functions that are mentioned below will be shown in *italics*.

### B.1 Position Switching

For the observations taken with the Arecibo and Green Bank Telescopes (GBT), we used the method of position switching which involves taking a series of ON and OFF pairs of images. In other words, for a specified amount of time the telescope will observe the source of interest and then for the same amount of time it will observe a portion of ‘blank’ sky that does not include the source. Best practices include tracking along the same hour angle so that the telescope tracks along the same portion of sky during the OFF image as it did for the ON image. This ensures
that both observations are observed through the same airmass and if the pair of images are taken in quick succession, the bandpass shape and gain curve should remain the same. This method has been proven to give the most stable baselines which is necessary for observing weak spectral lines such as H\textsc{i}.

Observations using the GBT are broken up into separate sessions typically three to six hours in length. During a session, the GBT will take a number of ON and OFF pairs of scans. The length of each scan can vary between two to ten minutes in length but are typically around five minutes long. Each scan is then broken down into individual integrations. The GBT can read data as fast as every 0.05 seconds or the user can read out once per scan. Typically, 5 s is the chosen length for an integration as there is a trade off between RFI mitigation and the amount of data created by reading out the telescope very quickly. Most RFI in the L-band (1.1 < \nu < 1.4 \text{ GHz}) is caused by Federal Aviation Administration (FAA) radar and other radio positioning signals (e.g. military, GPS, cell phones, etc.) that are typically pulsed and less than 1 s in duration. In order to minimize the effects of RFI, the data being collected during a scan is read out at a fast rate. If the user is confident that there is little to no RFI present in the observed band then slower readout times can be more useful. To recap: observations of an object are broken up into observing sessions, which are then broken up into ON and OFF pairs of scans, that are then broken into individual integrations.

\section*{B.2 Data Reduction}

After the observations were performed, we clean the data of RFI signals and generate the final spectra. The algorithm we used for this is as follows:

1. Step through each integration and check for RFI, flag any affected integrations.

2. Combine integrations for each scan into a single spectrum for each polarization.

3. Combine scans for each session into a single spectrum for each polarization.
Appendix B. Performing H\textsc{i} Spectral Line Data Reduction of GBT Data Using GBTIDL

4. Combine every session together into two final ‘master’ polarized spectra.

5. Combine the two polarizations together into a final spectrum.

6. Flag any narrowband RFI present.

7. Perform smoothing of the final spectrum.

8. Subtract a low order polynomial baseline.

9. Measure the signal.

B.2.1 Flagging Wideband RFI

For our observations, we broke each four minute scan into one second integrations so that we could flag bad integrations but keep the majority of the data. Below is a fairly generic code for automated flagging of RFI affected spectra. This code is an example of the methodology which was used to remove wideband RFI from our spectra that had good, stable baselines. Those spectra are presented in Chapter 5 and the details of the observations are presented within. We used the observing method of position switching (described above) and with only a little customization this code should work for most H\textsc{i} wideband RFI flagging purposes of position switched data. The variables that need to be customized are the failure criteria for causing an integration to be flagged due to RFI, the number of integrations per scan, the frequency range to search over, which sessions and scans to analyze, and the file path to the location of all the FITS files from the observations.

FAA and other radar signals are typically very pronounced, wide, gaussian-like, highly polarized features that are clearly seen in the spectrum (Figure B.1). A four minute scan can be rendered useless by just a few seconds of bad integrations. Therefore, it is important to investigate each individual integration separately to look for such obvious signals. This is complicated by the presence of narrowband RFI which typically occupies less than a few neighboring channels in a spectrum but can be extremely strong. So any automated software must be able to distinguish between one or two bad channels and significant RFI.
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Figure B.1: An example of the GBTIDL Plotter window and an RFI affected spectrum. Plotted in red is the spectrum of a wideband RFI signal that occurred during observations of source J1703+2451. This signal, when present, was seen every 12 seconds. The spectrum is a 1 second integration and has been smoothed by a 100 channel boxcar.

Here, we will step through the attached reduction code and describe the flagging and reduction process. We first produce a spectrum of each integration by using the `getps` command (get position switched data) and using the `intnum` (integration number) option to specify the integration number and `pnum` (polarization number, 0 for XX, 1 for YY) option to specify the polarization. This command grabs the appropriate OFF scan and produces a reduced spectrum by performing the standard (ON-OFF)/OFF calculation. Next, we smooth the spectrum by applying a 100 channel wide boxcar smoothing window function using `boxcar`. This calculates the running average through the spectrum which effectively eliminates narrowband RFI and highlights wideband RFI. We then determine if an integration is suffering from wideband RFI by comparing the spectrum against the
Appendix B. Performing H\textsc{i} Spectral Line Data Reduction of GBT Data Using \textsc{gbtidl}

Theoretical rms calculated via the radiometer equation.

\[
T_{\text{rms}} = \frac{\sqrt{2}T_{\text{sys}}}{\sqrt{N_{\text{pol}}\Delta f_{\text{ch}}t_{s}N_{\text{ch}}}}, \tag{B.1}
\]

where \( T_{\text{sys}} \) is the system temperature, \( N_{\text{pol}} \) is the number of polarizations being used (1 for an individual integration), \( \Delta f_{\text{ch}} \) is the width of a single channel in hertz, \( t_{s} \) is the exposure time of the integration, and \( N_{\text{ch}} \) is the number of channels that we smoothed over to highlight wideband RFI. Since we combine two spectra together in position switching observing, an extra factor of \( \sqrt{2} \) appears assuming similar noise levels in both the ON and OFF spectra. All this information appears in the header of each image so it is easy to calculate the theoretical rms for each individual spectrum since \textsc{gbtidl} stores this information in the !\text{g.s} structure. To see all the information that is stored in the !\text{g.s} structure and how to call it, see the User’s Manual (Thomas et al., 2012).

Once we have our expectation for what the signal should be, we find the statistics of the spectrum by using the \textit{stats} function, specifying the range over which we wish to look. This should be centered around where you expect a signal to be as there is no point in ignoring an otherwise good spectrum because of isolated RFI signals outside the region of interest. Finally we compare the maximum and minimum of the spectrum against the theoretical rms expectation. If it fails our criteria of having a maximum or minimum larger than 5\( \sigma \), we flag that individual integration by using the \textit{flag} function.

Depending on the amount of data, this operation can take a very long time since it can process about one integration per second.

\textbf{A Note on Bad Baselines}

For sources that were affected by bad baselines in individual integrations we applied a slightly different reduction strategy. For those integrations, we compared the measured rms versus the theoretical rms after a 100 channel boxcar smoothing. This has the effect of highlighting non-
thermal noise since thermal noise decreases as \((N_{ch})^{1/2}\). Therefore, exceptionally bad baselines (measured rms greater than 3 times the theoretical rms) were flagged, as were RFI affected spectra. For small scale baseline variations that remained after this flagging was performed, if they were non-stationary they were expected to average out in the same fashion as \((N_{sp})^{1/2}\) where \(N_{sp}\) is the number of spectra combined. However, for stationary baseline variations, the variations would be additive when combined. Therefore, we imposed a final rms check on the combined spectrum to ensure that this did not happen.

We did not apply this method for observations with good baselines because a single source of wideband RFI will not necessarily increase the rms above the threshold but may significantly impact results.
pro gbt_rfiflag

; This program will flag bad integrations based on RFI. It will
; find the max and min of the spectrum, compare it to the theoretical
; rms and make a determination about whether or not it fails. The user
; must input their information into the section below labeled USER
; DEFINED VALUES. They will need to define the failure criteria,
; the length of each scan and integration time in seconds, the session
; numbers as strings, the starting and final scan number for each
; session, and the frequency range over which to check for RFI in GHz.
; The user must also ensure that the correct path is used in the
; FOR loop.
;
; CREATED: March 17, 2017
; AUTHOR: Andy Lipnicky

; Set the y–axis so that it is easier to compare each spectrum visually.
sety, –2, 2

; USER DEFINED VALUES
fail = 5.

; Set the criteria for rms failure. The default is 5*rms.

; Set the integration length and scan length in seconds. This determines
; how many integrations were taken.
scan_length = 240
int_length = 1
num ints = fix (scan_length / int_length)

; Define the frequency range in GHz over which to check for RFI signals.
low_freq = 1.219
high_freq = 1.222

; Each session number corresponds to the session where J1135+3720 was
; observed, start corresponds to the first scan of the session, and
; last corresponds to the last scan of the session. This must be
; customized by the user to correspond to their observations.
session = ['01', '02', '04', '06', '07', '09', '10', '12', '13', '15']
start = [11, 8, 6, 8, 7, 8, 6, 6, 6]
last = [38, 39, 35, 43, 15, 41, 39, 45, 23, 11]
Appendix B. Performing HI Spectral Line Data Reduction of GBT Data Using GBTIDL

; Set loop over sessions.
for sesh=0,n_elements(session)−1 do begin
  ; Read in the data. MAKE SURE THIS IS THE CORRECT PATH.
  filein ,'/Volumes/Research_Data/GBT−14B/data_newflag/fitsfiles/' $ 
  +'GBT14B_073_'.$+session [sesh]+'.raw.vegas.A.fits'
  ; Set loop for polarization.
  for pol=0,1 do begin
    ; Set loop for the scans that apply to our object. Skip every
    ; other scan because we are looking at pairs of images.
    for scan=start [sesh],last [sesh],2 do begin
      ; Set loop for integrations.
      for i=0,num ints do begin
        getps,scan,plnum=pol,intnum=i,/quiet
        boxcar,100
        ; We make use of the !g.s structure that holds all the
        ; information in the header of the spectral line data.
        rms=2.ˆ0.5*!g.s[0].tsys/(!g.s[0].bandwidth/32768$ $ 
        !g.s[0].exposure*100.)^0.5
        stats,low_freq,high_freq,/quiet,ret=s
        ; This is our criteria for failure, max/rms > fail
        ; or |min|/rms > fail
        if (s.max−s.median)/rms GT fail then begin
          flag,scan,intnum=i,plnum=pol,$
          idstring='J1135−Failed RMS criteria'
          continue
        endif
        if abs((s.min−s.median))/rms GT fail then begin
          flag,scan,intnum=i,plnum=pol,$
          idstring='J1135−Failed RMS criteria'
          continue
        endif
      endfor
    endfor
  endfor
endfor

B.2.2 Creating a Combined Spectrum

After data flagging is performed, we can combine the remaining unaffected data together into a single spectrum. We first combine each polarization of each session into its own spectrum by using
Appendix B. Performing $^{1}$H Spectral Line Data Reduction of GBT Data Using gbtidl

$getps$ again. This time when we use it, it will automatically grab all the integrations of a scan that have not been flagged. For each polarization in each session, we must use $getps$ for every scan.

We then apply a simple polynomial baseline to get rid of any offsets between the ON and OFF observations. It is possible to set any order polynomial as a baseline; however, the higher order that you use, the more free parameters that you introduce and the more likely that you will accidentally remove your signal or introduce fake ones. Therefore, it is good practice to use a low order, no higher than $n = 3$, baseline. For our observations, we applied an $n = 3$ polynomial to all our spectra. We define this by using $nfit.3$. Next, we define the region of the spectrum that we want to fit the baseline to using $setregion$. This allows us to interactively select the regions of the spectrum that lie on either side of the expected signal location. We also made use of $nregion$ to select the regions of the spectrum we wanted to fit so that every baseline was fit to the same regions of the spectrum. After that is set, we then apply the baseline using $baseline$ to each spectrum.

Once we have the cleaned and baselined spectrum for a scan, we can add it to the data accumulator by using $accum$. This stores all the data we want to average together. Each spectrum that is added to the accumulator receives a weight that is equal to

$$w = \frac{t_s\nu_{\text{res}}}{T_{\text{sys}}^2}$$

(B.2)

where $t_s$ is the exposure time and $\nu_{\text{res}}$ is the frequency resolution. After we have accumulated all the scans of a polarization for one session, we can use $ave$ to average them all together and produce a polarized spectrum. We can then save this reduced spectrum using $fileout,’[filename]’, then $keep$.

Next, we begin gathering each polarized spectrum from each session by using $gettp$ (get total power) since we have already performed the position switching reduction. We accumulate all the similar polarized spectra together to create a master polarized spectrum. Thus, at the end of this process we have two spectra, one for each linear polarization. Since we know that our signal, a
Appendix B. *Performing H I Spectral Line Data Reduction of GBT Data Using GBTIDL*

spiral galaxy, is unpolarized, it should appear in both polarizations. Since RFI is typically highly polarized, any that was missed by our scrubbing will appear in one of the spectra. Finally, we combine the two polarizations together and baseline again to produce the final spectrum. Since we use the same order polynomial throughout, we can be assured that we aren’t adding more free parameters, just changing the constants of polynomial fit.

**B.2.3 Measuring the H I Mass of a Galaxy**

Once we have produced the final spectrum we can flag any narrowband RFI that is present. This is easily done by using the *flag* function and specifying the affected channels with the *chan* option. Typically only a few channels were affected by narrowband RFI. Once they were blanked, they were interpolated over using the *ginterp* function.

After flagging, we can smooth the spectrum to improve the signal to noise (S/N) of any features since, again, thermal noise will decrease as $(N_{\text{ch}})^{1/2}$ but other features will remain present. As a first step, we apply Hanning smoothing by using the *hanning* function which is a three–channel running mean across the spectrum with a triangle as a smoothing kernel. The central channel is weighted by 0.5 while the two adjacent channels are weighted by 0.25. Additionally, we choose to use the *decimate* option while smoothing which then only keeps every other channel. This has the effect of ‘spreading out’ the noise and helps to remove any ringing effects caused by narrowband RFI.

Next we need to smooth to our desired velocity resolution. Our observations were performed in mode 15 which corresponds to a bandwidth of $BW = 11.7188$ MHz and 32768 channels. Since we have hanning smoothed and decimated, we now have 16384 channels. This yields a frequency resolution of 715 Hz channel$^{-1}$ or a velocity resolution of

$$ v_{\text{res}} = \frac{\nu_{\text{res}} c}{\nu_c} \approx 170 \text{ m s}^{-1} \text{ channel}^{-1} $$  \hspace{1cm} (B.3)
Appendix B. Performing HI Spectral Line Data Reduction of GBT Data Using gbtidl

where \( \nu_c \) is the center frequency of the spectrum.\(^1\) Therefore, the number of channels we need to smooth over to reach our desired velocity resolution is set by

\[
N_{ch} = \frac{v_{sm}}{v_{res}}
\]

(B.4)

where \( v_{sm} \) is the desired smoothed velocity resolution.

Finally, we measure the signal and estimate an H\( \text{I} \) mass for our source. To do this, we utilize the \textit{gmeasure} function in mode 4 with the fraction set to either 0.5 or 0.2 which describes the fraction of the flux at which the width is defined. This function was specifically designed to measure the signal from H\( \text{I} \) observations and measures the area, width, velocity and their errors of a galaxy profile. It measures the area by summing the signal in a channel multiplied by the velocity width of that channel, i.e. \( \int Sdv \). Using mode 4 of the \textit{gmeasure} function means that a first order polynomial is fit to either side of the signal and the velocity width is measured by taking the difference of velocities between the two midpoints of the polynomials as described in Springob et al. (2007). This method averages out noise effects from either side of the profile.

Once we have this information, we can apply the standard equation

\[
M_{\text{H}\text{I}}(M_{\odot}) = \frac{2.356 \times 10^5}{1 + z} D_L^2 \int Sdv
\]

(B.5)

where \( M_{\text{H}\text{I}} \) is the total mass in H\( \text{I} \) in solar masses, \( z \) is the redshift, \( D_L \) is the luminosity distance in Mpc, \( S \) is the flux in Jy, and \( dv \) is the velocity width in km s\(^{-1} \) (Wild, 1952; Roberts, 1962). To estimate the S/N of the signal, we adopted the convention of Saintonge (2007) adapted

\(^1\)Note the difference between velocity, \( v \), and frequency, \( \nu \)!
Appendix B. Performing H i Spectral Line Data Reduction of GBT Data Using gbtidl

to our velocity resolution

$$S/N = \frac{F/W}{\sigma} \left( \frac{W/2}{20 \text{ km s}^{-1}} \right)^{1/2}.$$  \hfill (B.6)

Here, $F$ is the integrated flux in Jy km s$^{-1}$, $W$ is the width of the signal in km s$^{-1}$, $\sigma$ is the rms noise, and 20 km s$^{-1}$ is the velocity resolution of our spectrum. This definition of S/N takes into account the fact that for the same peak flux, a broader spectrum has more signal.

However, if no signal is present, then we can use an approximate form of the above equation

$$M_{\text{H}i}(M_\odot) \approx \frac{2.4 \times 10^5}{1 + z} D_L^2 S_{\text{peak}} W$$  \hfill (B.7)

where $W$ is the velocity width and $S_{\text{peak}}$ is the peak of the signal. With no signal present, we can estimate an upper limit by assuming that the peak of the signal can be no larger than $5\sigma$, where $\sigma$ is the rms of the spectrum measured using stats, or else we would have detected it. We must also assume a velocity width for the non-detection (typically 100 km s$^{-1}$). Finally, we know that the H i mass scales as $M_{\text{H}i} \propto SdV$ and the rms noise in a spectrum decreases as $S_{\text{rms}} \propto (dV)^{-1/2}$, thus the H i mass limit scales as $M_{\text{H}i} \propto (dV)^{1/2}$. We, therefore, make our assumptions explicit and state our H i mass limits with a $(dV/100 \text{ km s}^{-1})^{1/2}$ factor.


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