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As blessings leave, thankfully new ones arrive, so I would like to dedicate this thesis to little Sointu.

Contents

Abstract

This doctoral dissertation presents studies of the formation and evolution of galaxies, through observations and simulations of galactic halos. The halo is the component of galaxies which hosts some of the oldest objects we know of in the cosmos; it is where clues to the history of galaxies are found, for example, by how the chemical structure is related to the dynamics of objects in the halo. The dynamical and chemical structure of halos, both in the Milky Way's own halo, and in two elliptical galaxies, is the underlying theme in the research. I focus on the density falloff and chemistry of the two external halos, and on the dynamics, density falloff, and chemistry of the Milky Way halo.

I first study galactic halos via computer simulations, to test the long-term stability of an anomalous feature recently found in kinematics of the Milky Way's metal-poor stellar halo. I find that the feature is transient, making its origin unclear. I use a second set of simulations to test if an initially strong relation between the dynamics and chemistry of halo globular clusters in a Milky Way-type galaxy is affected by a merging satellite galaxy, and find that the relation remains strong despite a merger in which the satellite is a third of the mass of the host galaxy.

From simulations, I move to observing halos in nearby galaxies, a challenging procedure as most of the light from galaxies comes from the disk and bulge components as opposed to the halo. I use Hubble Space Telescope observations of the halo of the galaxy M87 and, comparing to similar observations of NGC 5128, find that the chemical structure of the inner halo is similar for both of these giant elliptical galaxies.

I use Very Large Telescope observations of the outer halo of NGC 5128 (Centaurus A) and, because of the difficultly in resolving dim extragalactic stellar halo populations, I introduce a new technique to subtract the contaminating background galaxies. A transition from a metal-rich stellar halo to a metal-poor has previously been discovered in two different types of galaxies, the disk galaxy M31 and the classic elliptical NGC 3379. Unex-

pectedly, I discover in this third type of galaxy, the merger remnant NGC 5128, that the density of metal-rich and metal-poor halo stars falls at the same rate within the galactocentric radii of $8 - 65$ kpc, the limit of our observations. This thesis presents new results which open opportunities for future investigations.

Tiivistelmä

Tässä väitöskirjassa tutkin galaksien muodostumista ja evoluutiota havaintojen ja galaksien halojen tietokonesimulaatioiden avulla. Galaksin halo sisältää maailmankaikkeuden vanhimpia tunnettuja kappaleita. Halosta löydetään viitteitä galaksien muodostumishistoriasta, mm. siitä, miten halotähtien kemiallinen koostumus liittyy niiden dynamiikkaan. Väitöskirjassani tutkin Linnunrataa sekä kahta muuta galaksia, erityisesti niiden halojen dynaamista ja kemiallista rakennetta. Keskityn kaikkien tutkimien kohteiden tiheysjakauman muutoksiin ja kemiaan ja lisäksi Linnunradan halotähtien dynamiikkaan.

Ensiksi tutkin galaksihaloja tietokonesimulaatioiden avulla. Niillä pystyy tarkistelemaan erään Linnunradan metallipitoisuudeltaan pienen halon poikkeavan ryhmittymän pitkäaikaista vakautta. Tämä ryhmittymä on luonteeltaan ohimenevä, joten sen alkuperästä ei ole tietoa. Käytän toisenlaista simulaatiota testatakseni, voiko pallomaisten tähtijoukkojen kemiallisen koostumuksen ja liikkeen välillä olevaa yhteyttä muuttaa, jos Linnunradan tyyppiseen galaksiin törmää toinen galaksi. Simulaatioista käy ilmi, että tämä yhteys säilyy, vaikka törmäävän galaksin massa on jopa kolmannes törmäyksen kohteena olevan galaksin massasta.

Simulaatioiden jälkeen käsittelen havaintoja lähigalaksien haloista. Tämä on haastavaa, koska suurin osa galaksien valosta tulee kiekosta ja keskuspullistumasta. Käytän Hubblen avaruusteleskoopin havaintoja M87-galaksista ja samanlaisia havaintoja NGC5128-galaksista. Havainnoistani käy ilmi, että M87:n halon kemiallinen koostumus on samanlainen kuin NGC5128-galaksilla. Molemmat galaksit ovat suuria elliptisiä galakseja.

Käytän Very Large Telescopen havaintoja NGC5128-galaksin (Centaurus A) halon tutkimiseen, koska pienemmällä teleskoopilla on vaikea havaita kaukaisen galaksin halon tähtiä. Esittelen myös uuden tekniikan, jolla saa taustalla olevat galaksit poistettua kuvista. Galaksin halossa oleva siirtymä metallipitoisuudeltaan suurten ja metallipitoisuudeltaan pienten tähtien välillä on löydetty kahdesta galaksista aikaisemmin: kiekko-galaksi

M31:stä ja klassisesta elliptisestä galaksista NGC3379:stä. Hieman odottamattomasti löydän samanlaisen piirteen NGC5128:sta. Metallipitoisuudeltaan suurten tähtien ja metallipitoisuudeltaan pienten tähtien tiheys vähenee samaa tahtia galaksin keskustasta kahdeksan kpc:n etäisyydeltä 65 kpc:n etäisyydelle, eli havaintojen rajalle asti. Tämä väitöskirja esittelee uusia tuloksia, jotka avaavat mahdollisuuksia tulevalle tutkimukselle.

List of Publications

This thesis consists of an introductory review of the subject (Chap. 1 – 6) and the following original research articles:

I **The Inner Halo of M87: a First Direct View of the Red-Giant Population**,
S. A. Bird, W. E. Harris, J. P. Blakeslee, and C. Flynn, A&A **524**, A71 (2010).

II **Red Giants in the Outer Halo of the Elliptical Galaxy NGC 5128/Centaurus A**,
S. A. Bird, C. Flynn, W. E. Harris, M. Valtonen, A&A (accepted for publicataion).

III **Fading Features Found in the Kinematics of the Far-Reaching Milky Way Stellar Halo**,
S. A. Bird, C. Flynn, (in progress)

Chapter 1

Galaxy Halo Studies

1.1 Introduction and Motivation

Galaxy halos are near-spherical distributions of stars, stellar globular clusters, and dark matter, in which the most visible parts of the galaxy, the disk and bulge, are embedded (see Fig. 1.1). Characteristic of the halo are the stellar orbits, which are highly random with little net rotation, and the metal content of the stars, which is low relative to the disk and bulge components of galaxies. The majority of the Galactic light across the spectrum is emitted from the Galactic disk and bulge. Only 1% of optical light comes from the halo (e.g. Freeman and Bland-Hawthorn (2002); Morrison (1993)). Studies began in the early twentieth century to figure out what new information this dim component of our Galaxy has to contribute, and the studies continue to significantly mature today. The current best telescopes like Hubble Space Telescope and Very Large Telescope are able to gather enough starlight to resolve individual halo stars in galaxies outside our local neighborhood. Part of the interest in the halo stars and globular clusters lies in their age; they are among the oldest components of galaxies and some of the first stars born. Motivation peaks as observations and simulations show that the dynamical and chemical properties of halo stars and globular clusters contain secrets of the formation and evolution of the entire galaxy.

1.2 Build-Up of Halo Observations and Theory

Galactic halos are composed of different populations: stars, globular clusters, dark matter, satellite galaxies, and stellar substructures such as

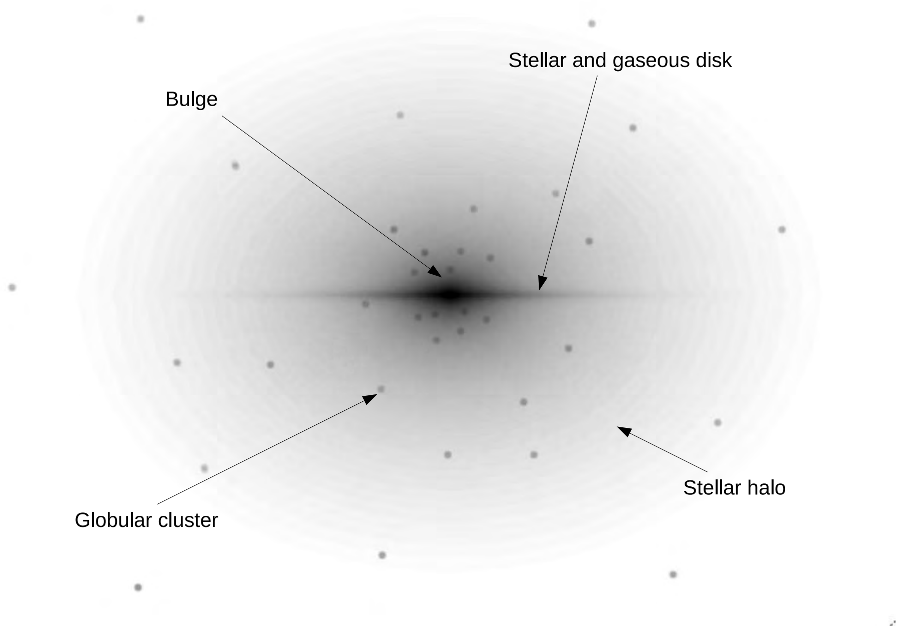

Figure 1.1: Schematic drawing of the Milky Way density distribution, including the bulge, stellar and gaseous disk, stellar halo, and globular clusters. Courtesy of Chris Flynn.

streams and overdensities. The best studied halo (see Fig. 1.1), that of the Milky Way, has an estimated 4×10^8 stars between radii of 1 and 40 kpc from the Galactic center (Bell et al., 2008), over 150 known globular clusters (Harris, 1996, 2010 edition), almost 10^{12} $M_\odot$ of dark matter within 100 kpc (Dehnen and Binney, 1998; McMillan, 2011), ~ 20 satellite galaxies (Helmi, 2008), and tens of different stellar substructures (Helmi, 2008), where the number of detections, especially satellite galaxies and substructures, continues to grow with deeper surveys. The correlation between the age, motion, and structure of these populations tells a story of how galaxies formed.

Surveys of the motions of Galactic stars or their *kinematics* largely began in the 1910's and lead to the discovery and investigation of high-velocity stars with space motions greater than 100 km s^{-1} (Adams and Kohlschutter, 1914; Adams and Joy, 1919; Strömberg, 1922). In the late 1930's, pioneering photometric studies of resolved extragalactic stars and globular clusters began with Shapley (1938a,b, 1939) and Baade and Hubble (1939). Baade (1944a,b) made several important conclusions from comparing these Galactic and extragalactic surveys. First, he introduced the concept of differing stellar populations, a conclusion made due to the differing intrinsic brightness of the Galactic and extragalactic stars. Second, he found that stars in elliptical galaxies and in the bulges of spiral galaxies were more similar to those in Galactic globular clusters than to Galactic disk stars. Third, he described the similarity between the Galactic high-velocity stars and globular clusters. The concept of stellar populations set the stage for the growth of knowledge in the 1950's concerning stellar evolution and the connection between age and chemistry. These ideas culminated in the 1957 Vatican Conference on Stellar Populations (O'Connell, 1958), leading to a more developed picture of halo and disk stellar populations and their connection with galaxy formation. Sandage (1986) succinctly reviews stellar populations and especially these early investigations.

During the 1940's and 50's, implications about the correlation between stellar dynamics and chemistry were made by Lohmann (1948), Newkirk (1952), Roman (1954), and Yasuda (1958), who found that stars with highly eccentric orbits were also highly metal poor. Eggen et al. (1962) highlighted the importance of such a correlation by drawing the first conclusions about Galactic evolution through the relationship between halo kinematics and chemistry. They suggested the Galaxy formed from an initial cloud which rapidly collapsed due to its gravitational attraction. As the cloud collapsed, stars and globular clusters which formed would remain to form the halo, while the cloud itself settled to form the disk of rotating stars and gas. Stars and globular clusters which formed at different times before, during, and after the collapse would develop with different motions and chemical composition, such that during the collapse metal-poor stars with eccentric orbits would form in the halo and at the end and after the collapse metal-rich stars would form rotating in the disk. Lynden-Bell (1967) explained that the newly forming galaxy should reach an equilibrium state by the rapidly changing overall potential of the galaxy. Because the potential's fluctuations were so rapid, Lynden-Bell (1967) termed the process *violent relaxation*. The evolution picture changed in its fundamentals with the proposal of Searle and Zinn (1978), such that the dynamical and chemical connection could be explained by the bulk of the Galactic halo forming gradually, after an initial collapse. They proposed that many small individual clouds falling together formed the Galactic halo. The kinematics and chemical composition of the merging clouds would define the characteristics observed in the Galactic halo. Freeman and Bland-Hawthorn (2002) review in more details Milky Way formation scenarios.

The discovery of the most massive component of galaxies, the dark halo, dates back to the 1970's. This component, initially referred to by several names like halo, corona, and bulge, adds mass to the halo but does not emit light. Key leaders who discovered the dark halo component though different evidence include Freeman et al. (1975), Roberts and Whitehurst (1975) via analysis of how the nearby galaxy M31 rotates, Ostriker et al. (1974), Rubin and Ford (1970), and Einasto et al. (1974a,b). With the addition of the dark matter halo and the Eggen et al. (1962) and Searle and Zinn (1978) theories developing to explain the observations, simulations began appearing to test the two theories.

After the initial studies of N-body systems by numerical methods such as by von Hörner (1960) who simulated clusters of up to 16 stars, the time was right in the 70's for computer power to be at a level that could process the dynamics of many bodied systems. A code widely used for halo simulations is that of Aarseth et al. (1979), which computed the orbital positions of a cluster consisting of 1000 point-like galaxies. The computer codes focused on the dark halo components, where most of the mass is. The leading structure formation theory used in the codes, *cold dark matter* (Peebles, 1974; White and Rees, 1978; Blumenthal et al., 1984), describes dark halos merging together to form a galaxy. The outcomes are impressively similar to observed galaxies although many interesting discrepancies still exist.

The Hubble Space Telescope flew in April 1990. Its images showed that young distant galaxies are less structured and more asymmetrical and clumpy. Dark matter halo simulations of the 1990's were able to reproduce similar results, showing the formation of Milky Way-type galaxies from early phases of clumpy structures building from smaller objects merging together (Dubinski and Carlberg, 1991; Navarro et al., 1996, 1997).

Besides the most well known halo, that of the Milky Way's halo, extragalactic halo studies show the vast variety of existing kinematical and chemical structure relations. Globular clusters have been the lead source of interest in extragalactic halos because they are bright components and easily visible over large distances (see the reviews by Harris (1991) and

Brodie and Strader (2006)). Globular cluster populations share many similarities, such as in their distributions in the galaxies and that they are old and metal-poor. They exhibit a bimodality, such that in each galaxy the globular cluster population has two peaks in their metal content. Within 20 Mpc, space-based and $8 - 10$ m telescopes are able to resolve individual stars within extragalactic halos. Large samples of resolved halo stars still have not been achieved, so making any generalized conclusions remains difficult. Two such galaxies are studied in this thesis.

A major result from the ten years of sky surveying with the Sloan Digital Sky Survey (York et al., 2000) $(2002 - 2012$, and surveying continues to the present) was refining the three components to the Galaxy, namely the disk, bulge, and halo. Finer details of the Galactic halo were accessible and showed that the halo was not a homogeneous structure. The most metal-poor Galactic stars are located in the halo and are discussed in detail in the review of Beers and Christlieb (2005).

These recent large-scale surveys continue to show the stellar component of the halo may not be a homogeneous mix (see the review of the intricacies of the stellar halo by Helmi (2008)). For example, the debated results of Carollo et al. (2007) use the Sloan Digital Sky Survey to show a two-component stellar halo such that the inner halo is flattened and slightly prograde, while the outer halo consists of a more metal-poor chemical composition, is rounder, and is in net retrograde rotation. Interesting features such as transitions in stellar halo kinematical and chemical structure are the topic of Paper II and Paper III of this thesis.

Halo substructure has been known as early as the Magellanic Clouds' H I filaments studied by Mathewson et al. (1974). Studies of substructures composed of stars began twenty years later, such as with the Sagittarius dwarf galaxy discovery by Ibata et al. (1994), and the counts of substructures continue to increase (e.g. Ivezić et al. (2000); Yanny et al. (2000); Majewski et al. (2003); Belokurov et al. (2006); Vivas and Zinn (2006)). Bullock et al. (2001) and Bullock and Johnston (2005) connect the Searle and Zinn (1978) galaxy formation scenario, simulations, and observations together by producing simulations with halo substructures similar to observations which result from a galactic halo formed by the merging and tearing apart of many smaller satellite galaxies. Ivezić et al. (2012) review substructures and other Galactic stellar populations.

Large-scale simulations of the Universe, such as the Millennium Survey (Springel et al., 2006) typically use dark matter particles only. The predictions from the simulations of galaxy clustering agree well with observations. Many simulations use dark matter particles in Milky Way-type galaxies. Less common are simulations which include the galactic halos with the combination of stars and globular clusters, or codes which simulate elliptical galaxies. Exceptions, for example, are Burkert et al. (2008); Naab et al. (2009); Johansson et al. (2012); Remus et al. (2013) and Schauer et al. (2014), who focus on simulating elliptical galaxies. These are the kind of simulations needed to compare with the observational studies in this work. Despite the increasing computer power, the many finer details observed in galaxies, such as resolving the large populations of individual stars and including their chemical composition, require still unreasonable computer time to include in galaxy formation simulations. Such computer power is probably still decades away!

1.3 Aims of the Study

The thesis focuses on probing halo structure in three galaxies—two ellipticals and the Milky Way. The flow of the thesis is graphically captured in Fig. 1.2, showing how the papers and research work together to describe the common theme of the thesis, the dynamical and chemical structure of galactic halos. The individual projects incorporated into the thesis are summarized in Table 1.1. The goal of the thesis is to investigate the dynamical and chemical structure of galactic halos using both simulations and observations, with the ultimate purpose of uncovering features in the halo which define possible galactic formation and evolution scenarios.

Paper I and Paper II use the observational method of resolved stellar populations in each of the two elliptical galaxies, as described in Chap. 4, to answer two key questions. Paper I asks: is it possible to resolve individual tip of the red-giant branch stars in the distant galaxy M87 and estimate the metal composition of the inner halo? The images totaling an exposure time of seven hours are from the archival data base of Hubble Space Telescope, one of the most powerful telescopes. Despite the deep images and powerful telescope, the distance of this elliptical galaxy at 16.4 Mpc allows only the brightest of the brightest individual stars, those of the type called tip of the red giants, to be resolved and analyzed. The metals in the stars are measured and their distribution is very broad with a likely peak near $[m/\mathrm{H}] \simeq -0.4$ (this measure is based on a scale in which the log of the

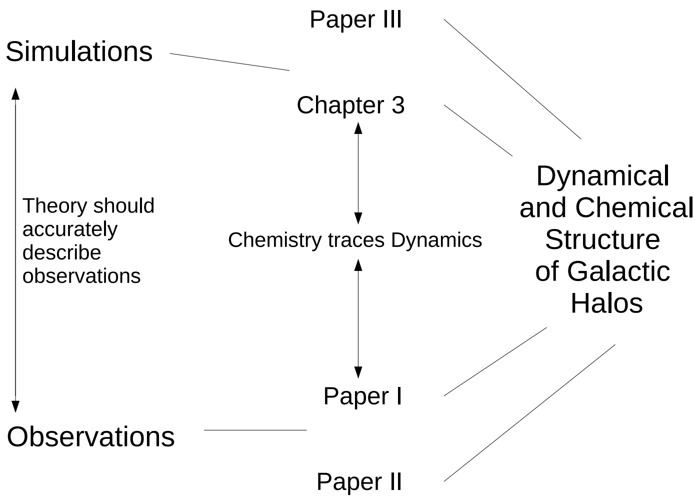

Figure 1.2: Flowchart of the organization of the thesis. The theme of the thesis, the dynamical and chemical structure of galactic halos is analyzed using two methods: simulations (as in Paper III and Chap. 3) and observations (Paper I and Paper II). The theoretical basis of the simulations should accurately describe the observations. Using both methods, the thesis investigates how chemistry traces dynamics.

amount of metals m relative to the amount of hydrogen in the object is compared to that of the Sun). Such a distribution of metals is very similar to that of the inner halo for the nearby giant elliptical galaxy NGC 5128.

Paper II studies the outer halo of NGC 5128, focusing on a field centered at 65 kpc from the galactic center. The key question is: does the outermost stellar halo of NGC 5128 house a transition similar to M31 and NGC 3379, such that the metal-rich component steeply dies away, leaving a much shallower and sparser metal-poor component to dominate? Similar to Paper I, only the tip of the red-giant stars are resolved with one and a half hours of observations from the ground-based European Southern Observatory Very Large Telescope, because NGC 5128 lies at the far distance of 3.8 Mpc. I find that the chemical structure of the halo stars shares a common distribution from $8 - 70$ kpc, revealing no such transition within these radii.

The data of Paper I and Paper II is of the highest quality from the best telescopes. Both studies focus on elliptical galaxies, likely to be formed through many mergers of smaller satellite galaxies. A recent merger is detectable in NGC 5128 by gas and dust streams in the halo. Mergers may mix any initial metal gradients found in the halo caused by its initial stages of formation. In this way, the metal content and the dynamics of the halo are inter-related. The similarity between the metal content in the inner halos of M87 and NGC 5128 may support a common formation scenario. The density of halo stars, both rich and poor in their chemical composition, in NGC 5128 smoothly falls out to 70 kpc from the galaxy's center. Such a falloff may support the galaxy formation scenario in which many mergers are needed to form large elliptical galaxies and would mix up any gradients of metals in the halo stars which may have been produced by the initial collapse of the pre-galactic cloud. The goal of simulations is to reproduce results from high quality observations such as those just mentioned. This is yet the case for large elliptical galaxy simulations, although such simulations are part of the plan for future projects, as discussed in Chap. 6.

Simulations are the method used to analyze the Milky Way in Paper III and the thesis research project presented in Chap. 3. Paper III asks the key question: do the Milky Way stellar halo kinematical profiles determined by Kafle et al. (2012) remain stable over many Gyr? Kafle et al. (2012) statistically analyze the velocities of over 4600 halo stars, using the velocity dispersions (in all three spherical coordinates) and the anisotropy parameter (which is a way of comparing the three different measurements of velocity dispersion). They found that the stars at 17 kpc from the center of our Galaxy move with a more tangential velocity dispersion as compared to other stars. I introduce this feature in my simulations and find that it quickly fades away within a short few 100 Myr.

The key question presented in Chap. 3 is: if the globular cluster system of a Milky Way-type galaxy harbors an initially very strong relationship between average distance and chemistry, to what extent could it be affected by the merger of a satellite galaxy? The simulations result with the strong relationship not substantially altered even for large merger ratios, with the satellite's mass equal to a third of the host Milky Way galaxy M_{host}.

Simulations should agree with observations. Paper III and Chap. 3 approach this in two different ways. The simulations in Paper III start initially in agreement with observations, with stellar orbits, density, and velocity reflective of Milky Way halo stars. Allowed to evolve with time, the orbits show that the current velocity dispersion of the halo is unstable. The simulations of Chap. 3 begin with a hypothetical situation: a Milky Way-type galaxy with an initially strong relation between globular cluster metal content and galactocentric radius. The simulated galaxy is then approached by a satellite galaxy. The resulting distribution of globular clusters is compared with the observed Milky Way globular clusters in order to determine if the true distribution can be reproduced under the simulated conditions. Chap. 3 is a good example of how chemical structure can be a tracer of dynamics: if initially such a gradient in the metal content of globular clusters existed along galactocentric radius, the simulations show that the merging satellites tested are not able to sufficiently mix the clusters dynamically, which would then correspond to observing such a gradient in chemical structure at the current time. In view of Paper III, further investigation of the halo star chemical structure would be interesting, as well as the introduction of metals into my simulations.

The new contributions this thesis brings to the studies of galactic halos are highlighted by the following summary.

- Paper I is the first study to resolve stars in the inner halo of M87. We use Hubble Space Telescope imaging in two bands to find the brightest red giants and measure their metal distribution.

- Paper II searches in NGC 5128 for the transition between two different halo star populations which has been recently found in two other galaxies—no such transition is found, but more galaxies should be searched.

- Paper III tests the stability of newly discovered kinematic features in the largest compilation to date of blue horizontal branch Galactic halo stars (Kafle et al., 2012)—features which quickly dissolve within a few 100 Myr. We deduce that this feature is thus transient.

- Chap. 3 presents the first tests of the effects which a satellite galaxy merging with a Milky Way-like galaxy has on an initially tight relationship between radial distribution and chemical structure of the host galaxy's globular cluster system. After the merger, the relation is still easily detectable.

After the motivation and history of the major advances in galaxy halo investigations presented above in Sec. 1.1 – 1.2, the thesis continues with a presentation of the two main methods to gather information about galactic halos: describing, first, simulations (Chap. 2) with a practical example (Chap. 3) and, second, observations (Chap. 4). The results and discussions of the contributing thesis papers are found in Chap. 5. The concluding Chap. 6 presents future projects stemming from the thesis work.

Table 1.1: Research questions and answers.

Project	Question	Answer
Paper I	Using images from one of the best telescopes for deep space studies, the Hubble Space Telescope, is it possible to resolve individual tip of the red-giant branch stars in the distant galaxy M87 and estimate the metal composition of the inner halo?	Yes, the distribution of metals is very broad and likely to peak near $[m/\mathrm{H}] \simeq -0.4$, which strongly resembles the metal composition of the inner halo for the nearby giant elliptical galaxy NGC 5128.
Paper II	Does the outermost stellar halo of NGC 5128 house a transition similar to M31 and NGC 3379, such that the metal-rich component steeply dies away, leaving a much shallower and sparser metal-poor component to dominate?	No, if any such transition existed, it must lie further out or have been dissolved due to mergers.
Paper III	Do the Milky Way stellar halo kinematical profiles determined by Kafle et al. (2012) remain stable over many Gyr?	No, the velocity dispersion and anisotropy profiles smooth in a short few 100 Myr.
Chap. 3	If the globular cluster system of a Milky Way-type galaxy harbors an initially very strong relationship between average distance and chemical structure, to what extent could it be affected by the merger of a satellite galaxy?	The strong relationship is not substantially altered even for large merger ratios (1/3 M_{host}).

Chapter 2

Galactic Halos: Simulations

The surest way to study the history of a galaxy would be to observe its whole life, how it forms, evolves, and ends. We can see many galaxies at different stages in evolution, but viewing the full life of one galaxy is out of the question. We do not have 10 billion years up our sleeves. On the other hand, with the help of computers, we can write programs to simulate the full life of a galaxy.

Like an archaeologist digging in the ground, we can search through the halos of galaxies to find clues to its history. Like in a city, a galaxy has a high concentration of action in the central regions. The center has a high density of stars and gas and new starbirth. The young and old stars have different properties, such as how they move (their dynamics) and what they are made from (their chemical composition). The old stars retain properties reflecting the initial stages of the galaxy's formation. Because the center of a galaxy is so crowded, finding the old stars located there is difficult to near impossible. But the old stars that are also located in the outer regions of a galaxy's halo are much easier to isolate than amongst the younger stellar populations more centralized in galaxies. The halo also contains remnants of past events. As galaxies swing past each other or even collide and merge into one galaxy, stars and gas from these interactions remain spread through out the halos.

Intriguingly, we are able to describe nature with mathematics. How things form and evolve often can be described with mathematical equations, sometimes very simply. Galaxies are no different. The orbits of stars can be calculated and described beginning with Isaac Newton's law of universal gravitation, which describes the force F that a point source of mass M exerts on a test particle of mass m and distance r from the source, and is scaled by the gravitational constant G,

$$F(r) = \frac{GMm}{r^2}. \tag{2.1}$$

These mathematical equations are cast in a language computers understand and the computer can then do the work of calculating the solutions. Each real galaxy we observe only shows us one snapshot of its life. Computer programs written to simulate galaxies allow a testbed for galaxy formation and evolution theories. We can backtrack in time and test what a galaxy's history has been.

2.1 Dynamics

One means to test theories of galaxy formation and evolution is to simulate the dynamics of the halo stars. A population of particles is designed with positions assigned according to the density distribution of stars or clusters in a real galactic halo. The particles are assigned initial velocities and the orbits are then integrated, which is to say the position and velocity are calculated after a small step in time. Two types of simulations are common, N-body simulations and potential theory. In an N-body simulation, the new position and velocity of one particle are calculated from the force exerted on it by all the other particles. This requires a lot of computation time if N is large, as it is in galaxies, and often needs supercomputer power. In Chap. 3 and Paper III, I used potential theory, a faster way to calculate the new position and velocity of a particle as determined by the potential model (density distribution of matter) given to the galaxy. I can use potential theory because the density of stars and clusters in the halo is low and their gravitational effect on the dark matter and disk, which dominate the potential, can be ignored. I only calculate their dynamics as influenced by the massive galaxy in which they live.

I describe my simulations of the Milky Way Galaxy and its population of 157 known globular clusters (Harris, 1996, 2010 edition) in Chap. 3 and its nearly 5,000 known blue horizontal branch halo stars (Kafle et al., 2012) in Paper III. In these simulations the stars are represented each as one particle; even the globular clusters, which in reality are dense groups of order $\sim 10^5$ stars, are each represented as one particle. In these projects my main goal is to study the overall dynamical and chemical structure of the halo, not to study the finer details of how individual stars or clusters themselves evolve over time. Because of my usage of potential theory and populations of $10^2 - 10^5$ particles, the computing power needed is available on my laptop—no supercomputer needed, although this in itself is super indeed.

Galaxy simulations are typically run for the time corresponding to the age of the Universe, also known as a Hubble time, which commonly is set to 10 Gyr (roughly the age of the Milky Way). Generally this amount of time allows enough orbiting of the particles to analyze the dynamics of the system and perform statistical tests such as calculating the velocity dispersion σ profile, the anisotropy β profile, and the stability of the system. These tools I discuss in the following Sec. 2.1.1, 2.1.2, and 2.1.3 respectively.

2.1.1 Velocity Dispersion

One way to analyze the orbits of stellar populations is to measure the velocity dispersion σ. Dispersion as a statistical method is used for analyzing the spread of a group of measurements. It describes the scatter of the measured quantity, in this case velocity v, about the average of all the measurements. Velocity dispersion is defined as

$$\sigma = \sqrt{\frac{\sum(v_i - \overline{v})^2}{N-1}}, \tag{2.2}$$

where N is the number of measurements. Disk stars in the Milky Way share velocities near a common average value and have low σ values. The velocity dispersion of the stars near the Sun are $(\sigma_U, \sigma_V, \sigma_W) = (40, 30, 10)$ km/s in the young disk and $(\sigma_U, \sigma_V, \sigma_W) = (46 \pm 4, 50 \pm 4, 35 \pm 3)$ km/s in the thick disk (Chiba and Beers, 2000), where U, V, and W are the time derivatives of the positions (X, Y, Z), respectively, in the system of Cartesian Galactic Coordinates.

On the other hand, halo stars have a more random and wider range of velocities, with $(\sigma_U, \sigma_V, \sigma_W) = (141 \pm 11, 106 \pm 9, 94 \pm 8)$ km/s near the Sun (Chiba and Beers, 2000), and elsewhere is the topic of Paper III. A profile is calculated by grouping the particles in bins of radial distance from the galactic center. The question that comes up in Paper III is what variation is found in the halo star velocity dispersion within different radial bins.

2.1.2 Anisotropy

The anisotropy β, as defined by Binney and Tremaine (1987), compares the radial velocity dispersion of a stellar population as functions of radius, σ_r, to the tangential, σ_t, following the definition

$$\beta(r) = 1 - \frac{\sigma_t(r)^2}{\sigma_r(r)^2}. \tag{2.3}$$

If σ_r and σ_t have the same value everywhere, $\beta = 0$ and the halo is termed *isotropic*, meaning the velocity dispersions are the same in all directions and at all radii. The significance of β is that it aids in understanding the type of orbits the objects must have. For example, for $\beta < 0$, the stellar orbits are tangentially dominated, moving in more ring-like orbits. In a completely smooth and axisymmetric galactic potential, $0 < \beta \leq 1$ implies radially dominated orbits.

Kafle et al. (2012) explore Sloan Digital Sky Survey data of nearly 5000 blue horizontal branch halo stars. These stars are bright, have prominent spectral features, and share a common temperature, thus making their detection more likely compared to other types of halo stars. From modeling the kinematics of these stars, Kafle et al. (2012) find strong anisotropic features in the Milky Way's stellar halo (Fig. 2.1, upper left panel). Kafle et al. (2012) measure slightly radially dominated orbits in the inner halo, $9 < R_{\mathrm{GC}}/\mathrm{kpc} < 12$ (where R_{GC} is Galactocentric radius, i.e. distance from the Galaxy's center), with $\beta \approx 0.5$. They predict the outer halo, $25 < R_{\mathrm{GC}}/\mathrm{kpc} < 56$, also to have $\beta \approx 0.5$. Suddenly between the outer and inner halo, $13 \lesssim R_{\mathrm{GC}}/\mathrm{kpc} \lesssim 18$, β drops to ≈ -1.2, such that the halo stars move in circular orbits. In Paper III, I test the stability of the Kafle et al. (2012) σ and β profiles and find these anomalous features wash out within a short 100 million years, leaving a more isotropic halo profile with $\beta \approx 0$ (Fig. 2.1, 2, 4, and 6 Gyr panels). Thus, they appear to be transient features of the Milky Way halo.

2.1.3 Stability Check

In order to simulate systems, we start by requiring that they can be set up to be stable in the long term, so we have a kinematic state to which we can compare. The stability of the system refers to the galaxy's retention of the same properties over a few Gyr. As we simulate different dynamical

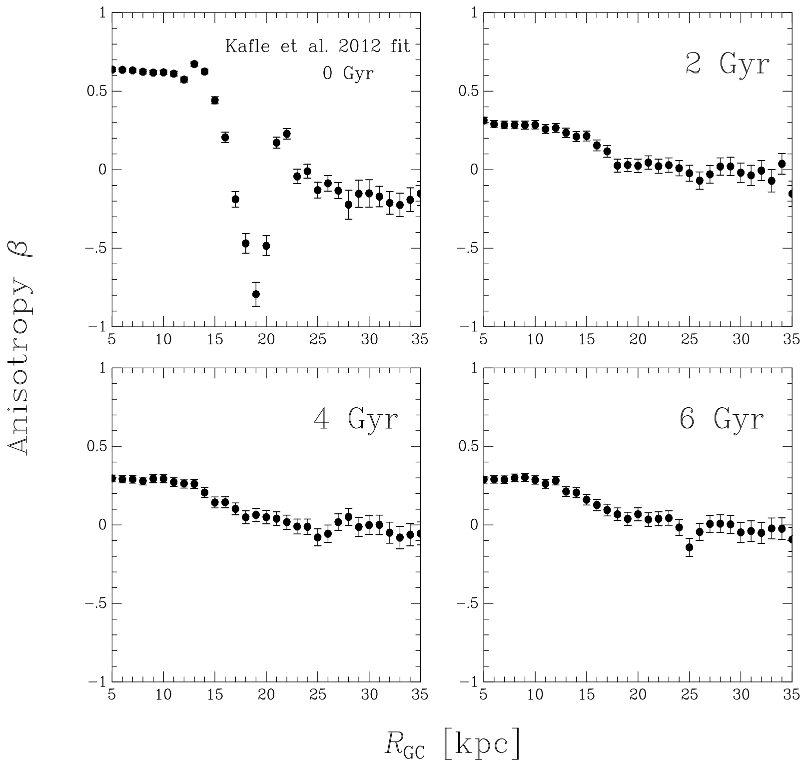

Figure 2.1: The anisotropy β profile from Paper III is plotted as a function of Galactocentric radius (i.e. distance from the Galaxy's center), R_{GC} (kpc), for over 2×10^5 simulated halo stars in a model of the Milky Way, with a potential similar to that of Flynn et al. (1996) using model parameters from Kafle et al. (2012) and Bovy and Rix (2013). At the start of the simulation (upper left panel), β is calculated from the initial Kafle et al. (2012) radial and tangential velocity dispersions, σ_r and σ_t, measured using nearly 5000 Milky Way blue horizontal branch stars from the Sloan Digital Sky Survey/Sloan Extension for Galactic Understanding and Exploration. The stars relaxed within the first 100 Myr of the simulation so that the striking feature at $13 \lesssim R_{\mathrm{GC}}/\mathrm{kpc} \lesssim 18$ dissolved away. The relaxed system remained stable for the remaining simulation time (2, 4, and 6 Gyr panels).

models, we check how the new systems compare to the stable model. In Chap. 3 and Paper III, I test whether the halo systems are dynamically stable.

The model tested in Paper III was developed by Kafle et al. (2012) using Milky Way stellar halo observations from the Sloan Digital Sky Survey. Our simulations show that the current velocity dispersion and β profiles of Galactic halo stars are unstable at least in the model of the Galaxy's potential we have used. The stars appear to be in a transient phase and are rearranging their velocities in order to settle upon a relaxed state, meaning a state that is stable or *stationary*, i.e. in a *steady state* in which the effects of motions of individual stars balance out. The reason is unknown as to why the Galactic halo stars are in a transient phase. Sloan Digital Sky Survey data reveal that greater than a distance of 20 kpc, the net rotation of the halo reverses direction as compared to the halo's net rotation within 20 kpc (Carollo et al., 2007). This may be related to the Kafle et al. (2012) findings. Testing the stability of halos with a net rotation profile (as has been observed), and the possible relations between the net rotation and the halo star's σ instability, are future projects. As I will describe in Chap. 3, massive mergers cause changes in the globular cluster population's σ profile. This could be evidence that all these instabilities are connected, but detailed simulations need to be carried out to test this idea. The Milky Way has experienced minor mergers and close interactions and we are viewing the halo now as it is trying to settle and regain stability. The issue is whether odd behavior such as seen in the β profile can be caused by such satellites sinking and dissolving into the Milky Way.

2.2 Chemistry as a Tracer of Dynamics

Another means in which simulations give new insights about galaxy formation and evolution is by assigning chemical structure to the halo stars. The dynamical and chemical structure parallel each other. As seen in observations, stars with the least metals typically are old and have similar dynamics, whereas metal-rich stars are young and have a different type of dynamics.

2.2.1 Measuring Chemical Abundance: Metallicity

In most fields of science (chemistry, biology, etc.) *metals* refer to 91 of the 118 elements of the periodic table, but this is not the case in astrophysics. In the Universe as a whole, hydrogen and helium are well known to be the dominant elements. They comprise the majority of visible matter. All other elements account for only a few percent of the matter. Because the percentage of all other elements in the Universe is so small, astrophysicists collectively group elements other than H and He together under a common name, metals, and use a special unit called metallicity to quantify their chemical abundance.

Metallicity is a logarithmic scale which describes the ratio of the amount of metals, m, to the amount of hydrogen, H, in the star, $[m/\mathrm{H}] = \log(\mathrm{Z}/\mathrm{Z}_{\odot})$, where Z is the fraction of all metals within a star and $\mathrm{Z}_{\odot}$ is the fraction of all metals in the Sun. Transitions associated with iron atoms cause many absorption lines in the Sun, thus traditionally metallicity has been compared between stars using the ratio [Fe/H] (see the review paper by Beers and Christlieb (2005)). Most stars in the local Milky Way stellar halo have a peak in the metallicity distribution at $[\mathrm{Fe/H}] \approx -1.6$ (Ryan and Norris, 1991). An et al. (2013) find a second more metal-poor component to the local stellar halo in which the largest number of stars have $[\mathrm{Fe/H}] = -2.3$. Few local halo stars with $[\mathrm{Fe/H}] < -4.0$ have been found (Beers and Christlieb, 2005) and the most iron deficient halo star found to date has $[\mathrm{Fe/H}] < -7.1$ (Keller et al., 2014).

2.2.2 Metallicity in the Halo

The number and type of astrophysical metals develop in a star according to its age: the older a star becomes, the more metals it produces through fusion. Most of these metals are trapped deep inside the star, only to be ejected from massive and intermediate mass stars as they blow off material as *stellar winds* and eventually some explode as supernovae. Ejected metals return to the interstellar medium, enriching the initial star forming gas and dust clouds such that newly formed stars begin life already with a more complex chemical composition compared to previous stellar generations.

Because the metal content increases with each stellar generation, thus, the more metal-poor a star, the older it is likely to be. The halo consists of some of the first formed stars within the galaxy and have low metallicity measurements: the Milky Way halo has $[m/\mathrm{H}] < -0.7$ (e.g. Carollo et al. (2007)). Metallicity and dynamics of the Milky Way are closely related. Old, metal-poor stars have higher velocity dispersion because their orbits have had more time to be disrupted by mergers and other stars. Old stars are easiest to isolate by observing the outer halo. Most of the star production in galaxies occurs in the denser, brighter regions where the light of the galaxy is found. These younger, more metal-rich generations of stars are on circular orbits in the disk, and do not extend into the outer regions of the halo at galactocentric distances such as $50 - 100$ kpc. The paradox is, although easier to isolate and separate from the young more populous stars, the old stars in the outer halo are difficult to observe because of the low number statistics, as discussed in Sec. 4.1.

In Chap. 3, I describe my simulation of Milky Way globular clusters in the halo. The clusters are assigned a percentage of metals so that the system begins with an initial chemical distribution in which metallicity correlates directly with the mean galactocentric distance. Each cluster keeps this assigned abundance, I do not test evolution of the cluster composition itself. What I test is how this initially very simple chemical distribution is affected by a minor merger and to what extent might it be erased.

Chapter 3

Practical Example—Galaxy Mergers and Galactic Globular Cluster Kinemacits

3.1 Introduction

Galaxies interact with each other and merge. These events are so common that in the review paper *Dynamics of Interacting Galaxies*, Barnes and Hernquist (1992) state in the first sentence, "Interacting galaxies encompass a tremendous range of phenomena—indeed, if events during galaxy formation are counted, there are probably few galaxies that were not shaped by interactions or even outright mergers." Ongoing and remnant interactions in the halos of galaxies are evidenced by streams of stars and dust in the halo which have been stripped from satellite galaxies that have merged into the host galaxy. As mentioned in Chap. 1, globular clusters are old stellar systems with a low metal content. Some may have been brought into galactic halos by mergers and some may be part of the early galaxy itself. See the review by Freeman and Norris (1981) for more about the Milky Way's globular cluster populations.

In an early halo study, Innanen and Valtonen (1977) simulated the Milky Way, Large and Small Magellanic Clouds, and a single globular cluster. The Large and Small Magellanic Clouds were given stable orbits around the Galaxy, such that the case of merging was not investigated. They tested 260 cases with varying initial conditions and orbital parameters of the system. The simulations showed that the presence of the Clouds was able to influence the dynamics of the single globular cluster, such as by increasing the semi-major axis, capturing it, or causing it to escape the system.

Valtonen et al. (1984) simulated the Milky Way with the Large and Small Magellanic Clouds using the same technique as Innanen and Valtonen (1977), but include 14 spherical shells of 50 globular clusters each, extending from 10 to 325 kpc from the galactic center. In agreement with Innanen and Valtonen (1977), they found the Clouds were able to significantly influence the orbits of the globular clusters, such as moving their radial distance on average further out from the Galactic center as well as causing globular clusters to be ejected from the halo.

Continuing from the work of Innanen and Valtonen (1977) and Valtonen et al. (1984), I use a code written by Seppo Mikkola (Tuorla Observatory) and test how the dynamics and distribution of 200 globular clusters change in the event of a single merger. The globular clusters populate the Milky Way-like host galaxy and none originate in the merging satellite. I investigate the relation between metallicity and dynamics and consider the results in light of galaxy formation theories.

3.2 My Simulations

3.2.1 Globular Clusters

The 157 observed objects classified as globular clusters in the Milky Way are located between $0.5 < R_{\mathrm{GC}}/\mathrm{kpc} < 125$. Harris (1996, 2010 edition) keeps an updated catalog of the Milky Way's globular clusters and their properties. To take account for those which are obscured by dust in the central regions of the Galaxy, I simulate a total of 200 globular clusters in a range of $2.0 - 100.0$ kpc. In accordance with observed Milky Way globular clusters, my simulated globulars are positioned according to a power law density distribution. The density is set up to fall like $\rho \propto R_{\mathrm{gc}}^{-\alpha}$ (see Fig. 3.1), where R_{gc} is the galactocentric distance, i.e. distance from the simulated galaxy's center. I choose the power $\alpha = 3.5$, which follows the observed density distribution of halo globular clusters in the Milky Way (Harris, 1976; Zinn, 1985; Bica et al., 2006). Each globular cluster has a mass of 1.0×10^5 $\mathrm{M}_\odot$ and a half mass radius of 3 pc adapted from Gnedin and Ostriker (1997) and Binney and Tremaine (2008, p 31, calculated medians from the compilation of Harris (1996), 2010 edition).

In addition, I add a metallicity gradient (upper left panel of Fig. 3.2) which linearly becomes more metal-poor at larger radii from the galactic

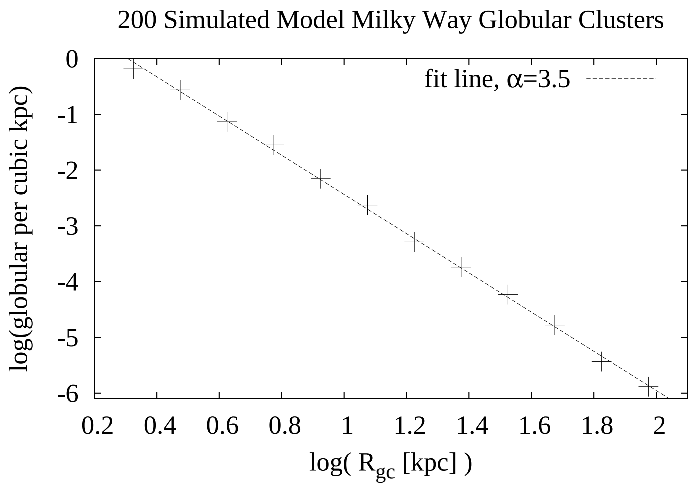

Figure 3.1: Density profile of the 200 halo globular clusters used for the simulations, showing the $\alpha = 3.5$ power law density distribution. These values are based from observations listed and updated by Harris (1996, 2010 edition) and as described in the informative coursebook *Saas-Fee Advanced Course 28: Star Clusters* by Harris (2001).

center. This distribution represents what a profile could have been in the beginning of the Galaxy's life.

3.2.2 Integration of Globular Cluster Orbits

Globular Cluster Set Up

The halo globular clusters start at (X, Y, Z) and (U, V, W) with an assumed, isotropic velocity dispersion. These values are consistent with those measured in the Milky Way (Harris, 1996, 2010 edition). Their dispersions are selected using a Gaussian centered on no net rotation. The definition of my adopted velocity dispersion begins with the Jeans equations for spherical stellar systems in equilibrium as described in Binney and Tremaine (2008,

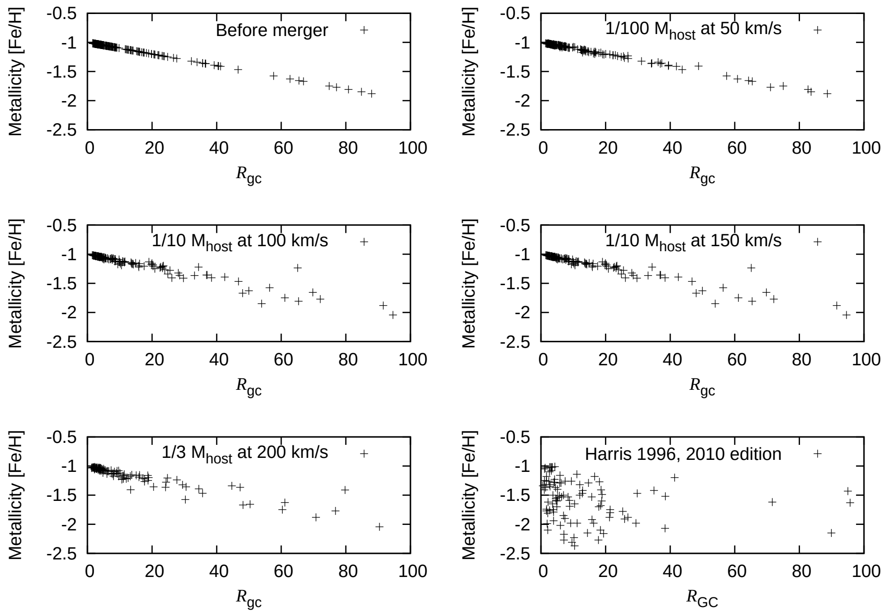

Figure 3.2: Metallicity profiles for simulated metal-poor globular clusters. The upper left panel shows the initial metallicity profile which my globular clusters begin with in each simulation. I assume a linear relation between distance and metallicity for simplicity. Satellite galaxies with varying masses and initial tangential velocities are introduced in the simulations and are allowed to merge with the host galaxy. The initially tight relation between the globular cluster chemistry and distribution relaxes slightly after the merger but remains easily detectable, as seen in the panels upper right (merger of mass 1/100 M_{host} with an initial tangential velocity of 50 km/s), left middle (1/10 M_{host} at 100 km/s), right middle (1/10 M_{host} at 150 km/s), and lower left (1/3 M_{host} at 200 km/s). The lower right panel shows the observed spread of halo globular cluster metallicities in the Milky Way (Harris, 1996, 2010 edition). The largest changes in the metallicity profile is caused by the merger 1/3 M_{host} at 200 km/s, but the remaining relation between metallicity and distribution does not resemble the metallicity profile of real metal-poor globular clusters.

Eqn. 4.215),

$$\frac{d(\rho\sigma_r^2)}{dr} + 2\frac{\beta}{r}\rho\sigma_r^2 = -\rho\frac{d\Phi}{dr}. \tag{3.1}$$

Eqn. 3.1 relates the stellar density distribution ρ, radial velocity dispersion σ_r (as discussed in Sec. 2.1.1), anisotropy (Sec. 2.1.2), and the galactic gravitational potential Φ. In general, Jeans equations relate observable properties of a galactic stellar system, e.g. velocity and density. Jeans equations are derived from Newton's second law and they describe the conservation of momentum of the stellar system in a manner comparable to how fluid mechanics describes a fluid with zero viscosity. The galactic gravitational potential and the density distribution of stars are related through Poisson's equation, $\nabla^2\Phi = 4\pi G\rho$. With this in mind, two different forms of Newton's second law, one expressing the relation between acceleration and potential $a = -d\Phi/dr$ and the second expressing the relation between acceleration and circular velocity $a = v_{\rm circ}^2/r$, can be combined such that

$$\frac{d\Phi}{dr} = \frac{v_{\rm circ}^2}{r}. \tag{3.2}$$

In the galaxy model, I assume that the halo is isothermal, i.e. σ_r is independent of radius and can be used more generally as $\sigma = \sigma_r$ and $\beta = 0$. With the assumed isothermal halo and using Eqn. 3.2, Eqn. 3.1 can be expressed as

$$\sigma^2\frac{d(\rho)}{dr} = \rho\frac{v_{\rm circ}^2}{r}. \tag{3.3}$$

Because the model halo has a power law falloff, I substitute $\rho \propto r^{-\alpha}$ into Eqn. 3.3, take the derivative with respect to radius, and solve for velocity dispersion,

$$\sigma = \frac{v_{\rm circ}}{\sqrt{\alpha}} = 118 \text{ km/s}, \tag{3.4}$$

where $v_{\rm circ} = 220$ km/s is the circular velocity of the Milky Way.

I set up the system by checking that the orbits are stable on long time scales and that the velocity dispersions and density profiles of the clusters do not change much. Without the presence of a satellite galaxy, the galactic system is generally stable and neither collapses toward the center nor flies apart.

Galaxy and Satellite Set Up

I use an isothermal, spherically symmetric potential such that the host galaxy density is proportional to $1/R_{\rm gc}^2$. As explained in Sec. 2.1, using potential theory greatly reduces the computation time of the program. The galaxy consists of an inner and outer part chosen to yield a better match to the Milky Way's mass distribution than what I obtained using tests on a single isothermal sphere. McMillan (2011) used their Galaxy model, constrained by photometrically and kinematically derived observations, to estimate the Milky Way mass out to 100 kpc as $9.0 \pm 0.5 \times 10^{11}$ $M_\odot$. Observationally the mass of the Milky Way is determined by, for example, the rotation curve from the disk objects and from globular clusters, dwarf galaxies, and other satellites past the disk. The parameters for the host galaxy I use are chosen to make the best fit rotation curve to the Milky Way, which is to say the figure plotting the galactocentric distance versus circular velocity of the Milky Way is flat out to at least 100 kpc with a circular velocity of 220 km/s (Fig. 3.3). The adopted parametric values to achieve a flat rotation curve are a total galactic mass of 1.1×10^{12} $M_\odot$, an inner galaxy which is 13% of the total galactic mass, an outer galaxy which includes the remaining 87% of the galactic mass, a half mass radius of the outer galaxy of 30 kpc, and a half mass radius of the inner galaxy of 3.3 kpc.

As with the host galaxy, the satellite is spherically symmetric. I test satellites of three different masses, 1.1×10^{10} $M_\odot$, 1.1×10^{11} $M_\odot$, and 4.0×10^{11} $M_\odot$ (which is respectively 1/100 $M_{\rm host}$, 1/10 $M_{\rm host}$, and 1/3 $M_{\rm host}$) with half mass radii of 1.0, 2.0, and 10.0 kpc, respectively. Each of the three satellites is tested with different transverse velocities, $V = 50$, 100, 150, and 200 km/s and begin at the same position for each simulation, $(X, Y, Z) = (200, 0, 0)$ kpc.

In the simulations, one satellite is introduced and is allowed time to merge with the host galaxy. In nature, satellites leave gas and stars behind as they merge. I make the simplification that all mass is added to the inner part of the host galaxy. The average orbital distance of the simulated satellite and globular clusters around the galaxy decays according to the dynamical friction estimates from Chandrasekhar (1943) and

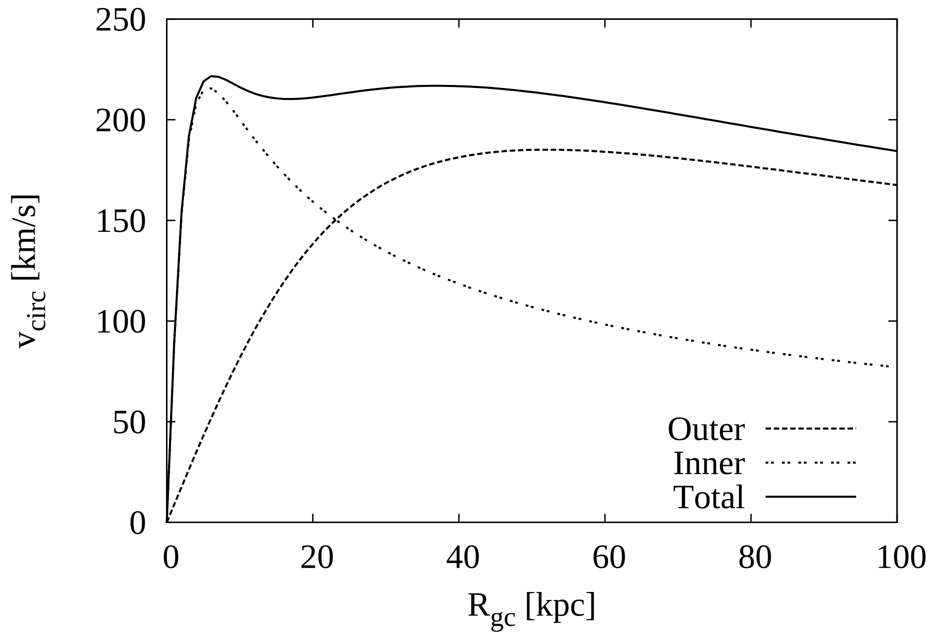

Figure 3.3: Milky Way model rotation curve, i.e. the model galaxy's circular velocity v_{circ} as a function of galactocentric distance R_{gc}. The dashed line represents the outer galaxy, the double-dotted line the inner galaxy, and the solid line the total rotation curve for the the model galaxy.

Binney and Tremaine (1987, pp 420 – 427). The dynamical friction used in Seppo Mikkola's code depends on the density of the galaxy, satellite, and globular clusters and on the velocity of the satellite and globular clusters.

Merging Process

The code operates in three temporal regimes. First, 200 globular clusters orbit the galaxy for 5 Gyr in order to check for stability, and to measure mean radii for the orbits. Then I add the satellite at a distance of 200 kpc from the galactic center and allow 10 Gyr for it to merge. Finally I allow the globular clusters to orbit for another 5 Gyr. I want to know how the orbits have changed due to the merger. A simple way to determine changes

Table 3.1: Merging results within 10 Gyr for satellites of mass in $M_\odot$ (rows) and initial transverse velocities in km/s (columns).

Satellite mass	V (km/s)			
($M_\odot$)	50	100	150	200
1.1×10^{10}	merger	merger	no merger	no merger
1.1×10^{11}	merger	merger	merger	no merger
4.0×10^{11}	merger	merger	merger	merger

in orbits is to calculate the largest and smallest galactocentric distance for each globular cluster before and after the merger. To do this, I calculate the average of the closest approaches and the furthest approaches in the orbits during the first 5 Gyr and then during the last 5 Gyr for each cluster. Without interactions from the satellite, the average galactocentric radius over all the globular clusters is $\sim$ 16 kpc.

3.3 Simulation Results and Discussion

As mentioned in Sec. 3.2.1, the clusters are distributed in the halo of a Milky Way-type galaxy between $2 - 100$ kpc; although a more realistic minimum radius would be $R_{\rm gc} = 0.5$ kpc, I chose for my simulations the minimum distance of $R_{\rm gc} = 2$ kpc, because clusters within 2 kpc merge before 5 Gyr due to dynamical friction. Fig. $3.4 - 3.6$ show the simulation results for the three masses of satellites with initial transverse velocity of $50 - 200$ km/s. A satellite with higher transverse velocity disturbs the globular clusters slightly more because the satellite orbits for a longer time in the host galaxy. Table 3.1 summarizes all tested satellites (varying in mass and initial tangential velocity) and records which satellites merged in the simulations before 10 Gyr. Low mass satellites at high velocities need more than 10 Gyr in order to merge. I do not consider the cases in which the satellite does not merge due to mass and transverse velocity since we are interested in how a merger affects the globular cluster system. As the satellite mass increases, the initial distribution of globular clusters is disturbed more, i.e. the satellite drags them inward and their average

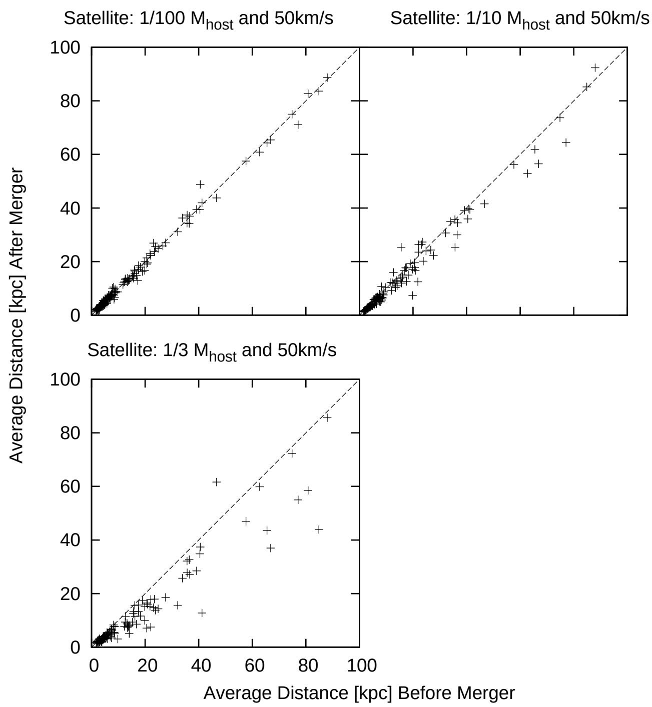

Figure 3.4: Globular cluster average distances are compared before and after a merger with an initial transverse velocity of 50 km/s. Each panel is for a different merger ratio of the host and satellite masses. The upper left panel shows that the least massive satellite, 1/100 M_{host}, has had negligible effects on the globular cluster orbits. The upper right panel is for the merger with mass 1/10 M_{host}. The lower left panel is for the merger with the largest mass, 1/3 M_{host}. The largest massed satellite has a modest effect on the orbits. The globular clusters have been shifted around, but the initial and final radii are still strongly related. If radius and metallicity are also strongly correlated at the start, the correlation is still strong and has not been substantially altered by the merger. The dashed line is a one to one ratio.

galactocentric distance decreases.

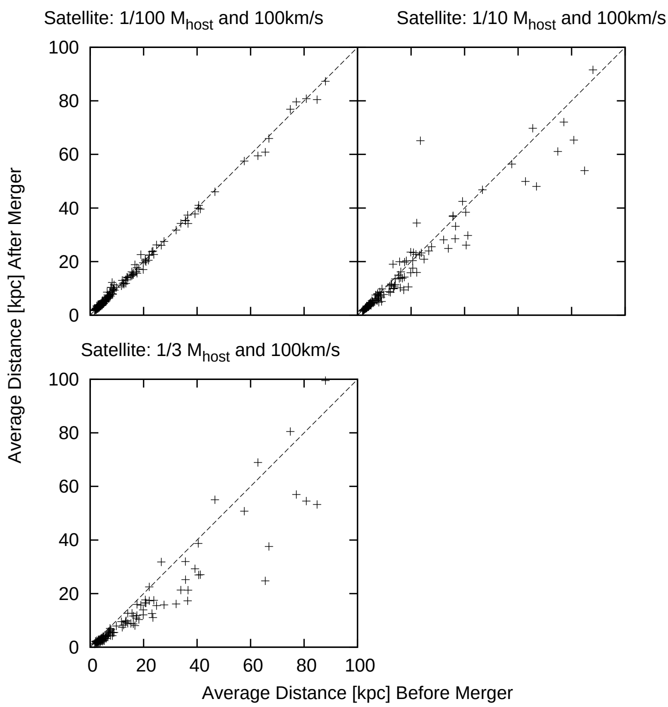

Figure 3.5: Globular cluster average distances are compared, similarly as in Fig. 3.4, but now before and after a merger of 100 km/s initial transverse velocity. Each panel is for a different merger ratio of the host and satellite masses. The upper left panel is for the lowest mass satellite simulated with a mass of 1/100 M_{host}. The upper right panel is for the merger with mass 1/10 M_{host}. The lower left panel is for the merger with the largest mass, 1/3 M_{host}. All three satellites have moderate effects on the globular cluster orbits, the more massive the satellite causing more of an effect. The globular clusters have been drawn closer to the host galaxy, but the initial and final radius are still strongly related. If radius and metallicity are also strongly correlated at the start, the correlation is still strong and has not been substantially altered by the merger. The dashed line is a one to one ratio.

As explained in Sec. 2.1.1 and 2.1.2, velocity dispersion and anisotropy profiles are tools to analyze simulations and compare with observations. These are plotted in Fig. 3.7, although unfortunately the number of observed Galactic globular clusters is low (and thus also low are the number of clusters in the our simulations) and anisotropy cannot fully be constrained (e.g. Wu and Tremaine (2006)). None-the-less, Fig. 3.7 exemplifies the analysis process described in Sec. 2.1.1 and 2.1.2. As described in Sec. 3.2.2 the simulated globular clusters are given an initial Gaussian distributed velocity dispersion (see radial velocity dispersion plotted in the left upper panel of Fig. 3.7), such that the system is isotropic ($\beta = 0$, right upper panel). The dispersion (especially within 20 kpc) increases with increasing satellite mass and initial tangential velocity (left middle and lower panels), although the system remains isotropic (right middle and lower panels).

My simulations show that the largest test satellites one third the mass of the Milky Way have enough mass to influence but not destroy the initial metallicity distribution, as seen in Fig. 3.2 where the simulated case causing the largest disturbance to the metallicity gradient in the lower left panel is far from representing the present metallicity profile of Milky Way globular clusters shown in the lower right panel. As seen in the lower right panel of Fig. 3.2 the globular clusters in the Milky Way do not exhibit a steep metallicity gradient, if a gradient exists at all. During a major merger event, such as my simulated satellite of one third the host galaxy, traces of the satellite could likely be found in the dynamics of the galaxies sharing the same group as the Milky Way; although, no such traces have been observed.

The conditions under which globular clusters predominantly formed are very much an open question. If a metallicity gradient had existed in the past, then the theory of galaxy formation developed by Eggen et al. (1962) would be a likely scenario such that the globular clusters would form from a collapsing pre-galactic cloud. Such a gradient could possibly have been disrupted by many mergers, but my simulations show that a single large merger could not be the lone culprit. The original spatial distribution, and thus also the metallicity distribution, of globular clusters also would likely be influenced by cluster destruction as they passed through the Galaxy's disk (Gnedin and Ostriker, 1997).

The scatter of metallicities observed in the Milky Way could alternatively be explained through multiple globular cluster populations. Although not investigated in my simulations, large satellites are likely to host their own system of globular clusters, some of which would be stripped off and remain in the host galaxy's halo after the satellite merges. Milky Way satellites are known to carry their own globular clusters (e.g. Magellanic Clouds (Gascoigne and Kron, 1952; van den Bergh, 1991), Sagittarius dwarf galaxy (Ibata et al., 1994, 1995), Canis Major dwarf galaxy (Crane et al., 2003; Frinchaboy et al., 2004; Forbes et al., 2004)). Two Galactic globular cluster populations could likely be the original which formed within the Milky Way over the first Gyr of formation and another brought in and left behind by merging satellites. The existence of two populations of globular clusters is supported through such observational studies as by Marín-Franch et al. (2009), Dotter et al. (2011), and Roediger et al. (2014) who investigated the relation between globular cluster metallicity and age. McCarthy et al. (2012) followed disk galaxy formation using simulations which included two populations of the halo: that formed within the galaxy and that accreted from satellite galaxies. A metallicity gradient could still exist, although the overlap of the multiple globular cluster populations would mask such a gradient.

Yet another possibility is that no metallicity gradient has ever existed. Such could be the case if the pre-galactic cloud collapsed quickly and left no time for new globular clusters to form in gas enriched by metals from a previous generation of globular clusters. Alternatively, the Galaxy halo could have formed completely by mergers as supported by Searle and Zinn (1978) and the latest N-body simulations (i.e. Bullock et al. (2001); Bullock and Johnston (2005)), such that no metallicity gradient existed.

3.4 Summary

In the simulations, I introduce satellite galaxies into a fixed, Milky Way potential, allowing them to merge by dynamical friction, and investigate the effects on the host galaxy's globular cluster population. I investigate the effects due to satellites of different mass and incoming velocity. As discussed in Sec. 3.1, the early halo simulations of Innanen and Valtonen (1977) and Valtonen et al. (1984) tested the effects on globular clusters due to the Large and Small Magellanic Clouds and found that these satellites were able to influence the orbits of the globular clusters, which is in agreement with our merging satellite simulations which show that even the smallest satellite tested with mass $1/100\ M_{host} = 1 \times 10^{10}\ M_{\odot}$ slightly influences the dynamics of the globular cluster population (top left panel of Fig. 3.4 and 3.5). After the merging of the more massive satellites, the orbits of the globular clusters shift to smaller average distances from the host galaxy's center (Fig. 3.4 – 3.6).

The goal of my study was to investigate if initially tight relations between metallicity and galactocentric distance can be rearranged by mergers enough to exhibit the metallicity profiles now found in the Galaxy. In this sense, the metallicity is tracing the dynamics of the globular clusters, because dynamically the globular clusters are becoming mixed similar to the metallicity profile. My simulations show that the smallest satellites 1/100 M_{host} do influence the metallicity distribution, but even the largest satellites one third the mass of the Milky Way do not have enough of an influence to destroy the initial metallicity distribution. The remaining relation is still too tight to represent the present metallicity profile of Milky Way globular clusters.

Many different galaxy formation scenarios and initial conditions exist to explain the origin of globular clusters as discussed in Sec. 1.2 and 3.3. Because my simulation results do not reflect the observations, my research shows that a merger could not be an all-inclusive event which mixes a metallicity gradient to form the observed distribution of globular clusters. My simulations rule out one scenario beginning with a metallicity gradient under the influence of a single merger. If the Galaxy's halo globular clusters started with a tight relation between metallicity and Galactocentric distance, my simulations show that one satellite can influence the orbits of globular clusters, and thus the initial metallicity distribution, although the initial metallicity gradient is still prominent after the merger.

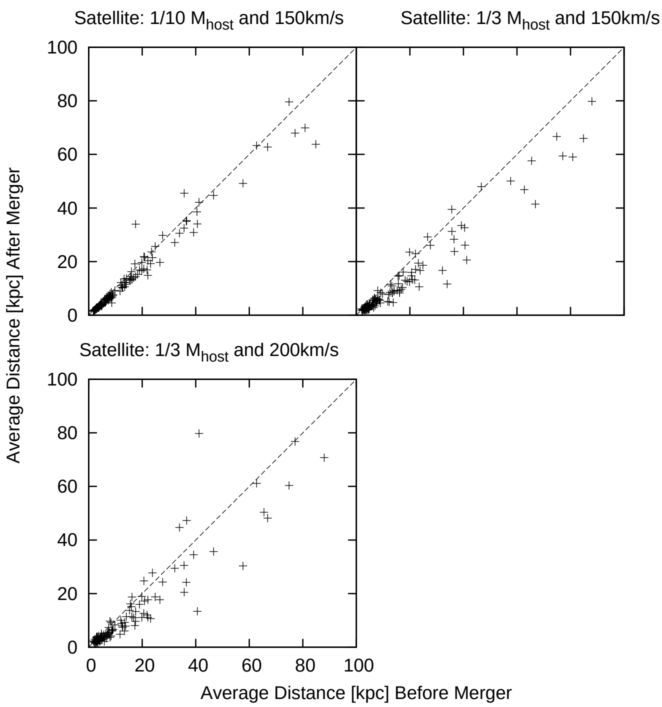

Figure 3.6: Globular cluster average distances are compared before and after mergers of mass 1/10 and 1/3 M_{host} with initial transverse velocities of 150 − 200 km/s, showing the largest orbital changes due to the mergers as compared to Fig. 3.4 − 3.5. The globular clusters decrease in average radius and orbit closer to the host galaxy. The upper left panel is for the medium-massed satellite of 1/10 M_{host} with an initial transverse velocity of 150 km/s. The upper right panel and the lower left panel are both for the most massive satellite of 1/3 M_{host} with an initial transverse velocity of 150 km/s and 200 km/s, respectively. The most massive merger, 1/3 M_{host}, with the highest initial transverse velocity, 200 km/s, causes the most change in the globular cluster orbits and brings them in closer to the host galaxy more than the other simulated mergers (such as Fig. 3.4 − 3.5). Despite causing the largest globular cluster orbital changes, the initial and final radii are still strongly related. An initially strong correlation between radius and metallicity is still strong at the end of the simulation and has not been dissolved by the merger. As opposed to Fig. 3.4 − 3.5, the least massive satellite, 1/100 M_{host}, is not plotted, because it does not merge at the high initial transverse velocity of 150 or 200 km/s. Nor does the 1/10 M_{host} satellite merge when beginning with a 200 km/s transverse velocity. The dashed line is a one to one ratio.

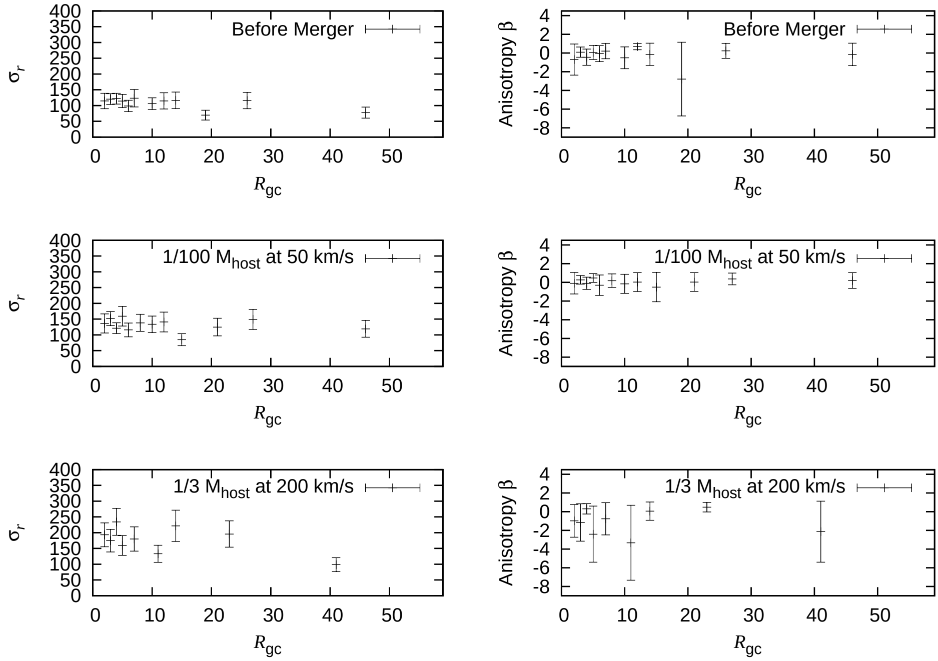

Figure 3.7: Radial velocity dispersion σ_r (left column) and corresponding anisotropy β profiles (right column). The upper two plots show σ_r and β after 5 Gyr of the simulation. The middle panels show the effects on σ_r and β after the merging of the least massive satellite of 1/100 M_{host} with the smallest initial transverse velocity of 50 km/s. This merging satellite causes the least effect on the globular cluster dynamics and metallicity gradient. The lower panel shows the effects on σ_r and β after the merging of the most massive satellite of 1/3 M_{host} with the largest initial velocity of 200 km/s. This merging satellite causes the largest changes in the globular cluster dynamics and metallicity gradient. The system of globular clusters is nearly isotropic ($\beta = 0$) initially and remains so after the satellites merge. Because the system consists of only 200 globular clusters, the error bars are quite large for both σ_r and β.

Chapter 4

Galactic Halos: Observations and Models

The initial conditions and models used for simulations are motivated by observations. So far I have been describing galaxy simulations, starting with initial conditions and models and giving the computer a program with mathematical equations to solve, and hopefully in the end producing galaxies which resemble what are observed today. How are these initial conditions gathered together and what is actually being sampling from the galaxies to determine these characteristic attributes found in nature?

4.1 Photometry

The samples taken from outside of the solar system are of photons and a few other elementary particles such as neutrinos. My focus is on photons. Telescopes are like buckets. Put a bucket outside on a snowy day and it can collect snow. Put a telescope out on a clear night and it can collect light. Light exists as a spectrum, and we can observe the light at different wavelengths and split the light into different wavelengths using diffractors or grisms. From this light, one can determine age, motion, physical composition, origin, and more. Even though there are not many things we can collect as samples from galaxies, the wealth of knowledge we extract from those samples we collect is astonishing.

In Paper I and Paper II, I study images of halo fields from two galaxies, M87 and NGC 5128, taken with the Hubble Space Telescope and the European Southern Observatory Very Large Telescope. The study of individual stars in the Milky Way's halo has a long history, as discussed in Sec. 1.2.

From galaxies outside our local neighborhood, we can learn about halos by observing their integrated light, even if we cannot resolve individual halo stars. Globular clusters are formed from $\sim 10^5$ stars. They are typically $\sim$ 1000 times brighter than a single red-giant branch star, $\sim 10^5$ times brighter than the Sun, and can be observed 30 times further than a red-giant branch star. The observations I use of M87 are space-based archival images from the Hubble Space Telescope, and my images of NGC 5128 are ground-based using the VIMOS imager on the Very Large Telescope-Unit Telescope 3, Melipal, (third out of the four 8 meter telescopes at Paranal Observatory). With seven hours of exposure on the Hubble Space Telescope and one and a half hours on the Very Large Telescope, and after careful image processing, I am able to resolve individual stars in these two distant halo fields. And only the brightest stars at that.

As stars age, they go through different phases and exhibit different properties. Stars emit energy because they are fusing elements together to form new elements, where the fusing process is called burning elements to form new ones. Stars spend most of their lives fusing hydrogen into helium. In my research, specifically Paper I and Paper II, I have been most interested when the stars have ended burning hydrogen and are just prior to begin burning helium by a few million years. In this phase, stars are called *red giants* or first-ascent red giants. After exhausting their source of hydrogen in their core, stars enter a phase in life called the red-giant branch. During this phase, pressure and temperature build up in the hydrogen exhausted core and the whole star gradually increases in brightness. When the stars reach the temperature and pressure needed to begin burning helium, they reach a characteristic peak in their brightness, and are much brighter than the majority of stars in the galaxy. At this peak brightness, the stars are at the stage called the tip of the red-giant branch. Because I am observing other galaxies, I can only see these bright stars because the majority of stars are too dim for me to detect as individual point sources in the images. The distance to the galaxy being studied is calculated by using the brightness measured and the known brightness of what the same type of stars are within the Milky Way.

Crowding was an issue in Paper I while studying the Hubble Space Telescope image of M87, such that within the inner regions of the galaxy the images of many stars merged into each other and could not be separated into individual sources. Thus we studied only the outer edges of the image, those halo stars which were at an angular distance of 149 arcsecond, galactocentric distance of 12 kpc (1.9 R_{eff}, where R_{eff} is the effective radius in the I band of 81 arcsecond (6.3 kpc) (Zeilinger et al., 1993)). We measured the brightest red-giant branch stars shining out of the light emitted from the densely packed, dimmer unresolved stars.

Paper II compares different regions of NGC 5128's halo, the fields of Harris et al. (1999), Harris and Harris (2000, 2002), and Rejkuba et al. (2005), closer in to the galactic center and my own much further out, and confirms that the number density of stars decreases radially with distance from the center of the galaxy. The 65 kpc field is so far from the center of NGC 5128, that crowding is not an issue as with M87. On the other hand, the number density of stars in our NGC 5128 field is low and is in competition with the number density of distant galaxies, some of which appear also as point sources. Careful analysis was needed to make sure the halo star population could be isolated from the background galaxy population. A very large effort was needed and a special technique was developed in this thesis to do this (namely making a comparison with Hubble Deep Field-South galaxy counts (Gardner et al., 2000; da Costa et al., 1998) as a function of magnitude and color).

4.2 Stellar Evolution Models and Tracing Dynamics from Observations

Stellar chemical abundances are measured in two main ways. Spectroscopy is the most direct way. Within the light spectra from the stars are absorption and emission lines which show what elements are in the star. My observations are confined to broadband imaging only and no spectra were taken.

To measure the metals in this case, I must rely on so called *stellar isochrone models.* The isochrones rely on the fact that stars born at the same time from the same gaseous nebula have the same chemical composition, that is to say they are made from the same starting material. Stars in the same nebula form with different masses, which determines their path of evolution and the rate at which they evolve. The most massive stars evolve the fastest and have more violent and explosive endings, thus enriching the interstellar medium with metals for further generations of stars.

The model isochrones relate the stars of the same metallicity and age (but different masses) to the brightness within one filter (*magnitude*) and the difference of two filters (note that the difference between two filters is termed as *color*). Because the same-aged stars are of different masses, they evolve at different rates, each being characterized by the magnitude and color from that stage of evolution. The method I use is to plot the stars in the color-magnitude diagram (e.g. Fig. 4.1), overlay a number of model isochrones which differ in metallicity, and interpolate star by star what metallicity they have (Fig. 4.2). This assumes that the stars I am observing are all of similar age, as stars in the outer halos of galaxies are likely to be. In the analysis of my halo red-giant branch observations, I

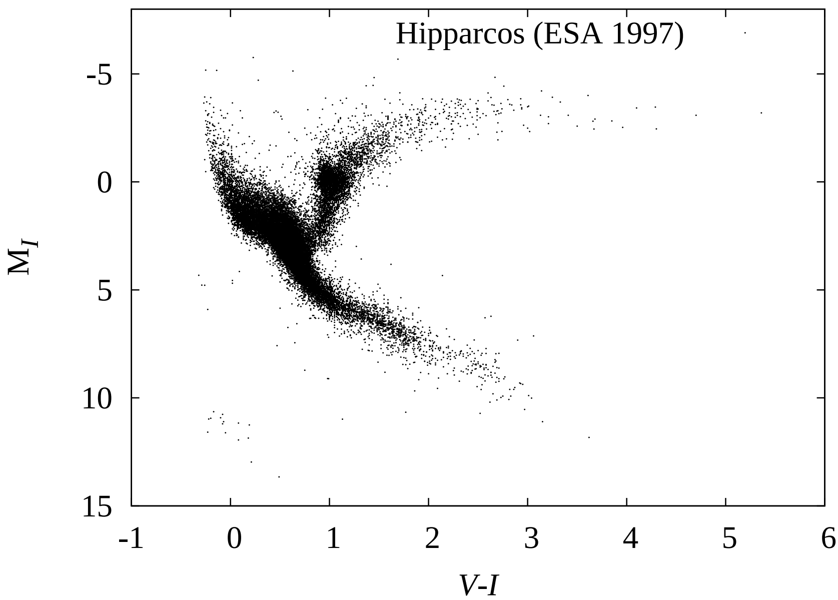

Figure 4.1: Color-magnitude diagram in $V - I$ color and absolute I magnitude produced from stars of the Hipparcos Catalogue ((ESA, 1997), also see Perryman and ESA (1997) and Perryman et al. (1997)). The stars have a standard $V - I$ error of $0.1 > \mathrm{e}(V - I) > 0.0$, parallax > 0, and a relative parallax error $< 15\%$. Unique to the $V - I$ versus I plane is the horizontal flatness of the tip of the red-giant branch at $M_I = -4.05$ (Rizzi et al., 2007) and $1.5 < V - I < 4$.

assume that the stars are old, $\sim 12 \times 10^9$ yr.

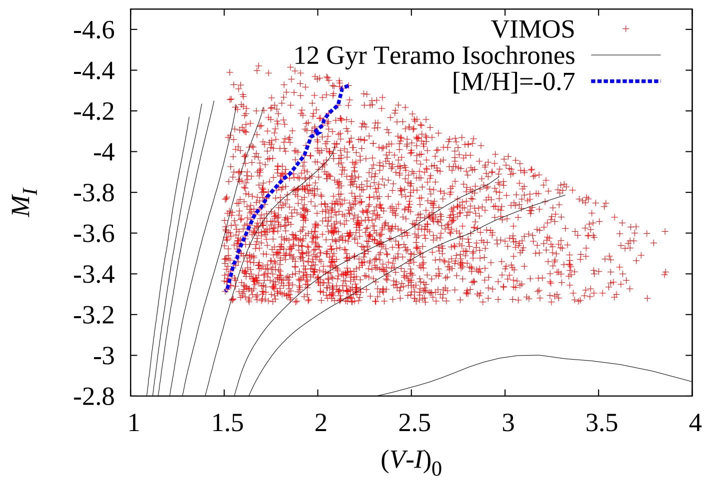

Figure 4.2: Stellar evolutionary isochrones superimposed over the color-magnitude diagram for the VIMOS Very Large Telescope NGC 5128 65 kpc field of Paper II. Plotted are the absolute magnitude M_I and $(V-I)_0$ color (these values have been corrected for reddening due to dust intervening from the Milky Way). The models assume red-giant branch stars of age 12 Gyr. Solid black lines are the α-enhanced isochrones from Pietrinferni et al. (2004, 2006); from left to right, the metallicities are $[m/\mathrm{H}] = -2.27, -1.79, -1.49, -1.27, -0.96, -0.66, -0.35, -0.25, 0.06$. The dashed blue line marks $[m/\mathrm{H}] = -0.7$, the cut at which we divide between metal-poor and metal-rich objects. The tip of the red-giant branch begins at $M_I = -4.05$ (Rizzi et al., 2007).

The resulting distribution of stellar metallicity is broad in both Paper I's M87 and Paper II's NGC 5128, peaking within $-1 < [m/\mathrm{H}] < 0$, and having a long tail reaching toward more metal-poor values. The inner halo ($\sim$ 12 kpc) field of M87 peaks likely at $[m/\mathrm{H}] \simeq -0.4$ and is most similar to the inner halo of NGC 5128 (Harris and Harris, 2002). M87 is the central galaxy of the large and highly populated Virgo Cluster, whereas NGC 5128 is the central galaxy of the smaller Centaurus Group. Despite the different environments of these two giant elliptical, centrally dominating galaxies, the similarity of their inner halo metallicity distributions may be evidence for similar processes operated in both galaxies during the formation phases. For example, one proposed scenario builds the stellar and globular halo populations from two phases of star formation within the galaxy (e.g. Forbes et al. (1997), Harris et al. (1999), and Chap. 1.9 of Harris (2001)): first within the protogalactic cloud, and second forming the bulk of the stellar halo within the already formed galaxy. These two phases do not depend on galaxy mergers from the surrounding environment, thus allowing M87 and NGC 5128 to develop similar halos independent of the number of cluster or group members.

Kalirai et al. (2006) and Harris et al. (2007) have found a transition in the outer halo of two different types of galaxies, in which the number density of the dominating metal-rich halo component suddenly drops, leaving the metal-poor stars to dominate in number density by default. Fig. 4.3 plots the transition Harris et al. (2007) found in NGC 3379. The metallicity is tracing the dynamics of the stellar halo. Some type of dynamical event has likely produced this transition found in the metallicity. The connection between these two galaxies is the galactocentric distance of $15 - 35$ kpc at which the transition was found. Galaxies span a range of sizes and brightnesses, but one way to compare distances within galaxies is to use the effective radius, R_{eff}, defined such that half of the galactic light is located within one R_{eff}. The significance lies in that the transition was found in both galaxies at $10 - 12$ R_{eff}.

This was the spark for Paper II which searches yet a third type of galaxy in order to draw clues as to if the transition at $10 - 12$ R_{eff} was ubiquitous to all large galaxies. M31 is a disk galaxy, very similar to the Milky Way. NGC 3379 is the prototype for classic elliptical galaxies. NGC 5128, on the other hand, is a giant elliptical which has seen many mergers in its history. Perhaps the not-so-surprising surprise was that no transition was found within $1.4 \leq R_{\mathrm{gc}}/R_{\mathrm{eff}} \leq 13$ in the halo of NGC 5128. Very few galaxies have been measured in this way—it is very difficult work! Paper II finds that the falloff of stars is independent of metallicity in this range for NGC 5128. If the metallicity is tracing the dynamics and the transition did in fact exist, then during the many mergers occurring within NGC 5128, the transition radius could have been washed out, or possibly could be found at a further radius still.

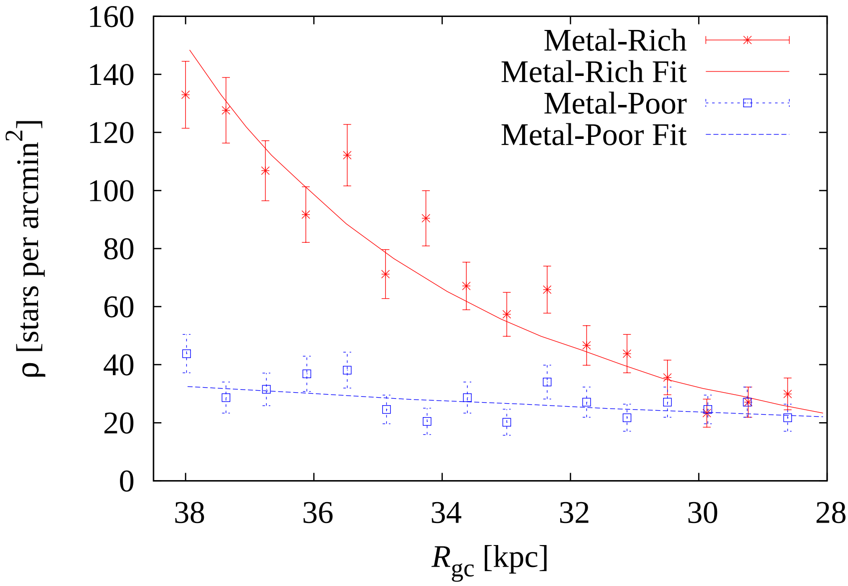

Figure 4.3: Transition (seen at the lower right where the two curves meet) between metal-rich ([m/H]> -0.7, red asterisks and solid line) and metal-poor ([m/H]< -0.7, blue squares and dashed line) halo stars in NGC 3379. Stellar density ρ, the number of stars per square arcminute, is along the vertical axis. The horizontal axis records the projected distance R_{gc} (in kpc) from the center of NGC 3379. The metal-poor population density falls off with radius as $\rho \sim R_{gc}^{-1.2}$ (dashed curve) while the metal-rich population falls off as $\rho \sim R_{gc}^{-6.0}$ (solid curve). From Harris et al. (2007). Courtesy of Bill Harris.

Chapter 5

Summary of Results

5.1 Paper I

The results of Paper I include the first-time measured brightnesses and metallicity distribution function of individual stars in M87. Photometry is measured for the brightest red-giant branch stars in the inner halo of M87 using V and I archival Hubble Space Telescope images, reaching the limiting magnitude of $M_I = -2.5$. The metallicity distribution is found to be very broad and likely to peak near $[m/\mathrm{H}] \simeq -0.4$ and perhaps higher. The shape of the metallicity distribution strongly resembles that of the inner halo for the nearby giant elliptical galaxy NGC 5128.

5.2 Paper II

Paper II studies one of the furthest resolved stellar halo populations in NGC 5128 (only out-distanced by the similar study of Crnojević et al. (2013) and the space-based observations of Rejkuba et al. (2014)). No transition is found in the outer halo within 13 $\mathrm{R_{eff}} \approx 70$ kpc, such that the metal-rich component steeply dies away and leaves a much shallower and sparser metal-poor component to dominate. Ground-based images were granted and successfully obtained using the European Southern Observatory Very Large Telescope. Both photometry in V and I and chemical abundance were measured. The metallicity distribution function is very broad and peaks near $[m/\mathrm{H}] \simeq -0.4$. The shape of the metallicity distribution does not significantly differ from that of the halo fields previously studied by Harris et al. (1999), Harris and Harris (2000, 2002), and Rejkuba et al. (2005) using the Hubble Space Telescope.

5.3 Paper III

The simulations of Paper III show that the Kafle et al. (2012) kinematical anomalies of the Milky Way stellar halo quickly fade and smooth out on a time scale of 100 million years. Specifically, the features in the velocity dispersion σ and anisotropy β profiles smooth out, although the density profile negligibly changes over the 10 Gyr simulation.

Chapter 6

Future Work—Resolving Disagreement Between Observations and Simulations

Three future projects stem from the two unexpected discoveries made during my doctoral studies. The discoveries are both discrepancies found between observations and simulations. The first discovery based on our simulations is the transient nature of features found in the kinematic profiles of our Galaxy. The second discovery based on our observations is the common slope of the number density falloff which is shared between the metal-poor and metal-rich stellar halo components of NGC 5128. With both discoveries, we have thoroughly compared the models with the observations, and have found discrepancies such that the theoretical models do not fit the observations. The first discrepancy lies in the fact that our models predict the instability of the Kafle et al. (2012) Galactic kinematic profiles, based on observations, such that the features found in the profiles smooth out after a few hundred million years. The second discrepancy stems from theoretical models predicting different stellar metallicity gradients in galactic halos than the dually shared metal-rich and metal-poor gradients we found from our observations of NGC 5128's stellar halo.

The first two projects will study the motion of the Galactic blue horizontal branch halo stars: our modeling shows the Kafle et al. (2012) feature does not remain a stable property of our Galaxy. I am especially interested in gaining access to the LAMOST data while holding the LAMOST Postdoctoral Fellowship position, because in the second project I will make use of LAMOST and its extension LEGUE and Gaia-ESO to further test my blue horizontal branch halo star simulations. The next discovery leading to the third project is the manner in which the number density of halo stars decreases with increasing distance from the center of the galaxy NGC 5128: our rigorous observational study does not match the expectations from models.

6.1 Discrepancy #1—Fading Features in the Milky Way's Halo

In the first project I would like to detail the dynamics of the Milky Way stellar halo by setting up simulations of tracer stars in a model potential. This simulations project is best conducted at the Shanghai Astronomical Observatory within Prof. Juntai Shen's Galaxies Group, where I will be located for two years as a LAMOST Postdoctoral Fellow. In Paper III I have set up simulations modeling the recent blue horizontal branch halo star observations of Kafle et al. (2012). The Galactic kinematic profiles determined by Kafle et al. (2012) revealed previously unobserved features, the most prominent feature being seen in the β profile (Fig. 2.1, 0 Gyr panel) which, within a short $\Delta R_{\rm GC} \approx 5$ kpc, suddenly decreases by $\Delta\beta \approx 1.0$, and then increases again by $\Delta\beta \approx 0.5$. When introduced into our simulations, the features dissolve quickly, within a few hundred million years (Fig. 2.1, $2-6$ Gyr panels, shows the dissolved β profile). The discovery of the inconsistency between the observation and our models is intriguing and I would like to determine what causes this discrepancy of the unstable velocity dispersion profile.

In order to find what causes the features in the Galactic kinematic profiles as interpreted by Kafle et al. (2012), I would like to set up a complete library of dynamically stable halos in the adopted Milky Way potential. I will test a range of density laws and velocity dispersion profiles for the halo which can be set up in the Milky Way model, integrated for ten billion years, and yield a long-term stable result. I have already set up isothermal and other types of models to do this as described in Paper III. I want to set up a wide range of simulations which address possible causes, for example, whether a satellite moving through the halo can leave behind such a transient feature. These models will be the possible representations of the actual Milky Way halo.

The second project will take advantage of the latest large surveys in order to compare the new blue horizontal branch halo star observations to the collection of models I will produce. This research is very timely, because the observations needed to check with the models are now being collected as parts of the large surveys with LAMOST and its extension LEGUE and with Gaia-ESO. In addition, I will search for features similar to that found by Kafle et al. (2012) – maybe many such instabilities can be found which change as satellites break up, for example. More observations needed to check with the models are also coming soon from the Gaia spacecraft. Gaia has a five year mission and has successfully been launched on the 19th of December 2013. It will measure the kinematics of millions of halo stars within 10 kpc of the Sun, including the same halo stars as measured by Kafle et al. (2012). Gaia will measure the stellar proper motions. Now is the time to produce a collection of models which will be ready to compare with the observations provided by these upcoming surveys.

6.2 Discrepancy #2—Stellar Falloff in NGC 5128's Halo

The third project stems from the Paper II discovery using Very Large Telescope imaging of NGC 5128's halo with VIMOS in V and I to 27th magnitude in I_0. Although unexpected from modeling such elliptical galaxies, we find that the number density of all halo stars, both metal-rich and metal-poor, falls off at the same rate from a galactocentric radial range of $8-70$ kpc. I plan to use the superior archived Hubble Space Telescope data to check our surprising discovery. I want to challenge modelers of elliptical galaxies to produce more models to compare to the data.

Large ground-based telescopes are now able to reach individual halo stars in nearby galaxies, but we are faced with the problem that they are of similar brightness and color to the very copious background galaxies. I wish to measure the falloff of these stars in NGC 5128's halo well into regions where the number of faint blue background galaxies starts to dominate the halo stars. Thus we need greater understanding of how many background galaxies are present and how they can be best distinguished from the nearby stars. In Paper I and Paper II I have learned the basic methods for counting objects and measuring brightness and colors from images, but the methods now need fine tuning for the particular case of dim, unresolved background galaxies which appear amongst the halo stars in local galaxies. A recent study of NGC 5128 by Crnojević et al. (2013) has found that galaxy contamination is a very serious problem and may explain why they are getting unexpected results for the number of stars in the outer parts of the galaxy. Going to archived space-based Hubble Space Telescope data of NGC 5128 seems the thing to do, so I can check both my results and others.

Peter Johansson (University of Helsinki, Finland) and Brad Gibson (University of Central Lancashire, England) are modeling large elliptical galaxies like NGC 5128. We are in the process of discussing the halo observations and simulations. As the simulations are refined, I continue to compare the models to the archived observations: the models should accurately represent the high quality observations.

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Author's Contributions to the Publications

The Inner Halo of M87: A First Direct View of the Red-Giant Population
The candidate performed the data reduction and analysis, and was a substantial contributor to the writing of the paper, on which she was lead author.

Red-Giants in the Outer Halo of the Elliptical Galaxy NGC 5128 / Centaurus A
The candidate lead the writing of the observing application to the European Southern Observatory Very Large Telescope, reduced and analyzed the data, and was the main writer and first author of the paper.

Fading Features Found in the Kinematics of the Far-Reaching Milky Way Stellar Halo
The candidate conducted and analyzed the simulations and was the main writer and first author of the paper (to be submitted).

Chapter 3: Distribution of Globular Clusters After a Late Merger
The candidate conducted simulations using Seppo Mikkola's code, analyzed the results, and wrote the thesis chapter. The research is to be written in a future publication.

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