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Chemical Abundances of Dwarf Galaxies

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Chemical Abundances of Dwarf Galaxies

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MASTER OF SCIENCE

in Physics

by

Natalie Sanborn

Thesis Committee:
Professor Asantha Cooray, Chair
Professor Aaron Barth
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ABSTRACT OF THE THESIS

Chemical Abundances of Dwarf Galaxies

By

Natalie Sanborn

Master of Science in Physics

University of California, Irvine, 2024

Professor Asantha Cooray, Chair

Dwarf galaxies, though small in size, play a crucial role in understanding the chemical evolution of galaxies. Dwarf galaxies make up the overwhelming majority of galaxies in our local group and have very low metallicities. This review explores the observed chemical abundances in dwarf galaxies, and how these observations fit into theoretical models of galactic chemical evolution. We also discuss the broader implications of these findings for understanding the universal mass-metallicity relation, near-field cosmology, and the hierarchical structure formation of galaxies. As observational techniques advance, these systems will continue to be essential for refining our understanding of galaxy evolutions on both small and large scales.

1. Introduction

In the last 100 years, our understanding of the Milky Way's place in the universe has evolved significantly, beginning with Hubble's discovery that the Andromeda Galaxy was separate from the Milky Way in 1923 (Hubble 1923). This breakthrough, made by using Cepheids to measure distance, prompted the reevaluation of objects previously classified as nebulae began to be reevaluated as potentially separate galaxies based on refined distance measurements, such as the Magellanic Clouds, NGC 6822, and NGC 205 (Tammann 1994). In the late 1930s, Shapley identified Sculptor and Fornax, two of the first stellar systems to be definitively classified as dwarf galaxies, specifically dwarf ellipticals, notable for their older populations of stars (Shapley 1939). By the mid-1950s, more astronomers joined the search for these extragalactic structures (Harrington and Wilson 1950; Reaves 1956) contributing to the realization that dwarf galaxies significantly outnumbered the larger galaxies in our local group. However, the inherently low apparent brightness of the dwarf galaxies presented a challenge for distant observations, so the most detailed observations of dwarf galaxies are still focused on those in our local group.

Since their initial discovery, the classification of dwarf galaxies has been continuously refined. It is now generally accepted that a dwarf galaxy must be fainter than $M_B \leq -16$ or $M_V \leq -17$, and more spatially extended than globular clusters (Tammann 1994; Tolstoy et al. 2009). In recent years, the number of detected dwarf galaxies has rapidly increased with surveys like the Sloan Digital Sky Survey (SDSS). In 1994, only 41 galaxies were known in the Local Group, including the larger Milky Way and Andromeda (Mateo 1998). By 2012, over 100 dwarf galaxies had been identified within 3 Mpc of the Sun, with at least 60 thought to be satellites of the Milky Way (McConnachie 2012). The number of galaxies detected in our Local Group continues to rise, suggesting that there are more unknown galaxies nearby. A class of dwarf galaxies known as Ultra-Faint Dwarfs with a luminosity of $L < 5L_{\odot}$ were not first identified until 2005 with SDSS (Willman et al. 2005). The faintest yet of these Ultra-Faint dwarfs has a magnitude of only $M_v = 2.2$, discovered in 2024 (Smith et al. 2024).

Identifying and classifying dwarf galaxies is only the first step in understanding their role, but it provides a basis for deeper investigation into their key characteristics. One such characteristic is chemical abundances, which are used to describe the composition of an observed object. This is often quantified with metallicity, the abundance of all elements heavier than hydrogen or helium. By mass, hydrogen makes up 74% of the universe's baryonic matter, helium makes up 24%, and all other elements account for only 2%. The relative abundance ratios in stars are often notated with X representing the mass fraction of hydrogen, Y for helium, and Z for all heavier elements combined, normalized to a sum $X + Y + Z = 1$. While many other scientific disciplines would use a different definition of "metal", grouping heavier elements into Z is the most practical in astronomy, given their relative abundances. For example, the Sun's values are $X = 0.73$, $Y = 0.24$, and $Z = 0.01$. This provides a reference point to why it is generally useful to group all of the other elements into one Z value unless a specific element's mass fraction is needed.

Chemical abundance measurements are a vital tool in understanding star formation histories and galaxy evolution. Tinsley (1980) separates galactic evolution into three categories: dynamical, chemical, and photometric. All three of these areas of study are essential to understanding the evolutionary processes of galaxies, but the discussion presented here will primarily focus on chemicals. Photometric properties provide some broad clues about the metallicity distributions in a galaxy, though they are not precise enough to determine the abundances of individual elements. Tinsley provides a foundation for motivating and understanding the chemical evolution processes of galaxies of all sizes.

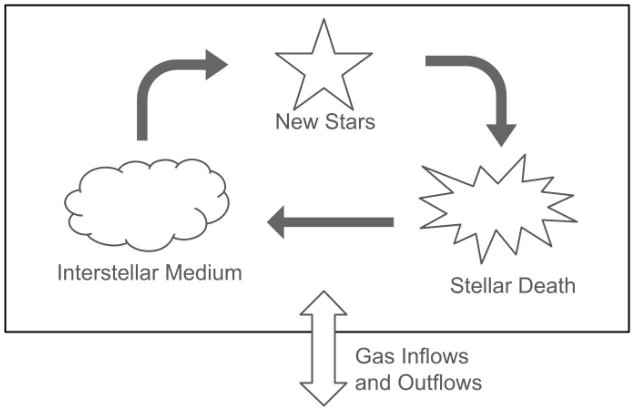

Figure 1.1: Galaxy Evolution Processes

A simplified schematic of the main processes in which matter cycles through galaxies. Stars form from matter in the interstellar medium and return the enriched matter to the interstellar medium at the end of their lives.

Figure 1.1 shows the basic cycle of matter throughout galaxies, with most of the chemical enrichment occurring from stellar death. The first stars that formed in the universe were the most metal-poor, made out of gas that had not been enriched by stars from previous populations. Subsequent generations of stars were formed with ingredients from the interstellar medium (ISM); their initial chemical composition is entirely dependent on the chemicals present in the ISM at the time of formation. The processes of stellar nucleosynthesis that produce elements heavier than hydrogen and helium are discussed in more detail in Section 2. While stars do not synthesize elements heavier than H and He on their own until later in their lifetime, they still contain these metals in their initial composition because they formed from gas enriched by previous stars. Baade (1944) used these characteristics to classify stars into two distinct populations based on when they formed: Population I stars are the youngest type and most metal-rich, having formed out of gas and dust that had was enriched by previous events, and Population II stars are older and metal-poor, like those in globular clusters. The study of galactic chemical evolution (GCE) uses these observed patterns and relationships of chemical composition present in a galaxy to determine the evolutionary processes leading from its formation to its appearance today.

In this review, we explore the chemical evolution of dwarf galaxies, focusing on the role these structures play in shaping our understanding of galactic formation and evolution. We begin with an overview of dwarf galaxy types and how these structures are well suited to studying chemical abundances in Section 2. In Section 3, we explore how chemical abundances are observed, and the strengths and weaknesses of the observational techniques. Section 4 emphasizes what the chemical properties of various types of dwarf galaxies tell us about their evolutionary history in the context of galactic chemical evolution models. Finally, Section 5 describes the broader implications of galaxy formation and evolution on a universal scale. The chemical composition of these small galaxies is vital to understanding their role in the cosmos as a whole, and the following paper is devoted to that topic.

2. Classification and Chemical Background

Dwarf galaxies have long been considered relatively “simple” systems, and there are many appeals to tracking GCE through dwarf galaxies instead of larger ones. Dwarf galaxies in particular have been observed to have many older Population II stars similar to those found in globular clusters, which offers an accessible way to study early stellar populations (Baade 1944). In addition, the intrinsically small size of dwarf galaxies allows us to study an entire individual galaxy on a more manageable scale. The vast majority of the galaxies close to the Milky Way are dwarfs, and this close distance allows us to study them in better detail and resolve individual stars more easily than at great distances. Their proximity also means that they may have a direct impact on the past, present, and future of our galaxy; whether they are disrupted fragments of the Milky Way, as proposed by (Zwicky 1957), or serve as the building blocks of larger galaxies (White and Rees 1978).

Dwarf galaxies, like larger galaxies, have frequently been categorized by their morphology. These classifications broadly include spheroidal, irregular, ultra-faint, and blue-compact dwarfs, and are represented in Figure 2.1. In recent years, Ultra-Faint Dwarfs have been of particular interest. The first Ultra-Faint Dwarf galaxy was not discovered until 2005 with SDSS (Willman et al. 2005). These Ultra-Faint Dwarf galaxies are interesting because of their low metallicity and high amounts of dark matter relative to their luminosity. However,

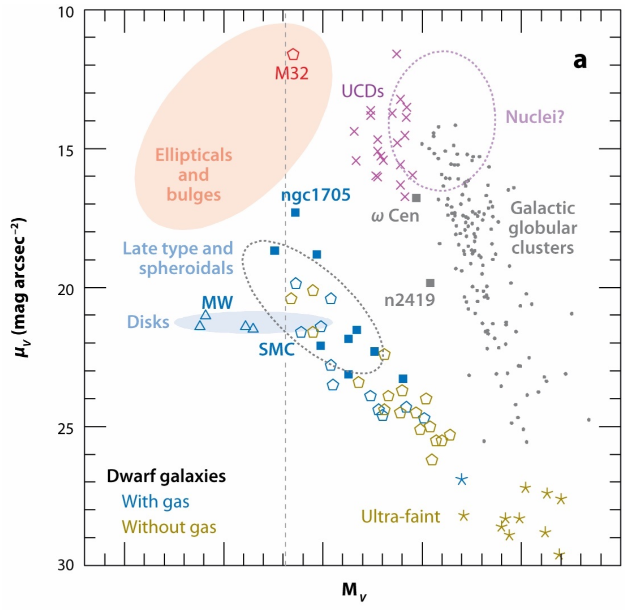

Figure 2.1: Dwarf Galaxies by Surface Brightness and Magnitude

The categories of dwarf galaxies compared to larger galaxies and globular clusters. The dotted grey lines represent the limits of the dwarf galaxy definition that we are using from Tammann (1994), $M_V \leq -17$ and less spatially extended than globular clusters. The central surface brightness, μ_V, versus absolute magnitude, M_V. Reprinted from *Star-Formation Histories, Abundances, and Kinematics of Dwarf Galaxies in the Local Group* by Tolstoy, E et al. 2009, Annual Reviews of Astronomy and Astrophysics, Volume 47, 373. Copyright 2009 by Annual Reviews, Inc. Reprinted with permission.

the importance of morphologically classifying these systems has been debated, with a preference for categorizing systems based on their structural properties such as luminosity, mass, and star formation rates instead (Tolstoy et al. 2009). Part of the argument for disregarding morphological classifications comes from the fact that these types are not always distinct, as seen in Figure 2.1. Additionally, treating each type as fundamentally different can impede the ability to compare dwarfs of two different morphological classifications, where they may be better compared against systems with similar star formation rates.

Rather than strictly by morphology, dwarf galaxies can also be categorized into early- and late-types. The early-type dwarf galaxies are generally older and more gas-poor than late-types, like dwarf spheroidals. Most of the satellites of the Milky Way are these early-type dwarf spheroidals, so they have been observed more extensively than late types. Spectro-

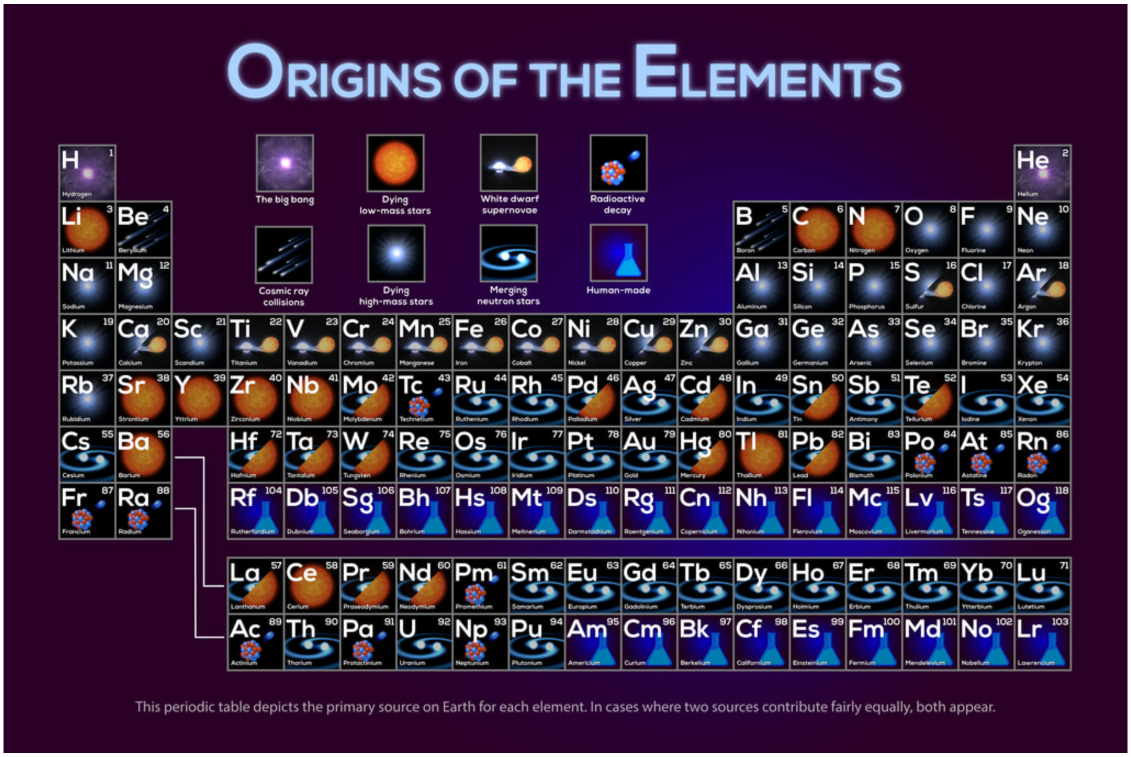

Figure 2.2: Origins of the Elements

A periodic table showing the primary sources of each element observed in our universe. Credit: NASA Goddard Space Flight Center

scopic observations of early-types relies primarily on Red Giant Branch stellar spectroscopy, since these dwarf galaxies do not have much gas or active star formation with young stars. In contrast, the late-type galaxies include irregular and blue compact dwarfs, and have dense regions of HII gas in the ISM. However, these systems are generally further away from us, making it difficult to observe individual resolved stars, and instead relying on the gas regions for observations of metal content.

One of the most important reasons for studying chemical abundances in the universe is that the chemicals present can hold information about the age and formation history of galaxies. While H and He were formed during the Big Bang, most heavier elements present throughout the universe were formed through stellar processes. In summary, stellar interiors produce energy through nuclear fusion, creating many of the elements we see on the periodic table. The primary fusion process is hydrogen burning, in which protons are combined to form He.

These hydrogen fusion processes differ with temperature; the proton-proton chain begins around $4 \times 10^6\,\mathrm{K}$ and the CNO cycle at $17 \times 10^6\,\mathrm{K}$. As the stellar temperature rises above $T > 10^8\,\mathrm{K}$ from hydrogen burning, heavier elements such as C and O are formed through helium burning. Elements from He fusion are referred to as alpha elements, primarily C, O, Ne, Mg, Si, Ar, Ca, and S. Figure 2.2 shows the periodic table of elements with the sources from where each element is released into the ISM. Dying low-mass stars eject the contents of their outer layers into the ISM as the core contracts and ends with a white dwarf. In high-mass stars, the internal temperature increases enough for heavier elements up to iron to be formed through the fusion processes. After iron, however, fusion is not an efficient energy source, and the star's mass can no longer be supported by its internal energy, causing a core-collapse supernova in stars with masses above $\sim 8\,M_\odot$. Elements heavier than iron are typically formed through catastrophic events with intense heat and pressure, such as supernovae and neutron star mergers.

With an established basis of what dwarf galaxies are, how they are categorized, and insights their chemical composition can provide for their evolutionary history, we can discuss how the abundances are measured in specific dwarf galaxies and the information they provide.

3. Observational Techniques for Chemical Abundances

Understanding the processes that contribute to the distribution of elements throughout the universe is necessary to be able to interpret data, but collecting the data through observation is the first step. There are two main observational techniques: spectroscopic and photometric. Spectroscopy offers more detailed measurements but often requires high-resolution observations, easiest on objects close by with powerful telescopes and long exposure times. Because of the high cost of spectroscopic observations, photometric techniques can be used in their stead. Photometric analysis uses the colors present in a stellar spectrum to determine composition but may be subject to more uncertainty than spectroscopy (Yang et al. 2013).

An early technique for estimating the average stellar metallicity of a galaxy uses the color of RGB stars, which is possible even when only photometric measurements of very bright stars are available. This technique uses a color-magnitude diagram (CMD) of the stars, such as $(M_I, (V-I)_0)$, to identify redder stars that indicate a higher metal-content using the relationship calibrated from stars in globular clusters (Da Costa and Armandroff 1990). Globular clusters are convenient structures to study the relationships between stellar properties because of their relatively uniform populations in terms of stellar age and composition. However, because this technique is primarily based on calibrations with old stars, it is highly susceptible to error from the age-metallicity degeneracy, in which stars can appear redder due to old age rather than high metallicity. For this reason, photometric estimates are most accurate when the ages of the stars are also available.

The Hertzsprung-Russell (HR) Diagram shows the relationship between stellar luminosity and temperature based on observations of color and magnitude. The relationship between these two stellar properties can be used to identify the evolutionary stages of stars, along with their approximate ages. The HR diagram gives a broad picture of stellar evolution over many stellar classification types and can be used alongside more detailed CMDs of specific clusters to analyze the characteristics of stars.

A collection of dwarf galaxy observations in and near our local group, within 3 Mpc of the Sun, is provided by McConnachie (2012). The mean stellar metallicities, $\langle [Fe/H] \rangle$ presented here were determined through a variety of methods, highlighting the diversity of techniques that can be used to analyze these dwarf galaxy structures.

Building on the early photometric methods, recent analysis of stellar metallicity often uses synthetic CMD fitting, in which a theoretical CMD can be constructed based on current understanding of star formation and evolution with the initial mass function, stellar ages, and metallicities. The modeled inputs can be adjusted to find the CMD that fits best with observed CMDs to determine the processes that contributed to the observed stellar population (Tolstoy et al. 2009). Although photometric observations are less precise than spectroscopy, they have the advantage of being used for large-scale surveys to create color-magnitude diagrams where it would be impractical to analyze the stellar spectrum of every star.

In late-type dwarf galaxies with active star formation, spectroscopic measurements of metallicity often focus on gas-phase metallicity, from emission lines of Oxygen in HII regions of ionized gas in between the stars in a galaxy. The clouds of gas and dust in between stars are what create new stars that will be formed, so the chemical abundances of these regions can provide information on the current enrichment levels of the galactic system. In 2004, spectroscopic observations from SDSS of 53,000 nearby (z $\sim$ 0.1) star-forming galaxies of various sizes revealed an inverse relationship between mass and metallicity, steeper at lower masses. The low-mass dwarf galaxies exhibited five times more metal depletion than galaxies similar in size to our Milky Way (Tremonti et al. 2004). The inverse relationship between mass and metallicity suggests that low-mass galaxies are more susceptible to losing chemical enrichment due to galactic wind outflows.

Although gas-phase metallicity indicates the current enrichment for late-type dwarf galaxies, most early-type dwarf galaxies do not have enough gas to easily observe. These quiescent galaxies have a low star-formation rate and typically older stars. To get a complete picture of galaxy evolution over time, it is crucial to study these galaxies alongside actively star-forming ones, as they are a key phase in the life cycle of galaxies. Instead of observing abundances in the gas, stellar abundances can be used to understand enrichment levels. However, the chemical abundances of stars do not indicate current galactic metallicity, but rather metallicity at the time of star formation. This characteristic also makes stellar abundances especially valuable when observing how a single galaxy evolved over time by studying stars of different ages.

The absorption lines used in observations of stellar spectroscopy occur when the gas present in a star's atmosphere absorbs photons before the light can escape, and depend not only on the element abundances, but also the temperature of the star. Because of this temperature dependence, different stellar types are probed to observe relative abundances of elements. Stellar spectroscopy is especially helpful for identifying young stars that indicate active star formation. For example, O-type stars have strong He II absorption lines, and B-type stars have strong He I lines. O and B spectral types have a relatively short lifespan compared to most stars, so the identification of their absorption lines signals recent star formation. A reliable method for average stellar metallicity with low- to medium-resolution spectroscopy uses the Calcium II triplet (CaT) equivalent widths alongside absolute magnitude. The CaT absorption lines at $\lambda = 8498, 8542,$ and $8662\,\text{Å}$ are stronger in stars with higher metallicity; this relationship has been calibrated with observations of globular clusters down to $[Fe/H] \approx -4$ (Rutledge et al. 1997; Starkenburg et al. 2010).

Measurements of diverse galaxies need to be compared with each other to obtain a complete picture of the universe. If the metallicity of star-forming galaxies is determined using emission spectra in HII regions, but quiescent galaxies are studied with stellar absorption spectra, comparisons need to account for these different observational methods. With a typical increase in chemical enrichment from dying stars over time, the enriched gas surrounding stars will have a greater average metallicity than the stars in the same area, because the absorption lines in a stellar spectrum indicate the enrichment at the time of star formation.

Grebel et al. (2003) observed the relationships between luminosity and metallicity for dwarf spheroidals compared to dwarf irregulars, concluding that the spheroidal ones had higher average metallicity than the irregular ones on similar luminosity scales. However, the observations analyzed by Grebel et al. used spectroscopic techniques for the spheroidals and photometric techniques for the irregulars, and failed to account for how the different methods affected the presentation of average metallicity. This contributed to an underestimate of the metallicity in irregular dwarf galaxies due to age-metallicity degeneracy, in which younger stars appear bluer, which would suggest lower metallicity without the knowledge of their ages.

This analysis was improved upon when Kirby et al. (2013) compared stellar spectroscopy from dwarf irregular galaxies in the local group to gas-phase metallicity of satellite dwarf spheroidal galaxies, determining a universal mass-metallicity relation consistent with the relationship seen in higher-mass galaxies. Their findings addressed the discrepancies from Grebel et al. (2003), which showed different relationships between average mass and metallicity for irregular dwarfs compared to spheroidal dwarfs. Developments in photometry have allowed this to be accounted for in more recent studies, as Kirby et al. used co-added spectra for the observed satellites of M31 to combat error from the age-metallicity degeneracy, finding evidence for the universal mass-metallicity relation that can be scaled up to apply to larger galaxies as well. It is essential to continuously refine observations of these galaxies so that the trends seen can be used to constrain models of galaxy formation.

4. Chemical Evolution Observations and Models

We can observe dwarf galaxies individually to determine how each system evolves over time, comparing observations to the theoretical closed, leaky, and accreting box models typically discussed in GCE. By observing these systems on a small-scale, we can isolate the processes driving the changes in their chemical composition over time.

One of the key ingredients in chemical evolution of a galaxy is the ISM, as it contains all of the baryonic material in a galaxy that is not contained within stars. This is what the stars throughout the galaxy are born out of, and what they enrich upon death, so it is essential to understanding how the chemicals change throughout the galaxy's evolution. Different approximations of the behavior of the ISM, varying in complexity, are referred to as the closed box, leaky box, and accreting box models. We discuss these models and how they align with observations of dwarf galaxies, and how we can refine them.

The closed box model is the simplest and easiest to work with, but this simplicity limits its ability to accurately describe the detailed processes occurring in galaxy evolution. The closed box model assumes that no gas is being added or lost in the system. With this assumption, all of the chemicals present in the initial ISM are converted into stars and cycled back into the ISM to be converted into more stars. The closed box model famously brought up the G-dwarf problem, where this approximation suggested that there should be more G-dwarf stars than were observed in reality. However, this problem has been addressed with more complex models that incorporate variations in the initial mass function or gas inflows and outflows. While effective for generalizations, the closed box model can have misleading results as it fails to take into account more gas being accreted into the system (as in the accreting box, which also accounts for outflow), or the gas being lost to the surrounding environment (into the CGM, as with the leaky box).

In earlier studies of dwarf galaxy properties and their relationships, luminosity was used as a proxy for mass in the luminosity-metallicity relation. This is because luminosity was easier to determine than mass. Skillman et al. (1989) measured oxygen abundances in HII regions of seven irregular dwarf galaxies. This study determined that oxygen abundances in these galaxies increased with luminosity, showing a correlation between the two properties. The mass-metallicity relation requires knowledge of the mass-to-light ratio determined by the star formation history and IMF to convert between luminosity and mass. Garnett (2002) also considered the correlation between rotation speed and metallicity and determined that at low rotations, there is some correlation with metallicity.

A critical piece of understanding the chemical evolution of a galaxy is the star formation history. The star formation history can be tracked with chemical abundances of stars of different ages. The primary way to do this using the abundance patterns is with the Metallicity Distribution Function (MDF). An MDF describes the distribution of stars with different metallicities within an area. Because stars retain metallicity from the gas that they formed out of, old stars have information about the past enrichment, and young stars have information about more recent enrichment. Characterizing the metallicities of many stars within a single galactic structure, like a relatively small dwarf galaxy, can show how the enrichment levels of the entire galaxy changed over time when analyzed alongside stellar ages.

This technique for studying the events in a galaxy's evolution are of particular interest for determining if particular structures have a common ancestor, like in the Milky Way halo. Models of GCE have been used alongside dwarf galaxy observations to determine the timescales of star formation histories for the Gaia-Sausage Enceladus system in the Milky Way halo relative to its infall time (Johnson et al. 2023). Ultra-faint dwarfs in the Local Group are the most difficult to detect due to their low luminosity, but are also the least chemically evolved and useful for insights of early galaxies, and their abundance trends indicate that few of them were affected by tidal stripping (Simon 2019).

The simplified models used in GCE are valuable tools for estimating MDFs in galaxies. Theoretical MDFs can be determined with assumptions of initial mass functions, initial metallicity, and enrichment or de-enrichment events like supernovae and gas inflows or outflows. These theoretical MDFs can be compared to the observational data to determine the best fit. This was done by Kirby et al. (2011) using Keck/DEIMOS medium-resolution spectroscopy on stars in eight satellite dwarf galaxies of the Milky Way: Sculptor, Fornax, Leo I, Sextans, Leo II, Canes Venatici I, Ursa Minor, and Draco.

The MDFs also have been seen to correlate with different morphological types of dwarf galaxies. Kirby et al. (2013) found that while average metallicity of the observed dwarf galaxies had a consistent relationship with mass, the detailed MDFs varied based on the galaxy types. The irregular dwarf galaxies showed a broad MDF that fits best with theoretical leaky box models, while the spheroidal dwarf galaxies have a more narrow and peaked MDF that can not be accurately predicted without gas accretion, like in accreting box models. These differences imply a variation in the formation and evolutionary history attributed to the different types of dwarf galaxies. Four of the most luminous spheroidal galaxies discussed in this study (Fornax, Leo I, Sculptor, and Leo II) exhibited a sharp cut-off for high-metallicity stars, which did not accurately match the simplified models presented. This likely indicates the effects of ram-pressure stripping from the host galaxy, in which the gas was rapidly removed from the satellites.

Escala et al. (2018) created models of MDFs in dwarf galaxies with simulated turbulent diffusion for ISM mixing. The turbulent diffusion models showed Fe and α-element abundance results consistent with observations of abundances in Local Group galaxies.

For the dwarf galaxies near the Milky Way, high-resolution spectroscopy can be used to conduct detailed observations of the chemical composition. An intensive study using this observational technique to examine galactic evolution of the Milky Way satellites observed five of the most massive satellites: the Large and Small Magellanic Clouds, Sagittarius, Fornax, and the Gaia Sausage/Enceladus (GSE) (Hasselquist et al. 2021). The observed abundance trends suggested a recent burst of star formation activity in both Magellanic clouds, as well as weaker periods of star formation in Sagittarius and Fornax. These patterns indicate that the systems in dense environments experience highly efficient star formation in their early stages compared to the lower star formation rates in more isolated systems.

Early-type dwarf galaxies like dwarf spheroidals and ultra-faint dwarfs typically have a lack of gas resulting in low star formation rates and a stellar population dominated by older stars. By observing these dwarf galaxies, we can draw conclusions about what happens to galaxies towards the later stages of galaxy lifetimes. Belokurov and Evans (2022) describe the early-type dwarf galaxies as "the final stages of the complete evolution of a galaxy," for they have depleted or lost their gas supply to environmental effects. Red Giant Branch stars show strong α element lines, and abundances of α elements in particular are associated with Type II SNe. Observations of Red Giant Branch stars in Early-type dwarf galaxies [Fe/H] versus [α/Fe] ratios across a range of stellar ages reveal a plateau and "knee" shape, where the α elements decrease relative to iron. This pattern reflects the onset of Type Ia SNe, which occurs later in a galaxy's chemical evolution compared to Type II SNe. The Type II SNe produce large amounts of α elements, but once Type Ia SNe begin to dominate, they dilute the ISM with iron-rich gas lacking significant α elements, causing an overall decrease in the [α/Fe] ratio (Belokurov and Evans 2022).

The low metallicity in dwarf galaxies with high star-formation rates like Blue Compact Dwarfs has intrigued observers since intense star formation would be expected to lead to enrichment of the ISM. In the simplest terms, there are three main explanations for this low metallicity: a bottom-heavy IMF, with many small stars that did not efficiently enrich the system over time; metal-poor gas was added to the system, diluting any present enrichment; or metal-rich gas was ejected from the system. These three explanations were first summarized by Matteucci and Chiosi in 1983, and each remains a plausible explanation today.

These three cases to explain low metallicity in dwarf systems with high star formation rates also echo the closed, leaky, and accreting box models of GCE. If the low metallicity can be explained exclusively by the IMF, then these dwarf galaxies can be represented with a closed-box model. While helpful for isolating the evolutionary enrichment processes, closed-box models of dwarf galaxies tend to overestimate the observed yield and cannot effectively describe all of the processes occurring in dwarf galaxies without considering other factors. The leaky box model recognizes the loss of gas within a galaxy, whether by tidal stripping or winds from stars or ejected in intense winds during a supernova. The inherently low mass of dwarf galaxies means that they have a low potential well to hold onto their gas, so they are susceptible to loss of material in this way. Robles-Valdez et al. (2017) models how the gas can be ejected out of the system, causing a high rate of metal loss without as much of an impact on the mass.

The more we uncover about GCE with observations of dwarf galaxies, it becomes clear that star formation, gas accretion, and outflows significantly shape the distribution of metallicities through each galaxy. While the simplified closed and leaky box models can provide high-level insights, more complex details of the metallicities require more complex models.

5. Small-Scale Observations to Universal Galaxy Evolution

While our conclusions about GCE to this point have primarily focused on the small-scale trends in dwarf galaxies, we can use these to interpret larger structures and they hold connections to the early universe. The main implications to note with dwarf galaxies is how they fit into the universal trends observed with larger galaxies, they look like primitive structures that can tell us about the early universe, and they serve as the building blocks for large galaxies.

Universal trends: Models of GCE incorporate various properties of galaxies including mass, metallicity, age, and luminosity. The relationships between each of these properties have been studied to draw conclusions about the evolution of galaxies and constrain subsequent models. The discovery of the universal mass-metallicity relation and how it applies to dwarf galaxies as well was crucial to confirming the connection between a galaxy's mass and its metallicity (Kirby et al. 2013). The application to galaxies over a wide range of sizes supports theories of a direct link between a galaxy's mass and its ability to retain metal abundances.

Near-Field Cosmology: Dwarf galaxies have been of particular interest for near-field cosmology studies. While cosmology has been traditionally studied at high redshifts to see what the universe looked like in its earlier stages, near-field cosmology uses nearby but ancient stellar populations to analyze the conditions of the early universe, as described by (Freeman and Bland-Hawthorn 2002). In particular, ultra-faint dwarfs have some of the oldest overall stellar population, and an increase in high-resolution spectroscopy has made these faint systems more accessible in recent years. Ultra-faint dwarfs have a very high mass-to-light ratio, dominated by dark matter. Early numbers of dwarf galaxies identified were alarming to some astronomers, who proposed what is known as the "missing satellite problem" (Klypin et al. 1999). The Dark Energy + Cold Dark Matter (ΛCDM) cosmological model suggests that halo density profiles increase towards small radii, with many more small dark matter halos than large ones. These dark matter simulations suggest there may be as many as 300 to 1000 satellites of the Milky Way that have not yet been observed (Kelley et al. 2019). This "problem" continues to persist in cosmological discussions even though many viable explanations have been proposed. One such solution is that star formation in the early universe was quenched by reionization, as seen with five of the ultra-faint Milky Way satellites that demonstrate star formation histories consistent with over 75% of the stars being formed 13.3 Gyr ago, before the epoch of reionization (Brown et al. 2014).

Heirarchical Galaxy Formation: Comparisons of the chemical abundances in the MW halo and neighboring dwarf spheroidal satellites show that for stars with the same [Fe/H] ratios, the [α/Fe] ratios are significantly lower in the satellite galaxies (Venn et al. 2004). This suggests that either the stars do not share a common origin, or were enriched by processes in the Milky Way halo after accretion. Nissen and Schuster (1997), noted a correlation between distance in the galaxy and the lower ratio of α elements, suggesting that the accreted dwarf galaxies retain their low α element abundances until they are enriched by processes in the Milky Way halo. This observation implies that the MW formed from the inside out: accreting dwarf galaxies throughout its evolution, with the most recently accreted ones in the furthest reaches of the halo. This agrees with the abundance patterns of the M31 halo and its satellites, where α enrichment patterns revealed that the inner halo was composed of larger dwarf galaxies that were accreted long ago, while the stars in the outer halo more closely resembled the properties of the remaining dwarf satellites (Kirby et al. 2020). The argument that large galaxies are formed by the accretion of smaller satellites is known as the “hierarchical structure formation scenario.” The main characteristics of the abundance patterns can also be reconstructed when modeled within the context of a ΛCDM universe, reinforcing confidence in the ΛCDM model of the universe (Font et al. 2006).

Studying dwarf galaxies gives a unique perspective to the large-scale processes in the universe with new ways to examine the history of the Milky Way and other galaxies.

6. Conclusion

In this paper, we explore the processes involved in the chemical evolution of dwarf galaxies with both theoretical models and observational data, and highlight why dwarf galaxies are central to broader evolutionary studies. They vastly outnumber larger galaxies, and their size and proximity to us make them ideal candidates for very detailed observations. Chemical abundance observations are a key component of galaxy evolution, and we see how the processes occurring in the galaxies contribute to their enrichment. The mass-metallicity relation across a range of galaxy sizes has contributed to the galactic models that we can hope to apply to the whole universe. By tracing the abundances in a variety of dwarf galaxies, we can understand the conditions in the early universe, addressing previous questions like the missing satellite problem and how the epoch of reionization affected star formation in small galaxies.

The most recently discovered ultra-faint dwarfs should continue to be investigated further, as they contain some of the oldest and most primitive stellar populations in the local group. Although their faintness provides a challenge in observing, advances in telescopes and simulations will continue to provide greater access to higher-resolution data for deeper study. A complete survey of all of the satellites of the Milky Way, and eventually all of the dwarf galaxies in the local group, would be pivotal in advancing our understanding of our neighborhood in the universe and extending our local knowledge to larger scales.

Since their initial discovery 100 years ago, a wealth of information has been uncovered about dwarf galaxies, and there is no doubt that the next century will bring even greater insights. Although they are small, we have established that dwarf galaxies and their chemical abundances play a big role in revealing information about how galaxies evolve.

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