

EXPLORING THE ORIGIN OF THE MAGELLANIC PERIPHERY WITH  
SMASH PHOTOMETRIC METALLICITIES

by

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## NOMENCLATURE

|        |                                                           |
|--------|-----------------------------------------------------------|
| LMC    | Large Magellanic Cloud                                    |
| SMC    | Small Magellanic Cloud                                    |
| MCs    | Magellanic Clouds                                         |
| MW     | Milky Way                                                 |
| MS     | Main-Sequence                                             |
| MSTO   | Main-Sequence Turnoff                                     |
| RA     | Right Ascension                                           |
| DEC    | Declination                                               |
| HR     | Hertzsprung-Russell                                       |
| CMD    | Color-Magnitude Diagram                                   |
| DECam  | Dark Energy Camera                                        |
| CTIO   | Cerro Tololo Inter-American Observatory                   |
| SMASH  | Survey of the Magellanic Stellar Periphery                |
| SDSS   | Sloane Digital Sky Survey                                 |
| LAMOST | Large Sky Area Multi-Object Fibre Spectroscopic Telescope |

## ABSTRACT

The distribution of stellar metallicities across the Large and Small Magellanic Clouds is a key ingredient to understanding the processes that have shaped their evolution, and remains a rich ground for exploration. I use data from the Survey of Magellanic Stellar History (SMASH), a photometric survey of the Magellanic Clouds that contains approximately 400 million objects in 197 fields that were obtained with DECam on the CTIO Blanco 4m telescope. SMASH covers 2400 square degrees to  $24^{th}$  magnitude in *ugriz*, encompassing a depth of 2 magnitudes below the oldest main-sequence turnoff stars. The DECam *u*-band is sensitive to metallicity for main-sequence turn-off stars, which is calibrated using SDSS and LAMOST spectroscopy in overlapping regions. This analysis is used to make accurate metallicity maps of the main bodies of the Clouds and their peripheries. Ultimately, these metallicity maps will help us trace out population gradients in the Clouds and uncover the origin of their very extended stellar peripheries.

## INTRODUCTION

The Large and Small Magellanic Clouds (LMC and SMC, respectively) are a binary system of galaxies that are currently interacting with and gravitationally bound to the Milky Way (MW) (Kontizas et al., 2001; Dufton et al., 2008). The LMC is classified as a barred Magellanic spiral and the SMC as a dwarf irregular galaxy (El Youssoufi et al., 2019). However, both galaxy types are a “dime a dozen” in our universe (Carrera et al., 2011). In fact, there are over 55 dwarf galaxies orbiting the MW alone (Bechtol et al., 2015)! This begs the question: why are they even worth studying?

First of all, the Magellanic Clouds (MCs) are the closest galaxies to the MW with significant mass (Smecker-Hane et al., 2002). Their proximity ( $\sim 50$  kpc to the LMC and  $\sim 55$  to the SMC (Choudhury et al., 2018)) makes it possible to resolve individual stars—presently, an impossible feat for galaxies beyond  $\sim 100$  Mpc—and study their chemical evolution in detail (Smecker-Hane et al., 2002). Actually, the MCs are even closer than some MW clusters (Johnson et al., 2006). Unlike the Sagittarius dwarf galaxy, the MCs are oriented on the sky such that they undergo little attenuation from foreground MW dust extinction (Grocholski et al., 2006). Additionally, the MCs are believed to be interacting with each other (Bekki & Chiba, 2005). Moreover, most agree that both galaxies will eventually merge with the MW in about 2 Gyr (Cautun et al., 2019).

The previous paragraph hits the high notes, but now I’ll insert the MCs into a cosmological perspective. Overall, a complete theory of how galaxies form and evolve in our universe does not exist. Nonetheless, interactions between galaxies

are thought to play a major role in drastically transforming galaxies’ morphological properties (Bekki & Chiba, 2005; Harris, 2007). In the prevailing model of big-bang cosmology—also known as the Lambda Cold Dark Matter ( $\Lambda$ CDM) model—smaller galaxies are thought to be the fundamental building blocks of larger galaxies like our MW (Grocholski et al., 2006). This is also known as “hierarchical” galaxy evolution (Paudel et al., 2018): smaller bodies (dwarf galaxies) form first and then merge to form larger bodies (our MW). A  $\Lambda$ CDM universe, especially one in which the halos of larger galaxies are built by the accretion/merger of smaller galaxies, seems to agree with observations (Frebel et al., 2010; Majewski et al., 2003). Additionally, cosmological simulations show that huge galaxies were most likely created by the mergers of disk-like galaxies (Paudel et al., 2018). To understand astrophysical mechanisms that direct galaxy evolution, the mergers and interactions of galaxies are essential to research more (Paudel et al., 2018).

To summarize, two of the largest MW satellite galaxies are oriented such that Earth has a great view and they are interacting with each other. The most promising theory of how galaxies form and evolve is built upon the theoretically and observationally driven theory that merger and interaction processes play a pivotal role. Therefore, the MCs are an invaluable laboratory to study the effects of dynamical interactions of the formation and evolution of smaller systems. By studying them, humans can unlock more unknowns of the processes of galaxy evolution.

Recent studies suggest that the MCs are approaching the MW for the first time and had a collision  $\sim 200$  Myr ago (Besla et al., 2007, 2010a, 2012, 2016). In order to confirm these theories, more observational studies must be conducted. One region that desperately needs to be probed further to understand the history and future of the MCs are their extended peripheries. To better understand the origin of the Magellanic periphery, one parameter that is essential is the chemical



abundances in the associated stellar populations. The chemical abundances (also known as “metallicities”) are imperative to derive, since any interaction between the SMC and LMC would have had to leave signatures on the chemical history of both galaxies (Piatti et al., 2009). The outskirts of the MCs must be more systematically investigated to provide a complete view of their interaction history (Cioni, 2009). Observing both galaxies’ morphologies, it is clear that the interactions between them left strong imprints. Mapping the true extent and metallicities of the periphery populations must be completed to derive the masses, orbits, and interaction histories of the galaxies (Besla et al., 2007, 2012).

A goal of the Survey of Magellanic Stellar History (SMASH) is to study the Magellanic periphery (Nidever et al., 2017). The purpose of this paper is to outline how I used SMASH photometric data to map out the photometric metallicity of the extended peripheries of the LMC and SMC. Choudhury et al. (2016, 2018) used photometric data to map the metallicity using red giant branch stars of the LMC to  $\sim 4.5^\circ$  and the SMC to  $\sim 2.5^\circ$ , respectively. However, the metallicities of stars located in the inner regions of the SMC and LMC have previously been studied numerous times (Dirsch et al. 2000, Cole et al. 2000, Hill et al. 2000, Larsen et al. 2000, Piatti et al. 2001, Glatt et al. 2008, Da Costa & Hatzidimitriou 1998, and Parisi et al. 2009, to name a few). The farthest past studies have mapped the metallicity in the LMC is out to about  $21^\circ$  from the LMC center (Majewski et al. 2009 and Nidever et al. 2019a). For the SMC, the farthest is only  $\sim 6^\circ$ . Using SMASH  $u - g$  and  $g - r$  colors along with a small sample of SDSS (Ahn et al., 2014) and LAMOST (Luo et al., 2015) spectroscopically determined metallicities, I mapped the metallicity in the LMC from  $2.5\text{--}25^\circ$  from the LMC center and in the SMC from  $2\text{--}10^\circ$  from the SMC center. Analyzing F and G type dwarf stars, I calculated the photometric metallicities of over 2 million stars in the peripheries of the MCs. To the best of my knowledge, the

metallicities of the extended regions have never been calculated to these radii with this large amount of stars.

This paper is organized first with three chapters of introduction. In Chapter 2, I delve deep into the history and methods of analyzing starlight. Next, in Chapter 3 I provide an in-depth explanation of the metallicity parameter and how, historically, studies have undergone calculating photometric metallicity. In Chapter 4, I explore the detailed morphologies of the MCs and discusses theories of their past and future dynamics. In Chapter 5, I describe the data that I use and that are essential to my study. In Chapter 6, I outline every step of my procedure of calculating photometric metallicities of over 2 million MC stars. Finally, I share my results in Chapter 7 and discuss their broad implications in Chapter 8.

## ANALYZING STARLIGHT

Data is absolutely essential to test all astrophysical theories. Observing light from visible objects in the universe commenced with humans' eyes and has progressed from there. With this progression has come nomenclature and definitions of esoteric fluxes and magnitudes. Scientists in the last millennium moved on from just using eyes as instruments and developed telescopes to more efficiently gather light and to magnify stellar objects. In the last century, the equipment and technology used to collect and analyze light has advanced dramatically. The most prominent features of this advancement are the enormous ground and space based photometric and spectroscopic surveys. In this section, I will cover essential astronomical definitions and parameters for my study: blackbodies, fluxes, magnitudes, colors, color-magnitude diagrams, photometry, spectroscopy, and stellar atmospheric parameters.

### Astronomical Definitions

#### Blackbodies

Light is electromagnetic radiation that exists in a large range of wavelengths and energies, from radio waves (  $10^{12}$  nm), to visible waves ( 1000 nm), and finally gamma waves (0.001 nm). A blackbody is a perfect object emitter and absorber of light: it absorbs all light energy and reradiates it in the shape of a blackbody spectrum. Any object with a temperature above absolute zero radiates light of all wavelengths in the shape of a blackbody spectrum. The spectra of three blackbodies at different temperatures is shown in Figure 2.1. In reality a true blackbody doesn't exist, but stars, planets, and other stellar objects are approximated as blackbodies. The monochromatic flux (see Section 2) of a blackbody of a specific temperature is described in Equation 2.1 with units  $\text{W}^{-2}\text{m}^{-3}\text{sr}^{-1}$ . In Equation 2.1,  $h$  is the Planck

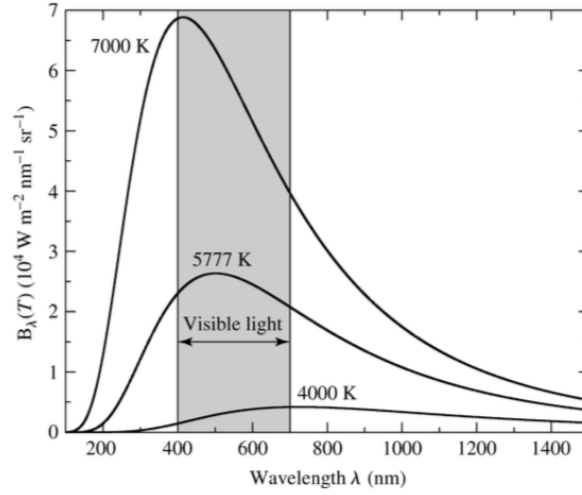


Figure 2.1: Blackbody spectrum (Carroll & Ostlie, 2006).

constant,  $c$  is the speed of light,  $k$  is Boltzmann's constant, and  $T$  is the temperature of the blackbody (Carroll & Ostlie, 2006).

$$B_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}}} \quad (2.1)$$

### Fluxes

Astronomers need to quantify the electromagnetic energy output of stellar sources. There are several different types of astronomical fluxes that need to be defined. The surface flux of a blackbody can be found by integrating Equation 2.1 and is known as the Stefan-Boltzmann Law. It is quantified in Equation 2.2, with units  $\text{W m}^{-2}$ .  $\sigma$  is the Stefan-Boltzmann constant and  $T$  is the temperature of the black body (Carroll & Ostlie, 2006).

$$F = \int_{\lambda=0}^{\infty} B_\lambda \pi d\lambda = \sigma T^4 \quad (2.2)$$

From Equation 2.2, as the temperature of an object increases,  $\lambda$  decreases and

the brightness increases (as  $F$  increases). The bolometric luminosity of a blackbody is expressed in equation 2.3. Bolometric means integrated over all wavelengths (Carroll & Ostlie, 2006).

$$L = \int_A F dA \quad (2.3)$$

For a approximately spherical object with constant  $F$ , Equation 2.3 can be condensed to Equation 2.4.

$$L = 4\pi R^2 F = 4\pi R^2 \sigma T^4 \quad (2.4)$$

As is showcased by Equations 2.3 and 2.4, the luminosity of an object is dependent on its size. It is impossible to measure with a single detector the flux of a stellar source over the entire range of wavelengths, known as the bolometric flux. Bolometric fluxes may eventually be inferred by either a combination of partial electromagnetic information and knowledge of physics of the emanating source or assembling observations from the source at all regions of electromagnetic spectrum. Instead of trying to measure fluxes over the entire electromagnetic spectrum, often fluxes at specific energies, also known as monochromatic fluxes or spectral flux densities, are used. They are fluxes that are within infinitesimally small bands, labeled as  $f_\lambda$  with units  $\text{erg s}^{-1}\text{cm}^{-2}\text{\AA}^{-1}$ . The actual energy flux harvested by an earthbound instrument is described in Equation 2.5 (Carroll & Ostlie, 2006; Binney & Merrifield, 1998),

$$f = \int_0^\infty f_\lambda^0 T_\lambda R_\lambda S_\lambda d\lambda \quad (2.5)$$

where  $f_\lambda^0$  is the incident spectral flux density on Earth's atmosphere,  $T_\lambda$  is the

transmission of the atmosphere,  $R_\lambda$  is the efficiency of the telescope and detector, and  $S_\lambda$  is the transmission function of the filter.  $f_\lambda^0$  depends on a source's luminosity and distance, as  $f \propto \frac{1}{d^2}$ . Another definition of  $f$  that displays the dependence on distance is Equation 2.6 (Binney & Merrifield, 1998).

$$f = \frac{L_\lambda}{4\pi d^2} \quad (2.6)$$

It is also important to think of the ratio of two fluxes; this relationship is shown in Equation 2.7.

$$\frac{f_1}{f_2} = \frac{d_2^2}{d_1^2} \quad (2.7)$$

### Magnitudes and Colors

Astronomical magnitudes are a unit-less measure of the spectral flux density, or brightness, of an object. They are a logarithmic brightness scale designed so that each magnitude step down is brighter by the fifth root of 100, or about 2.512. Therefore, the ratio between successive magnitudes is about 2.512. Smaller magnitudes are brighter and larger magnitudes are fainter. Magnitudes are measured in a specific bandpass, where “band” means a range of  $\lambda$  (Binney & Merrifield, 1998).

Magnitude Differences The measurement of one star's brightness to another can be compared using magnitude differences. Two stars' integrated band fluxes  $f_1$  and  $f_2$  have a magnitude difference given by Equation 2.8. From this equation, 5 steps in magnitude is 100x ratio in brightness.

$$\frac{f_1}{f_2} = 2.512^{m_2 - m_1} \quad (2.8)$$

Taking the log of Equation 2.8, two more important equations comparing stars' brightness can be derived: Equations 2.9 and 2.10.

$$\log_{10} \left( \frac{f_1}{f_2} \right) = (m_2 - m_1) \log_{10} 2.512 \quad (2.9)$$

$$m_1 - m_2 = -2.5 \log_{10} \left( \frac{f_1}{f_2} \right) \quad (2.10)$$

These equations are comparing stars on a relative scale (Binney & Merrifield, 1998).

Apparent Magnitude The apparent magnitude, denoted with a lowercase  $m_\star$ , within a bandpass of  $\lambda$  is related to the observed monochromatic flux  $f_\star$  by Equation 2.11.

$$m_\star = -2.5 \log_{10} f_\star + c_\star \quad (2.11)$$

Note that because of the observed monochromatic flux definition in Equation 2.6, the apparent magnitude depends on luminosity and distance. The  $c_\star$  in Equation 2.11 is called the absolute zero-point constant; it defines the magnitude system relative to some comparison. There are two main systems that are used: the Vega System and the AB system (Binney & Merrifield, 1998).

Vega System In this system, the star Vega, also known as  $\alpha$  Lyrae, is chosen to have zero magnitude in all bandpasses. Manipulating equation 2.10, the method through which the Vega System is defined is displayed in Equation 2.12.

$$2.5 \log_{10} \left( \frac{f_\star}{f_{vega}} \right) = 0 - m_\star \quad (2.12)$$

Manipulating Equation 2.12 further, Equation 2.13 is derived.

$$m_{\star} = -2.5 \log_{10}(f_{\star}) + 2.5 \log_{10}(f_{vega}) \quad (2.13)$$

Comparing Equation 2.13 with Equation 2.11, the constant within the Vega System is defined as  $const. = 2.5 \log_{10}(f_{vega})$ . Using the information in this section, there are notable advantages and disadvantages to the Vega System. The advantage is that any measure of brightness for  $f_{\star}$  and  $f_{vega}$  may be used; therefore, the Vega System can be easily defined for different telescopes, different detectors, and different filters. To use the Vega System, the magnitude the star can be found by using the same equipment to measure the star Vega. A disadvantage of this system is that  $f_{vega}$  will be different for each bandpass (Binney & Merrifield, 1998). An example of the extensive calibrations the Vega system requires is shown in Bessell et al. (1998).

AB System A different magnitude system is the AB system, which is not centered on the star Vega; instead, it adopts the constant in Equation 2.11 to be identical for all bandpasses. The AB system was introduced in Oke (1974) and is defined using Equation 2.14.

$$m_{AB} = -2.5 \log_{10}(f_{AB}) - 48.6 \quad (2.14)$$

The AB system was calibrated using the spectral energy distribution of the star Vega as measured by Oke & Schild (1970). It is simpler than the Vega system.

Absolute Magnitude Referencing Equation 2.7, it is clear the relationship between the ratio of fluxes and distances may be exploited to use flux measurements to derive the distance to a star. Using the ratio, Equation 2.10 may be set equal to new terms as shown in equation 2.15, where  $m_1$  and  $m_2$  are two different magnitudes



for the same star (Binney & Merrifield, 1998).

$$m_1 - m_2 = -2.5 \log_{10} \left( \frac{f_1}{f_2} \right) = -2.5 \log_{10} \left( \frac{d_2^2}{d_1^2} \right) = -5 \log_{10} \left( \frac{d_2}{d_1} \right) \quad (2.15)$$

It is often convenient to compare the brightness of stars positioned at the same distance. The absolute magnitude, written with a capital  $M$ , is defined as the apparent magnitude if the star is 10 parsecs away. The definition of absolute magnitude stems from the fact that by finding the  $M$  value, it is possible to determine the distance of the star by manipulating Equation 2.15. The result is Equation 2.16; the term  $m - M$  is referred to as the “distance modulus” (Binney & Merrifield, 1998).

$$m - M = -5 \log_{10} \left( \frac{10}{d} \right) = 5 \log_d - 5 \quad (2.16)$$

Colors Astronomical colors are defined using numerical color indices. If the monochromatic flux of a star is measured in two passbands, A and B, then their magnitudes are defined in Equations 2.17 and 2.18 (Binney & Merrifield, 1998).

$$m_A = -2.5 \log_{10} f_A + c_A \quad (2.17)$$

$$m_B = -2.5 \log_{10} f_B + c_B \quad (2.18)$$

The color index is defined as the difference in magnitude (apparent or absolute) between the two passbands. The definition is Equation 2.19; as evidenced by this definition, the color index using either absolute magnitude or apparent magnitude is equivalent. Additionally, color indexes are generally written using the letters of the

passbands being used, so  $A - B$  in Equation 2.19 (Binney & Merrifield, 1998).

$$A - B = m_A - m_B = M_A - M_B = -2.5 \log_{10} \left( \frac{f_A}{f_B} \right) + (c_A - c_B) \quad (2.19)$$

For the Vega system, the term  $c_A - c_B$  is defined so that  $A - B = 0$ . Alternatively, for the AB system,  $c_A - c_B$  is the same constant for all filters. Due to the logarithmic nature of magnitudes, color indexes are flux ratios. They are convenient because they are much easier to obtain than the entire spectrum of an object. Another important feature of color indexes is that usually, they are written so that the shorter wavelength passband is first. Using this convention, smaller numbers mean “bluer” and larger numbers mean “redder” (Binney & Merrifield, 1998). The bluer color indexes also correlate to hotter stars, whereas the redder color indexes correspond to cooler stars. Depending upon the region of the electromagnetic spectrum color indexes reside, properties like temperature, metallicity, and optical color can be gleaned from the simple color index.

Another way to obtain information from colors to plot two colors together, known as a color-color diagram. Ordinary stars fall onto a locus in color-color space. This locus runs from the lower left to the upper-right in a  $u - g$  versus  $g - r$  diagram. Hotter stars reside at the left-hand side of this plot, whereas cooler stars are found at the right.

### Stellar Spectra and the HR Diagram

Although stars may be approximated as blackbodies as mentioned in Section 2, the profile of a real star’s light spectrum is more complicated than an ideal blackbody spectrum. Real stellar spectra show a clear blackbody shape but also contain

absorption and emission lines, caused by scattering processes and atomic/molecular transitions. Spectral classification has been historically used to classify stars; although it doesn't make as much sense presently, astronomers still use this classification scheme to discuss different types of stars. Spectral classification can also be obtained by looking at Hertsprung-Russel (HR) diagram, along with many other properties of stars. In this section, I will discuss the spectral classification scheme and the HR Diagram and it's observational counterpart: the Color-Magnitude Diagram (CMD).

### Spectral Classification

#### **SPECTRAL CLASSIFICATION**

**Table 11.1** The full range of spectral classes in current use.

|             |             |           |           |           |           |           |
|-------------|-------------|-----------|-----------|-----------|-----------|-----------|
| <b>O4</b>   | <b>B0</b>   | <b>A0</b> | <b>F0</b> | <b>G0</b> | <b>K0</b> | <b>M0</b> |
| <b>O5</b>   | <b>B0.5</b> | <b>A2</b> | <b>F2</b> | <b>G2</b> | <b>K2</b> | <b>M1</b> |
| <b>O6</b>   | <b>B1</b>   | <b>A3</b> | <b>F3</b> | <b>G5</b> | <b>K3</b> | <b>M2</b> |
| <b>O7</b>   | <b>B2</b>   | <b>A5</b> | <b>F5</b> | <b>G8</b> | <b>K4</b> | <b>M3</b> |
| <b>O8</b>   | <b>B3</b>   | <b>A7</b> | <b>F7</b> |           | <b>K5</b> | <b>M4</b> |
| <b>O9</b>   | <b>B5</b>   |           | <b>F8</b> |           |           | <b>M7</b> |
| <b>O9.5</b> | <b>B7</b>   |           | <b>F9</b> |           |           | <b>M8</b> |
|             | <b>B8</b>   |           |           |           |           | <b>M9</b> |
|             | <b>B9.5</b> |           |           |           |           |           |

Figure 2.2: The MK system taken from Binney & Merrifield (1998).

The spectral classification scheme is also known as the “MK system.” It is an empirical classification done by putting different stellar spectra into similar groupings. Figure 2.2 shows the range of spectral class and subtypes. The left types are known as “early types” of stars and are bluer and hotter, whereas the right types are known as “late types” and are redder and cooler. The letter denotes subclasses within each type. This nomenclature is based on antiquated theories of stellar evolution (Binney & Merrifield, 1998).

## HR Diagram

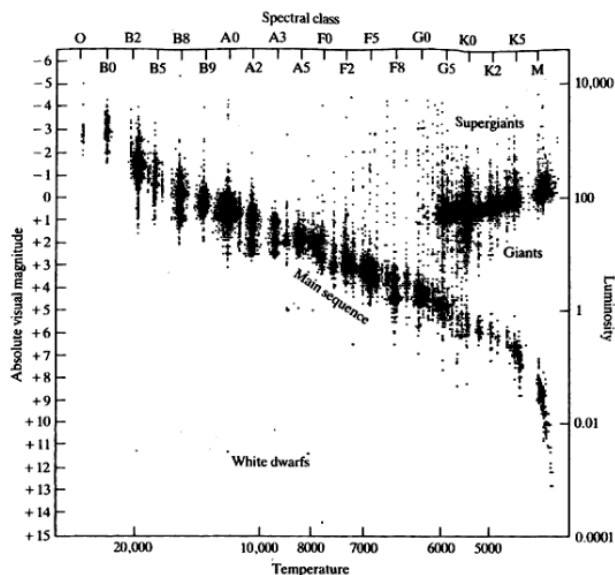


Figure 2.3: One of the original HR diagrams taken from Struve (1950). Most stars reside in the region of space known as the “main-sequence”.

The first versions of the HR Diagram (named after the two astronomers, Hertzsprung and Russell, who independently discovered it) are plots of spectral type versus luminosity. Figure 2.3 (Struve, 1950) shows an HR diagram. Most stars fall into the long, thin region that runs from the top left to the bottom right, known as the “main-sequence”. It is now known that stars on the main-sequence are in the stage of their lives where they are converting hydrogen into helium in their cores through nuclear fusion. As they evolve, stars move into the supergiant and giant branches and undergo complex stages of restructuring and different nuclear fusion processes. Eventually, many stars become small, leftover cores, known as white dwarfs (Binney & Merrifield, 1998). The history of a star’s life can be effectively described by the path it follows on an HR diagram. The temperature and magnitude scales were added after the first creation of this plot. HR diagrams and CMDs are arranged such that

temperature decreases along the x-axis and magnitude increases along the y-axis.

### Color–Magnitude Diagrams

CMDs are the observational counterpart to the HR diagram. In a CMD, magnitude is plotted on the y-axis and color is plotted on the x-axis. Therefore, the magnitude is plotted so that brightness is increasing up along the axis and the color is plotted so that temperature is decreasing to the right. Figure 2.4 shows four different stellar field CMDs that live in the Magellanic Clouds (see Chapter 5). The top left shows a CMD with many groups present: young main-sequence (young MS), older main-sequence (MS), subgiant branch (SG), red clump (RC), red giant branch (RGB), and stars that exist in the MW (MW foreground). The other three CMDs show that depending upon the star population being observed, there are many different types of objects that exist there. The top left CMD shows a younger stellar population, indicated by the fact that there is a dense main sequences. The bottom left CMD shows the contaminants: stars from the Monoceros stream (part of the MW) and background galaxies. Finally, the bottom right CMD shows almost no discernible main-sequence and lots of contamination from MW stars (Nidever et al., 2017).

### Observational Astronomy Data

The development of a deep understanding of the evolution of stars and the production of elements via astrophysical processes in stars and supernova explosions has been a monumental triumph of 20<sup>th</sup> century astrophysicists (Bessell, 2005). Essential to this research is observational data gathered in the form of photometric and spectroscopic data of objects in space. In this section, I will describe two of the main types of light data that I use in my study: photometry and spectroscopy.

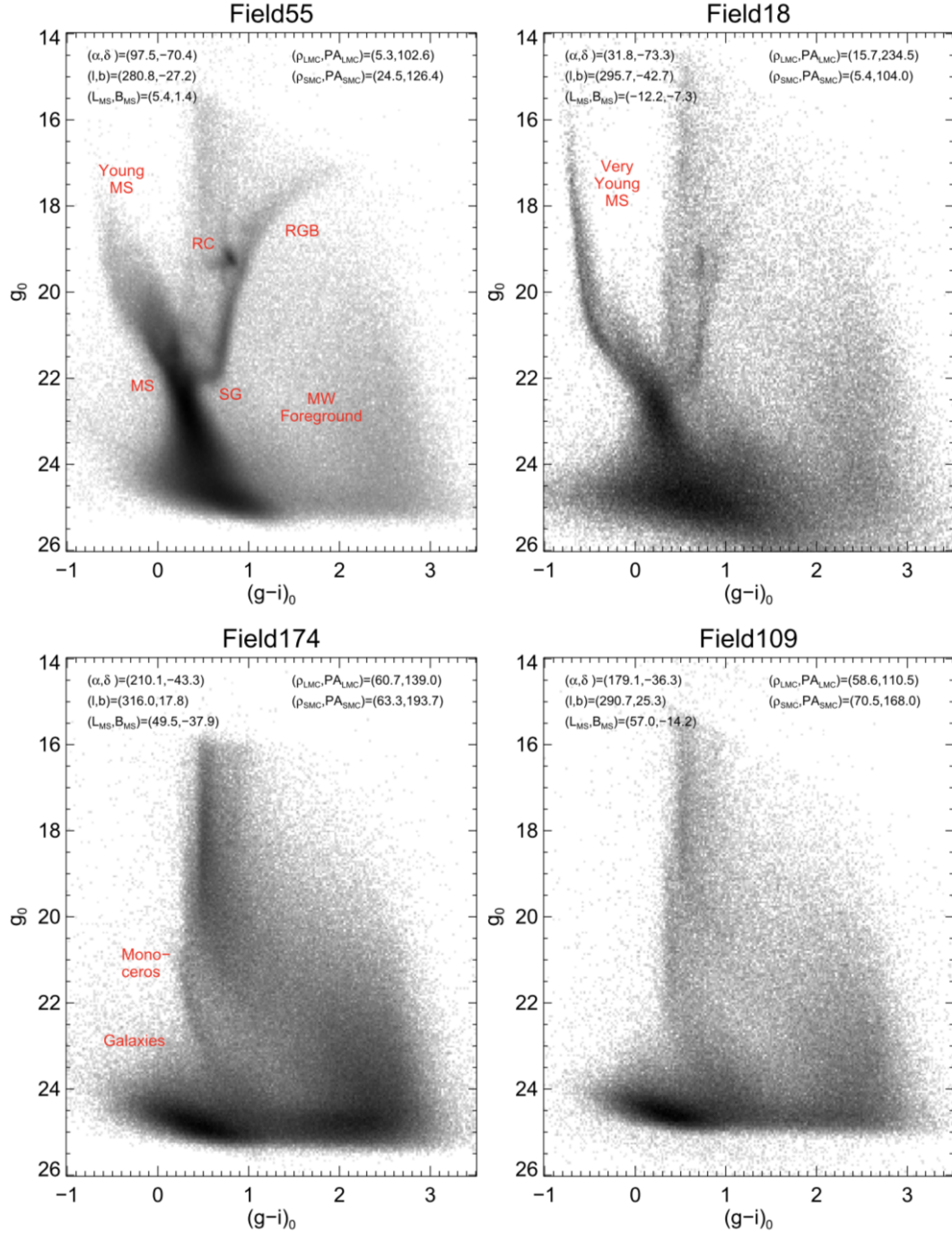


Figure 2.4: Four different color magnitude diagrams of different stellar populations on the Magellanic Clouds taken from Nidever et al. (2017). On each panel, there are three different coordinates in the top left: equatorial, galactic, and Magellanic Stream coordinates. On the top left, there are position angles from either LMC or SMC center. The red text indicates different stellar objects.

## Photometry

Commonly in astronomy, filters are used to measure light across a small section, or passband, of the electromagnetic spectrum. Measuring light from stellar sources in this manner is known as astronomical photometry, which translates to “light measurement.” Photometry is essentially extremely low-resolution spectroscopy. Photometry is taken between roughly 200–20,000 nm in the electromagnetic spectrum; therefore, many ground-based telescopes gather this type of data, since Earth’s atmosphere doesn’t attenuate it too drastically (Milone & Sterken, 2011). The technology of gathering this data progressed in the last century from photographic plates to photomultiplier tubes. Since the 1980s, Charged Coupled Devices (CCDs) became the dominant detectors at most observatories (Milone & Sterken, 2011). Another helpful way of describing photometry is the measurement of all fluctuation from ideal blackbody radiation.

Astronomers gather this type of data and then store it in the form of magnitudes and colors. Much work is done to convert luminosities to integrated magnitudes and colors, and, eventually, to transform observed magnitude to bolometric magnitudes, effective temperature (defined in Equation 2.4), mass, ages, and compositions of stars. These processes comprise of relations found from studying stars with established luminosities and physical properties along with theoretical atmospheric models (Bessell, 2005).

One detriment of photometry is the great amount of different telescopes, instruments, filters, and effects of absorption by Earth’s atmosphere at varying locations on Earth. Due to these differences, astronomers must develop photometric systems, known as “standard systems”, to place magnitudes on a standard flux scale. There are elemental posits on which astronomical photometry exists upon, shown as Equations 2.20 and 2.21, taken from Bessell (2005). If  $N_B$  is the total number of

electrons detected from a source in  $t$  seconds through a filter  $B$ , the measured  $B_i$  magnitude is described in equation 2.20. Further, for two stars with fluxes  $N_1$  and  $N_2$ , the magnitude difference is described in Equation 2.21.

$$B_i = \text{const} - 2.5 \log_{10} \left( \frac{N_B}{t} \right) \quad (2.20)$$

$$B_1 - B_2 = \text{const} - 2.5 \log_{10} \left( \frac{N_1}{N_2} \right) \quad (2.21)$$

A standard photometric system is a set of magnitudes measured in wavelength bands that are pretty evenly distributed around the sky, with magnitudes defined in the form of Equations 2.20 and 2.21. Some standard photometric systems are described in the Chapter 5. Different photometric systems are separated into three categories: broadband ( $\Delta \lambda < 1000 \text{ \AA}$ ), intermediate band: ( $70 < \Delta \lambda < 400 \text{ \AA}$ ), and narrow band: ( $\Delta \lambda < 70 \text{ \AA}$ ) (Bessell et al., 1998).

Synthetic photometry is also an important step in defining a standard system; it is derived by convolving model stellar atmospheres to find magnitudes and colors associated with the photometric passbands. To do this, it is essential that there be a large number of stars to create synthetic photometry (Bessell, 2005).

The creation of enormous photometric surveys has revolutionized modern astronomy. There are now many ground-based telescopes that are solely dedicated to taking and storing large amounts of data. Currently, it is the beginning of an age where we can look up magnitudes and colors of most objects instead of having to take new measurements. There are a 100 billion stars in our MW and we now have photometry of a few billion of them (SDSS: Ahn et al. 2014, DESI-legacy: Dey et al. 2019, DES: Abbott et al. 2018, GAIA: Gaia Collaboration et al. 2016, and SMASH: Nidever et al. 2017).



## Spectroscopy

One of the most groundbreaking discoveries of 20th century astronomy is that not all stars have the same chemical makeup. Astronomers realized this after passing starlight through spectrographs and analyzing the resulting spectra. By analyzing absorption lines in stars' spectra, elemental abundances can be calculated. These observed elemental abundances in stars are acknowledged to apply to stars outer atmospheres because this is the region of the star where the absorption lines are formed. To do this analysis, astronomers gather spectroscopic data.

As I mentioned in Section 2, photometry is essentially extremely low resolution spectroscopy. Spectroscopic is more powerful than photometry, but harder to obtain. It is also limited to brighter stars. Nevertheless, we are now obtaining on the order of 100,000–1 million spectra (APOGEE: Abolfathi et al. 2018, GALAH: Buder et al. 2018, RAVE: Steinmetz et al. 2006, LAMOST: Luo et al. 2015, and SDSS: Ahn et al. 2014) and in the near future 10 million (DESI: Dey et al. 2019).

Through detailed analysis of high-resolution spectroscopy, three fundamental stellar atmospheric properties can be derived: effective temperature, surface gravity, and the chemical composition of a star. Effective temperature ( $T_{\text{eff}}$ ) is defined using equation 2.4 and is determined by the strengths of various lines in stellar spectra. Surface gravity ( $\log g$ ) is defined by equation 2.22 and is determined by the wings of the Hydrogen lines and comparing Fe I to Fe II absorption lines.  $\log g$  can also be determined if the distance or parallax is also known. Finally, the chemical composition of a star can be found through analysis of the absorption lines in a star's spectrum. Chemical composition is generally quantified using  $[\text{Fe}/\text{H}]$ , also known as “metallicity,” explained in detail in Chapter 3.

$$g = \frac{GM}{R^2} \tag{2.22}$$

Now, spectra can be analyzed through fast automated procedures on computers, as described in Chapter 5. As I mentioned above, with the staggering amount of photometric data that exists now, the number of spectra is growing too. Used together, astronomers are able to effectively measuring an enormous amount of the sky and astronomical objects.

## METALLICITY

Definition

In astronomy, “metals” refer to all elements heavier than hydrogen and helium. This unusual nomenclature can partially be attributed to the fact that hydrogen and helium are by far the most abundant elements in the universe: 92% of the universe is hydrogen, 7% is helium, and the rest is the remaining heavier elements. Heavier elements, metals, are seen in trace amounts in the atmospheric layers of stars. The abundance of one element with respect to another is generally quantified as

$$[A/B] = \log_{10} \left( \frac{N_A}{N_B} \right)_{\star} - \log_{10} \left( \frac{N_A}{N_B} \right)_{\odot} \quad (3.1)$$

where  $N_X$  refers to the number of atoms per unit volume of species  $X$ . Due to the large amount of iron absorption lines in the sun's spectrum, Fe is commonly used to compare the metal-content, or metallicity, of one star with another, written as  $[\text{Fe}/\text{H}]$  (Beers & Christlieb, 2005).

In order to convey the importance of analyzing metallicity of stars, the following is the general picture of galactic chemical evolution (in reality the processes are more complex). These processes depend on the star formation rate in the galaxy. Metallicities of stars provide knowledge about the number of stars of varying types that have formed and evolved throughout the duration of a galaxy's existence. When a galaxy is initially born, there is a large amount of interstellar gas that is free of heavy elements. With the progression of time, stars form from the gas clouds and eventually massive stars return hydrogen, helium, and heavy elements to the interstellar medium, through processes of stellar winds and explosions when stars die (supernova). The supply of gas is steadily consumed as more stars form, and the lingering gas becomes

more enriched with heavy elements. Older stars are seen to be metal-poor, while younger stars are observed to be metal-rich. However, this is a simplistic take and not always true: for example, the center of the MW and the bulge have old, metal-rich stars. Regardless, calculating metallicities of the constituent stars of a galaxy will help us understand its evolution (Binney & Merrifield, 1998).

The most accurate methods of deriving metallicity are found by analyzing high-resolution spectroscopy. The history of deriving these methods is involved and impressive. Scientists working in laboratories on Earth have spent years establishing the wavelengths at which hot gases of each chemical element have absorption lines. Books and databases have been created that list the absorption lines of the elements that exist at different temperatures. Using these resources, astronomers compare the spectra recorded from distant stars with that of chemical elements on Earth. They calculate the abundances of the atoms from strengths of the absorption lines and with knowledge about the efficiency of absorption of each particular element. Along with these laboratory experiments, the definitive wavelengths of particular atomic transitions are known from complex quantum mechanics calculations and from analyzing stellar spectra. For instance, helium was only discovered after analyzing the spectrum of the Sun (Binney & Merrifield, 1998).

### Photometric Metallicities

There are more stellar spectra available now than ever before. Despite this, photometric data are easier and cheaper to obtain. The number of stars detected in imaging surveys is much greater. Photometric surveys afford superior sky area and magnitude depth coverage compared to spectroscopic surveys. By relating photometric data to spectroscopic data, astronomers have been able to attain a strong relationship between photometric colors and metal abundance. Here, I will

briefly outline this conquest.

It was first brought forth in the 1950s that a deficiency of metals in the outer atmosphere of a star has an effect on the flux measured in the blue (ultraviolet) passbands of light (Schwarzschild et al., 1955). This region is particularly sensitive to this effect because of the thousands of metal lines that exist in this region. Schwarzschild et al. (1955) noticed that subdwarfs have absorption lines much weaker than that of a dwarf star. These absorption lines are extremely close together and crowded in the blue region of the electromagnetic spectrum. Therefore, photospheric differences cause a subdwarf to appear bluer than a dwarf of the same effective temperature. He concluded that subdwarfs have a huge depletion of heavy elements compared to dwarf stars. The importance of their work to my study is that stars that are heavy-metal deficient show an excess flux in the blue regions of the electromagnetic spectrum because they do not have as many and as deep of absorption lines as metal-rich stars.

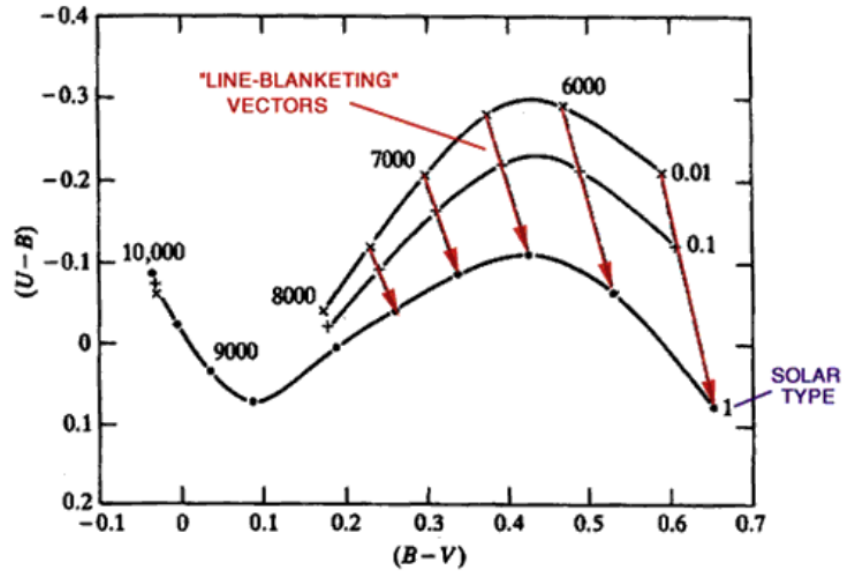


Figure 3.1: U-B versus B-V color-color diagram showing line-blanketing effects, reprinted from Wildey et al. (1962a).

To expand on Schwarzschild et al. (1955)’s finding, I will again emphasize the main points and how they fit into my study. Since most metal lines are in the ultraviolet region of the electromagnetic spectrum, a star with more lines (due to being of a later spectral type or due to a higher metal abundance) will have more absorption lines in this region and therefore will have less overall flux in this region. This is also known as “line-blanketing:” when astronomical metals absorb a fraction of a star’s energy and then re-emit it at redder wavelengths. In the Johnson photometric system (see Chapter 5), the U-B color is sensitive to the temperature and metallicity of a star. To break this degeneracy, astronomers began to make color-color diagrams in the form of B-V versus U-B. B-V organizes the stars according to temperature and U-B organizes stars by metallicity. Figure 3.1 is one such color-color diagram showing the effects of line-blanketing. As the labels on the figure show, temperature of the stars is ordered so that it decreases to the right of the x-axis. Vertically, metallicity decreases going up the y-axis. The loci of three different metal-abundances along a range of temperatures is shown in the figure. The bottom line represents Solar type, the middle represents 0.1 solar type, and the top represents 0.001 solar type. Therefore, as metallicity decreases, the stars are bluer in the color-color space than metal-rich stars at the same temperature. As the solar type line in Figure 3.1 demonstrates, stars with more metals get redder in B-V but even redder in U-B. Astronomers define the metal-poor stars in Figure 3.1 as having an “ultraviolet excess,” because they have more flux in this region than metal-rich stars in this region due to their abundance of absorption lines.

Astronomers following Schwarzschild et al. (1955) exploited his discovery by demonstrating evidence of a strong correlation existing for F and G dwarf stars between metal-abundance ( $[\text{Fe}/\text{H}]$ ) and the so-called ultraviolet excess. To quantify ultraviolet excess, they generally used the Hyades star cluster to represent solar

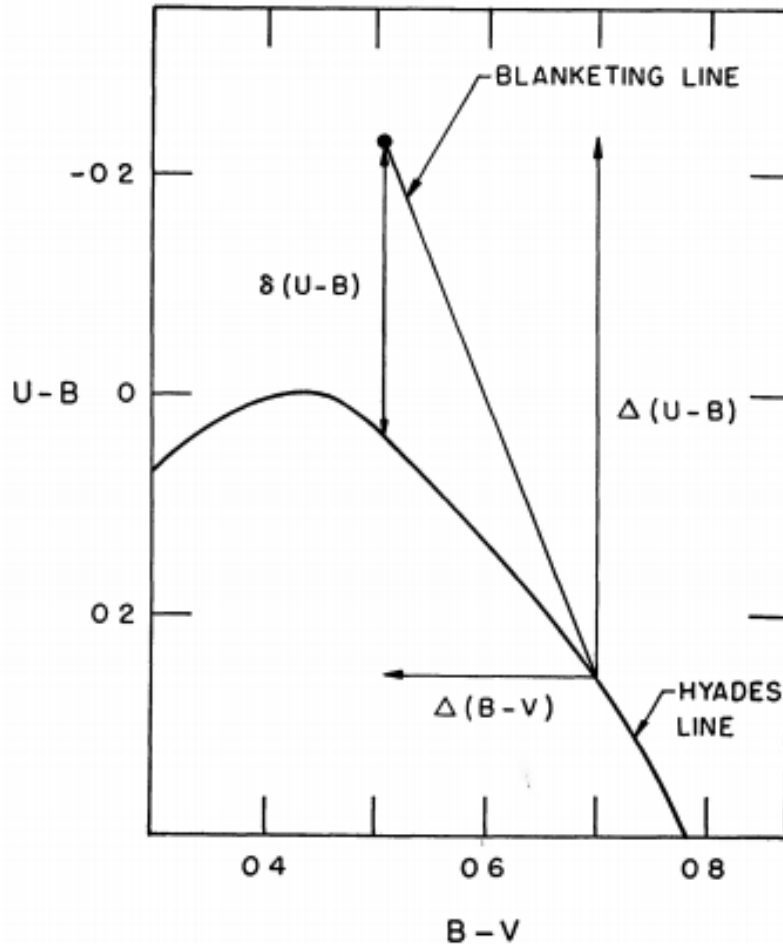


Figure 3.2: The definition of ultraviolet excess ( $\delta(U-B)$ ) and line-blanketing vectors  $\Delta(B-V)$  and  $\Delta(U-B)$ , reprinted from Wildey et al. (1962b).

metallicity. With this adaption, ultraviolet excess is written as  $UVX = \delta(U-B)$ . Therefore, UVX is the difference of a star's U-B color compared to a star in the Hyades of the same U-B color. Figure 3.2 shows how UVX is defined.

After studying the magnitudes, colors, and metal abundances of stars in globular clusters, Arp (1959) wrote that derived ultraviolet excess is a pure parameter of metal abundance and expanded that chemical compositions of stars could be calculated all over the MW and into neighboring galaxies. In the subsequent two decades, astronomers would do just that.

After analyzing data of 23 early type G and late type F stars, Wallerstein & Carlson (1960) concluded that for main sequence stars that have a color in the region of  $B-V = 0.45$  and  $0.65$ , metal abundances can be inferred from three-color photometry about as well as by spectrophotometric analysis. They showcased this statement through Figure 3.3.

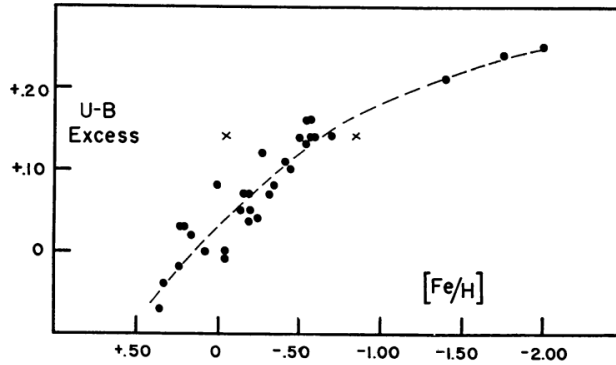


Figure 3.3: Correlation between ultraviolet excess and  $[Fe/H]$  found by Wallerstein & Carlson (1960).

Wallerstein (1962) analyzed 21 field stars of very nearly solar type and 13 other G dwarf stars. Through this study, they confirmed and strengthened the relationship between ultraviolet excess and  $[Fe/H]$ . They wrote that ultraviolet excess is an excellent measure of a stars metal abundance.



Carney (1979) analyzed the metal abundances of 101 F and G dwarf stars. Using data of these stars, he reexamined the relationship between ultraviolet excess and metal abundance. He decided, with use of Figure 3.4 reproduced here, that the relationship provides a good method of estimating dwarf metallicities from UBV colors. The relationship, he wrote, is a good calibrator of globular cluster metallicities.

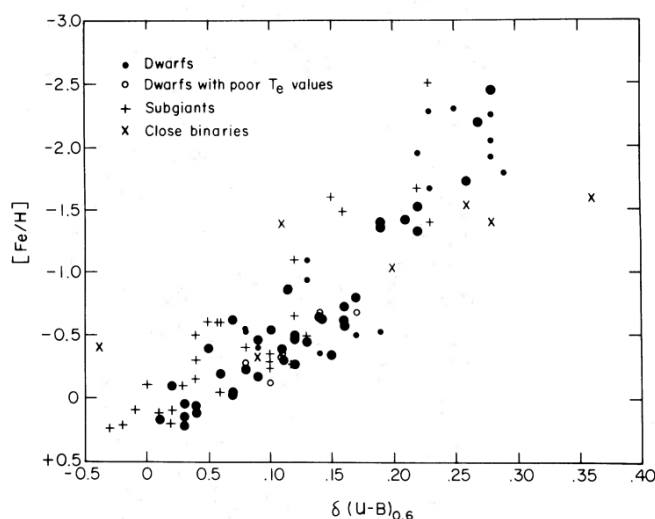


Figure 3.4: Correlation between ultraviolet excess and  $[Fe/H]$  found by Carney (1979).

Much later, Ivezić et al. (2008) exploited the advent of large surveys of stars and estimated the photometric metallicity of 2 million F and G dwarf stars in the MW. They first crossmatched spectroscopic and photometric SDSS data. This crossmatched data of  $\sim 60,000$  F and G stars made up their calibration sample, all of which included effective temperature,  $\log(g)$ , and metallicity calculations derived from SDSS spectra, as well as  $u - g$  and  $g - r$  SDSS photometric colors. Using this calibration sample, they created a more sophisticated method for calculating photometric metallicities. First, using their calibration sample, they created a median metallicity as a function of two SDSS colors diagram, Figure 3.5. This figure is similar to Figures 3.1 and 3.2, the main difference being the use of a different photometric

system: SDSS. For the SDSS system,  $u - g$  is sensitive to metallicity and  $g - r$  is sensitive to temperature. Using Figure 3.5, the authors were able to calculate the metallicity of 2 million F and G MW stars for which they only had SDSS photometric data by reading off the metallicity value for a star's given  $u - g$  and  $g - r$  colors.

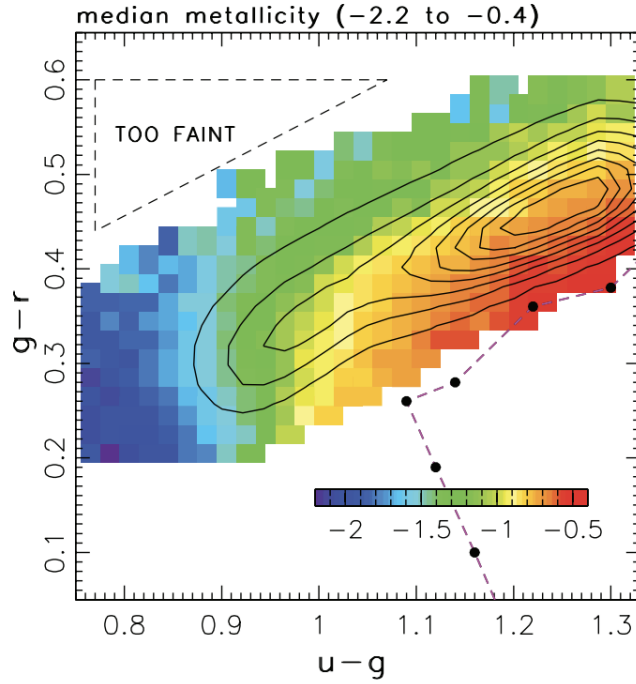


Figure 3.5: Median metallicity as a function of two SDSS colors reprinted from Ivezić et al. (2008).

In my study, I follow the methods of Ivezić et al. (2008) closely. I use a slightly different photometric system, DECam system, to the SDSS system that Ivezić et al. (2008) uses. Therefore, I recalibrate the Ivezić et al. (2008) method by remaking Figure 3.5 with SMASH (Nidever et al., 2017), SDSS (Ahn et al., 2014), and LAMOST (Luo et al., 2015) data.

## LARGE AND SMALL MAGELLANIC CLOUDS

Galaxies exist in many shapes and sizes. Humans are drawn to the marvelous optical light they emit in structural forms of spirals, ellipticals, and irregulars. A galaxy's morphological properties carry information of their formation and evolution. The MCs are two of the largest and closest Galactic neighbors. Thankfully, they are oriented in such a way so that humans can observe them on Earth. Now that I have introduced the relevant physical parameters, it is time to describe the LMC and SMC in detail. In this Chapter, I will go through detailed properties of the structure, past and future dynamics, and previous studies on metallicity.

### Structure

In broad terms, the MCs are usually classified as dwarf galaxies. Bullock & Boylan-Kolchin (2017) describe dwarf galaxies as galaxies with stellar masses of  $M_\star \leq 10^9 M_\odot$  divided into three subclasses: bright dwarfs ( $M_\star \approx 10^{7-9} M_\odot$ ); classical dwarfs ( $M_\star \approx 10^{5-7} M_\odot$ ); and ultra-faint dwarfs ( $M_\star \approx 10^{2-5} M_\odot$ ). The LMC actually has a stellar mass that exceeds the upper limit of the bright dwarf category (as defined by Bullock & Boylan-Kolchin), but most authors still classify the LMC as a dwarf galaxy on the largest end of the spectrum. Another classification of dwarf galaxies is between dwarf spheroidals (dSphs) and dwarf irregulars (dIrrs). dIrr denote dwarfs that contain gas and have current star formation, while dSphs are dwarfs with little to no gas and no current star formation. Using these definitions, both the LMC and SMC are bright dwarfs type dIrr. In this section, I will delve deep in the morphology, extent, mass, distance, and components of the MCs.

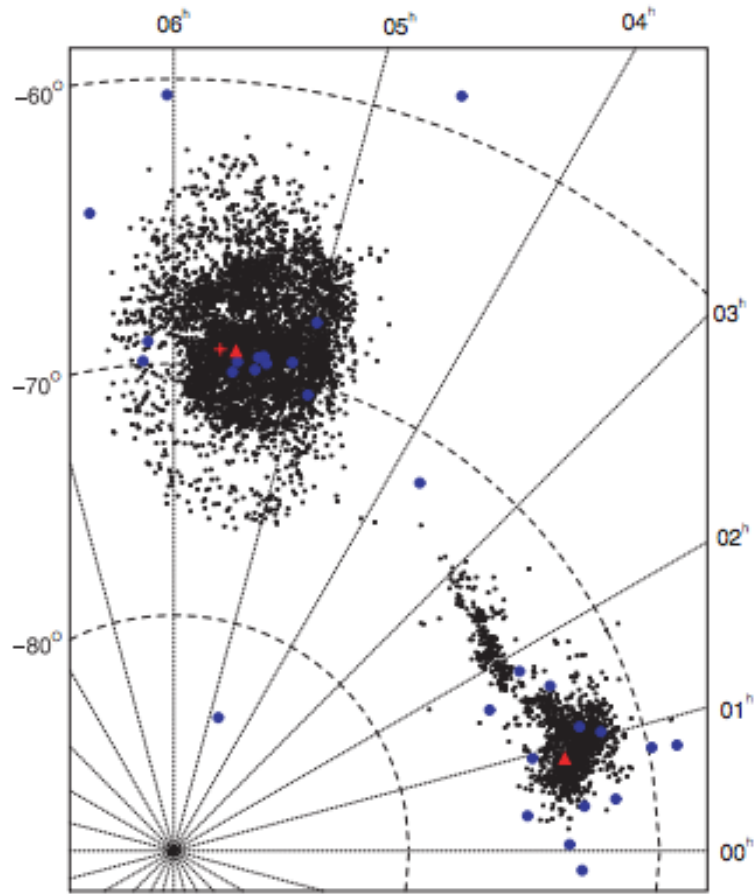


Figure 4.1: Angular positions of all 9305 objects in the Bica et al. (2008) catalog. The red triangles are Bica et al.'s calculated central positions of each galaxy. Star clusters with ages older than 4Gyr are shown as blue circles while the red cross indicates 30 Dor.

## Morphology

The MCs are dIrr galaxies; in particular, they are gas-rich, their shape is amorphous, and in general they contain metal-poor stars, compared to the MW. Bica et al. (2008) cataloged 1,445 emission nebulae, 3,740 star clusters, 3,326 associations and 794 H I shells and supershells in the LMC, SMC, and Magellanic Bridge—described in Section 4. Figure 4.1 shows the angular distribution of all the objects. Figure 4.2 shows optical images of the MCs compiled from SMASH data (Nidever et al., 2017).

From the Sun, the orientation of the LMC is face-on and its inclination well determined (Parisi et al., 2009). It is a late-type spiral with an abundance of gas and active star formation. Along the line-of-sight, the LMC is approximately  $\sim 2$  kpc thick (Cioni, 2009). As well as being a bright dIrr galaxy, the LMC is also the prototypical barred Magellanic spiral (El Youssoufi et al., 2019). Barred Magellanic spirals are found frequently in the universe (Carrera et al., 2011). It has one spiral arm and spiral features, as well as a lopsided bar, no bulge at its center, and a region of active star-formation at one end of the bar (El Youssoufi et al., 2019). The LMC has an disc inclined by roughly  $30^\circ$  that is thick and stretched; the bar’s center is not aligned with the disc (Choi et al., 2018). Choi et al. (2018) found a significant warp in the LMC’s southeast region spreading to 2.5 kpc in the direction of the midplane that extends out to 4 kpc in the direction of the SMC, at a distance of 6–7 kpc from the center of the LMC. The LMC looks elliptical at longer radii. The LMC’s inner and outer regions are located at different inclination angles, with the eastern part closer to Sun. The northern periphery contains a stellar arc and spiral arms, but there is no southern equivalent (El Youssoufi et al., 2019). In terms of stellar populations, older stars are seen to trace an elliptical structure, whereas young stars dominate the apparent LMC morphology (Cioni, 2009). Younger stars are concentrated in the

spiral arms and tidally disturbed sections, whereas older stars that make up the bulk of the stellar populations are more evenly placed (El Youssoufi et al., 2019). Like most galaxies, the LMC is surrounded and permeated by a dark matter matter halo that emits no radiation and interacts via only the gravitational force. The estimated mass of the dark matter halo is  $\sim 10^{11} M_{\odot}$  (Garavito-Camargo et al., 2019), the total stellar mass is estimated to be  $3.2 \times 10^{10} M_{\odot}$  (van der Marel et al., 2009), and the total mass of gas in the LMC is  $\sim 5.3 \times 10^9 M_{\odot}$  (Alves & Nelson, 2000).

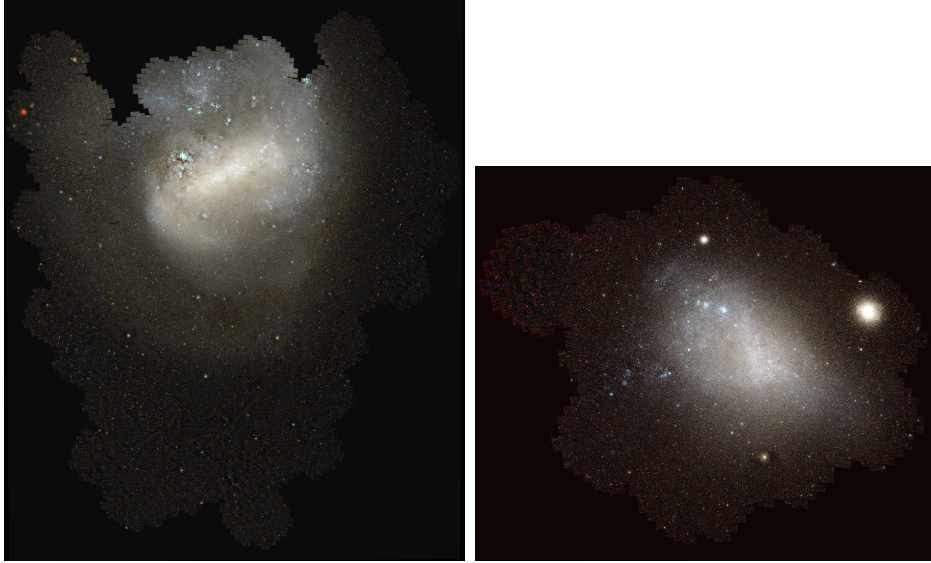


Figure 4.2: Images of the MCs compiled with data from SMASH DR2 (D. Nidever, in preparation). (Left) The Large Magellanic Cloud, and (right) the Small Magellanic Cloud.

In contrast to the LMC, the orientation of the SMC is much less understood (Parisi et al., 2009). Also characterized as a bright dIrr galaxy, the SMC is smaller than the LMC, with a very irregular and disturbed shape. The SMC is highly inclined with much less active star formation (Cioni, 2009). While the LMC is relatively thin along the line-of-sight, the SMC might extend 20 kpc along line-of-sight (Cioni, 2009). It contains a more subtle bar. It is connected to a component known as the Magellanic

Bridge—explained in the successive Section 4—through an eastern extension known as the Wing (El Youssoufi et al., 2019). Older stars are regularly spread about the galaxy in elliptical shape. In contrast, young populations are found around the center of the galaxy, with current ongoing star formation occurring (El Youssoufi et al., 2019). Subramanian et al. (2017) discovered a distinct population of Red Clump stars that can be tracked to the Magellanic Bridge. The distorted structures of both galaxies is very probably explained by a recent (200 Myr ago) collision between the LMC and SMC, which is further explored in Section 4. Both galaxies are embedded in a common envelope in neutral hydrogen, further indicating these galaxies have had a close encounter and are still interacting (Choudhury et al., 2018). The SMC’s total mass is about ten times smaller than the LMC’s (Garavito-Camargo et al., 2019). The SMC dark matter halo’s mass is estimated to be  $\sim 1.5 \times 10^9 M_\odot$  (Starkenburg et al., 2013), the stellar mass is estimated to be  $\sim 3\text{--}3.5 \times 10^8 M_\odot$  Skibba et al. (2012), and the total gas mass was found to be  $\sim 4.7 \times 10^8 M_\odot$  (Stanimirovic et al., 1999).

### Radial Extent

The true extent of both MCs has been growing with each new observation. As surveys probe deeper, fainter stellar populations are detected around the Clouds. Starting off with the LMC, Staveley-Smith et al. (2003) found that the gas component of the disk has a radius of  $4^\circ$ . In contrast, the stellar component has been found to extend much further. Epchtein et al. (1997), using The Deep Near-Infrared Sky Survey (DENIS), and Skrutskie et al. (2006), employing the Two Micron All Sky Survey (2MASS), noted that the stellar populations reach out to at least  $8^\circ$  from the center. Utilizing deep photometry, the Outer Limits Survey (OLS; Saha et al. 2010) investigated old main-sequence stellar populations in the outer periphery of the LMC and discovered that in the north they extended as far out as  $\sim 16^\circ$ .

Majewski et al. (2009) detected a halo component covering a radius of  $\sim 22^\circ$  by using spectroscopically-validated red giant branch stars with the MAgellanic Periphery Survey (MAPS). Mackey et al. (2016) examined Dark Energy Survey (DES, Abbott et al. 2018) data and detected an “arc” shape  $\sim 15^\circ$  from the center; they note this feature is probably a tidally disrupted region of the LMC disk due to the recent collision of the two galaxies (see Section 4). Garavito-Camargo et al. (2019) found the LMC disk to have an extent out to a radius of  $\sim 18.5$  kpc from its center. Nidever et al. (2019a) used Survey of MAgellanic Stellar History’s (SMASH) deep photometric data to explore the extended peripheries of the LMC using MSTO stars, finding stellar components extending to  $R \sim 22^\circ$ . These results indicate a highly disturbed envelope of stellar material exists that encompasses the LMC. The authors note that the origin of this low-density envelope is not certain, with two top explanations: (1) a “classical” accreted halo of ultra-faint satellite galaxies, or (2) tidally stripped outer LMC disc matter. Finally, Belokurov & Koposov (2016) used DES data to find that there are stream components of the Clouds out to  $\sim 30^\circ$  that may contain stars.

Knowledge of the SMC’s stellar extent is also growing. The deep CCD photometry of Noël & Gallart (2007)’s showed old stars reaching to  $5.8^\circ$ , and red giant stars were spectroscopically-confirmed out to  $R \sim 6^\circ$  by De Propris et al. (2010). Nidever et al. (2011a) selected red giant stars photometrically with MAPS and discovered that older stellar populations follow a common exponential profile out to  $R \sim 6^\circ$ , beyond which they follow a shallower profile to  $\sim 11^\circ$ . The authors explained that this could be a classical accreted halo (see Section 4). Using DES data, Pieres et al. (2017) found a stellar overdensity at  $R \sim 8^\circ$  that could be a tidally disrupted dwarf galaxy. Finally, Nidever et al. (2013) uncovered evidence that there is a stellar component of the SMC in the Magellanic Bridge.

The works listed above illustrate the enormous stellar extent of the LMC and



SMC. The extended peripheries of the Clouds have been and will continue to be sites for interesting discoveries. As stated above, the extent of the LMC is truly large. Only now, with surveys like SMASH (Nidever et al., 2017), that can probe the faintest stellar populations around the LMC, can we begin to conclusively determine the origin of the stellar material. There are two main theories for the extended LMC periphery: (1) a “classical” halo of accreted satellite galaxies, or (2) tidally stripped outer LMC disk material from the recent collision with the SMC. Majewski et al. (2009) supported the accreted halo theory for the LMC due to the large spatial extent, radial profile, and low metallicity they found. They asserted that an accreted halo of the LMC would have  $[\text{Fe}/\text{H}]$  value of  $\sim -2.0$  dex. However, Saha et al. (2010) found that the LMC’s disc reaches out to at least  $16^\circ$  in the north. Mackey et al. (2016) then claimed that this northern feature was probably material stripped from the LMC due to the MW’s gravitational force. Nidever et al. (2019a) used SMASH data to explore the extended peripheries of the LMC. Their results revealed an old and metal-poor population of stars encompassing the LMC covering a large range in position angle. They concluded that the explanation for the structures found in the periphery of the MCs are naturally explained by a recent collision with the galaxies. They also state that the extended LMC population is likely due to both a “classical” halo of accreted satellite galaxies and an interaction with the SMC caused the LMC disc to be tidally stripped and elongated into its extended periphery.

### Distance

Bica et al. (2008) cites that recent distance measurements from Sun to the MCs are  $\sim 50$  kpc to the LMC and  $\sim 60$  kpc to the SMC. A study in 2017 (Wielgorski et al. (2017)) estimated the distance to the SMC using optical and near-infrared photometric data. By using multiple bands, they determined the distance modulus.

Wielgorski et al. (2017) obtained a relative distance modulus of 18.975 mag for the SMC, while citing a relative distance modulus of 18.493 mag for the LMC. Using equation 2.16, solving for distance, and substituting in the two distance moduli for each galaxy, the results are 49.96 kpc to the LMC and 62.37 kpc to the SMC.

#### Magellanic Bridge, Magellanic Stream, and the Leading Arm

Besla et al. (2010a) notes that the distance between the Clouds is  $\sim 20$  kpc. Between the Clouds, there exists the Magellanic Bridge, with stellar and gaseous components. Trailing behind the MCs is the enormous gaseous Magellanic Stream. Finally, preceding the Clouds' orbit is the Leading Arm, which has a gaseous component. Both the Magellanic Stream and Leading Arm are thought to potentially also contain stellar components, although these have not yet been observed. Figure 4.3 shows H1 observations of these components over the MCs from Nidever et al. (2010).

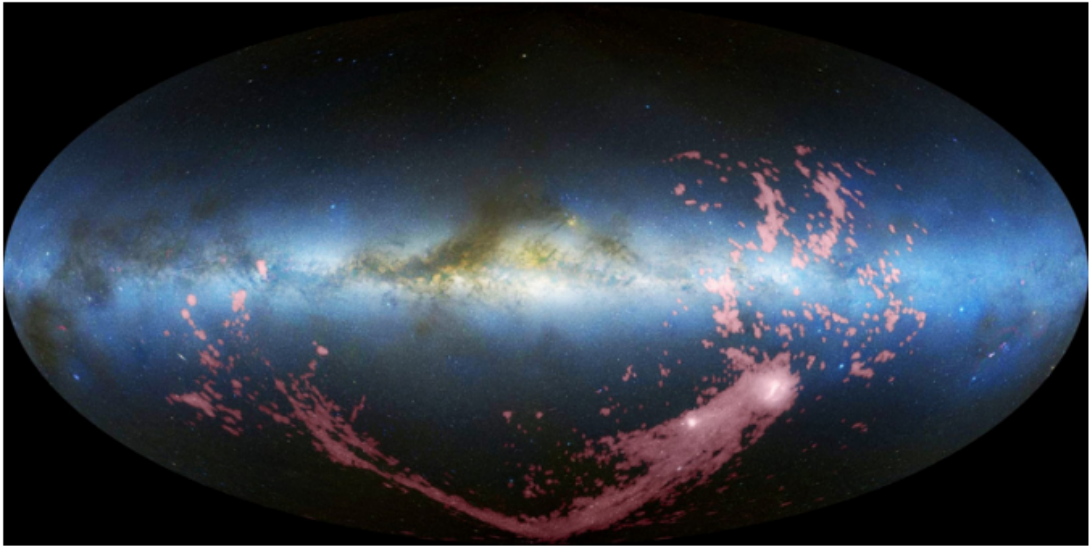


Figure 4.3: An Aitoff projection showing the MW's central region in the center. Overlaid on the optical all-sky image are the H1 observations of the Magellanic Clouds and their components in red.

Olano (2004) studied high-velocity gas clouds around the MCs and found evidence for young stellar populations in the Magellanic Bridge region. They speculated that this material was thrown out of the Clouds via a recent collision (see Section 4) and as a consequence a large number of stars were born during the interaction. Harris (2007) further studied the stellar populations in the Bridge. They conjectured that the observed young stars formed in situ in the Bridge region and, therefore, represent the closest star population born in tidal debris. They state that tidal forces between the Clouds formed the gaseous Bridge and name the stellar component of the Bridge the “inter-Cloud region”. Harris (2007) found no evidence of older stellar populations stripped from either the LMC or the SMC, and then suggested that the only material ejected from the Clouds via the collision was very nearly pure gas. They also estimated the age of these young stellar populations to be  $\sim 10^8$  Gyr. However, Olsen et al. (2011) discovered a population of accreted SMC stars in both the LMC and the Bridge. Belokurov & Koposov (2016) then went on to use Gaia DR1 data to locate both young and old stellar populations in the Bridge. Nidever et al. (2013) also found evidence for older stars stripped from the SMC in the Bridge. There is now a consensus that the Bridge is mostly gas stripped from the SMC by a recent close encounter with the LMC  $\sim 200$  Myr ago (Nidever et al., 2013). This also coincides with a burst of star formation in the Bridge (Harris, 2007).

Almost half a century ago, an extremely long ( $\sim 100^\circ$ ) H I stream was found trailing the MCs (Wannier & Wrixon, 1972; Mathewson et al., 1974). The Leading Arm is a gaseous component leading the orbit of the MCs. Like the Magellanic Stream, it has been known for nearly half a century (Mathewson et al., 1974), but it was not conclusively connected to the MCs until over two decades later (Putman et al., 1998). Nidever et al. (2010) conducted a 21cm survey beyond the “classical” Magellanic Stream and demonstrated that it is at least  $140^\circ$  long; therefore, together

with the Leading Arm, it is at least  $200^\circ$ .

### Past and Future Dynamics

Kallivayalil et al. (2006b,a) conducted proper motion measurements of the LMC and SMC using the Hubble Space Telescope. These measurements suggest that the current three-dimensional galactocentric velocities of the Clouds are much larger than were previously thought. Employing this information, Besla et al. (2007) made the groundbreaking proposition that the MCs are falling into the MW's potential for the first time; in other words, they are still on their first orbit around the MW. This idea is very different from the canonical assertion that the Clouds had made several passages around the MW already and that the MW is the primary perturber of the MCs (Fujimoto & Sofue, 1977).

To investigate this scenario, Besla et al. (2007) ran simulations consistent with a  $\Lambda$ CDM universe. They suggested that it is probable that the MCs are on their first orbit around the MW. Gómez et al. (2015) also supported the first infall scenario. This conclusion suggests the orbits of the MCs mean that these two galaxies have been isolated from the MW in the past. This has huge implications for past theories of the formation of the Magellanic components; namely, tidal stripping by the MW. That mechanism of formation requires that the MCs have undergone multiple pericentric passages about the MW. As Nidever et al. (2017) mentioned, the features of the Magellanic system have been duplicated in simulations using a model using tidal stripping through multiple close passages to the MW by the MCs on a bound orbit. But under this new regime, the Clouds would have only been close to the MW for 0.2 Gyr (Besla et al., 2007). Besla et al.'s orbits strongly suggest that the MCs have spent most of their existence isolated.

For at least several decades, astronomers have put forth the idea of a close-interaction or collision between the clouds. Olano (2004) agreed with other authors that the MCs must have had a very close encounter, with a separation less than 3 kpc, between 200 and 500 Myr ago. As evidence, they note that the morphological irregularities point to such an interaction, as well as the evolution of the Magellanic Stream and Bridge. Besla et al. (2012) and Besla et al. (2010a) demonstrated that the observed irregular structure and kinematics in both gas and stars can be explained through interactions between the LMC and SMC, instead of through interactions with the MW. They show that the interactions between the Clouds can be responsible for the morphological peculiarities, as well as the Magellanic components. This assertion is in stark contrast to the outdated assumption that gravitational interactions with the MW are alone responsible. This conclusion further supported their proposition that the MCs are undergoing their first passage around the MW. Besla et al. (2012) also estimated the MCs have been gravitationally bound to each other for at least  $\sim 2$  Gyr.

Recent Magellanic simulations (Besla et al. 2016 and Mackey et al. 2016) were able to reproduce structures observed in the LMC periphery through only a LMC-SMC interaction. They show that tidal interactions between the two galaxies could account for the asymmetries seen on the LMC. Additionally, the outer LMC disc is observed to be metal-poor compared to the inner LMC (see Section 4); this low metallicity could match the profile of outer LMC periphery stars. Looking at observational studies, Cioni (2009) assert that the interactions between the two galaxies themselves, instead of with the MW, fundamentally shaped their star formation histories and metallicity gradients (see Section 4).

Presently, most astronomers that study the Clouds agree that they had a collision around 200 Myr ago and are on their first passage around the MW. Something that

still remains a mystery is the origin of the extended peripheries of the Clouds. Nidever et al. (2017) correctly asserts that structure found in these regions needs to account for the recent collision. But even accounting for this, there are two main theories for material around the LMC: its own “classical” halo of accreted satellite galaxies or tidally stripped outer LMC disc material (Nidever et al., 2019a). In contrast, most agree that the material around the SMC is disrupted material from the SMC due to a recent collision with the larger LMC (Nidever et al., 2017). Due to the smaller size of the SMC, it is likely that it has been more disrupted from any past close interaction with the LMC (Nidever et al., 2013).

Several authors have suggested that both the SMC and LMC might have their own systems of satellite galaxies orbiting their centers of mass (Garavito-Camargo et al., 2019; Kallivayalil et al., 2018). This is also known as a galaxy having a classical halo of accreted satellite galaxies. This theory has gained more traction recently, as several ultra-faint dwarf galaxies have been found very close to the MCs (Bechtol et al., 2015; Drlica-Wagner et al., 2015). Cosmological simulations also strongly suggest that galaxies the size of the LMC and SMC have their own satellite galaxy systems. More in-depth studies of the peripheries are necessary to further investigate the extended peripheries of these two galaxies.

In the future, it is widely believed that the long term interacting MCs will eventually be consumed by the MW (Parisi et al., 2009). Cautun et al. (2019) demonstrated that the LMC is indeed on course to collide and merge with the MW in  $\sim 2.4$  Gyr. They state it will be a catastrophic event and fundamentally change the morphology of the MW.

### Past Metallicity Studies

Compared to the MW, the MCs are very metal deficient, which has been known for decades (Korn et al., 2000). This is a literature review of the past studies of metallicity on the LMC and SMC, mostly based on star clusters. Overall, the LMC is more metal-rich compared to the SMC. The LMC star cluster system is known to be made of a broad range of metallicities and ages, with a few older clusters and many young clusters and a gap in between them. The SMC also shows a broad distribution of abundances, but has a more tight distribution in ages (Grocholski et al., 2009). In the following subsections, I will discuss past studies on the metallicity of the LMC, SMC, and overall trends in both galaxies. Before I begin, I reiterate that the most accurate calculations of metallicity are derived with high-resolution spectroscopic data. Other estimations using photometry and CMD analysis are less accurate. In particular, while isochrone fitting exists for a large number of Magellanic CMDs, the degeneracy between age and metallicity makes isochrone metallicity measurements intrinsically uncertain compared to spectroscopic measurements (Grocholski et al., 2006).

#### Large Magellanic Cloud

Figure 4.4 shows the results from 17 past studies on calculating  $[\text{Fe}/\text{H}]$  in various locations on the LMC, plotted versus radius from the center of the LMC. Here, I take the center of the LMC to be  $(\alpha = 81.90, \delta = -69.87; \text{Nidever et al., 2017})$ . I created `SkyCoord` objects within `astropy.coordinates` python package and then computed on-sky distance with the `SkyCoord` method `separation`. The radial distance I computed is not the true 3D distance between these objects and the center of the galaxy. I also did not differentiate for different azimuthal positions on the LMC. It is

important to keep that in mind when contemplating the presentation of the 17 past LMC metallicity studies.

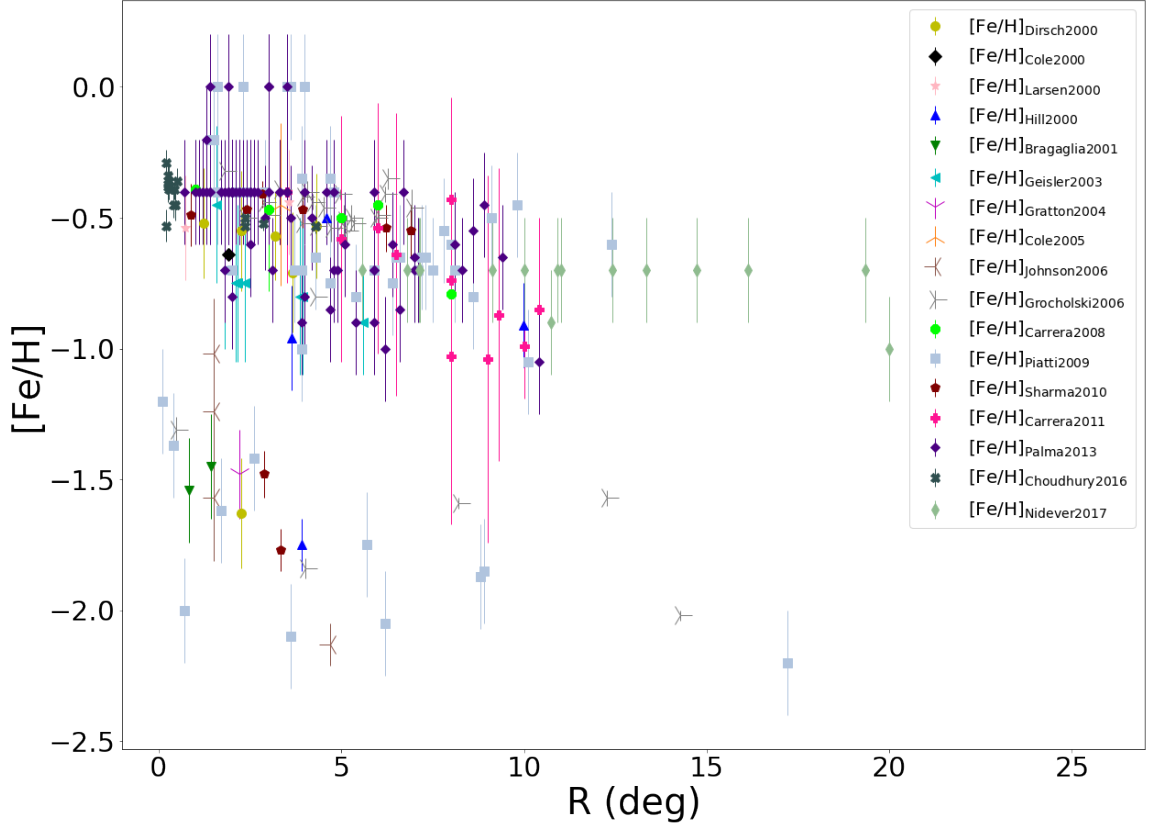


Figure 4.4: Plot of 17 past studies of metallicity values for the LMC versus radius from the center of the LMC. The subscripts in the legend denote the studies I reference.

The 17 studies I cite calculated metallicity with different methods, stars, and locations on the sky. Dirsch et al. (2000) employed Stromgren photometry to estimate metallicity in six LMC clusters. Cole et al. (2000) studied 39 red giants located at  $R \sim 3.5^\circ$  and calculated metallicity using spectroscopy of the CaII infrared triplet line. Larsen et al. (2000) used Stromgren photometry to calculate metallicity for G, K giant field stars. Hill et al. (2000) studied 10 giant stars in LMC globular clusters with high-resolution spectroscopy. Bragaglia et al. (2001) examined RR Lyrae stars and exploited the luminosity-metallicity relation to calculate metallicities. Geisler



et al. (2003) looked at eight star clusters in the inner LMC region with Washington photometry; Washington photometry CMDs can be analysed to derive metallicities by comparing the giant branches to standard calibrating clusters. Gratton et al. (2004) used low-resolution spectra for 98 RR Lyrae and found metallicities from the luminosity-metallicity relation. Cole et al. (2005) calculated metallicities from spectroscopy at the near infrared calcium triplet for 373 red giants around  $\sim 3^\circ$  from the LMC center. Johnson et al. (2006) used high-resolution spectroscopy of 10 red giants. Grocholski et al. (2006) employed near-infrared spectroscopy of more than 200 stars in 28 LMC clusters. Carrera et al. (2008) used Ca II triplet spectroscopy to derive metallicity for stars in four fields around the LMC. Piatti et al. (2009) used photometry in the Washington system and compiled a large table (Table 9 in Piatti et al. 2009) of past studies of the metallicities of LMC clusters and fields, referencing 11 studies: four used CMD analysis to calculate metallicities Hill et al. (2000), Geisler et al. (2003), Brocato et al. (1996) and Johnson et al. (1999); one used the relation between the zero-age horizontal branch absolute magnitude and metallicity for the nine program clusters Carretta et al. (2000); one used abundances obtained from measurements of the height of the red giant branch Olsen et al. (1998); four used the a Washington photometry method Piatti et al. (2003), Bica et al. (1998), Piatti et al. (2002), and Piatti et al. (1999); and one used spectroscopy Dutra et al. (2001). Sharma et al. (2010) studied 10 stars in each of eight massive LMC clusters with near-infrared spectroscopy and used the CaII triplet lines to calculate metallicity. Carrera et al. (2011) studied low-res spectroscopy in the infrared Ca II triplet region for 150 stars. Palma et al. (2013) found metallicities in LMC star clusters from Washington photometry and compiled a table (Table 5 in Paudel et al. 2018) of past studies that also used Washington photometry: Bica et al. (1998), Piatti et al. (2009), Piatti et al. (2003), Piatti (2012), Geisler et al. (2003), and Piatti et al. (2002). Nidever

et al. (2017) fitted isochrones to SMASH CMDs and found metallicity values for 14 SMASH fields. Finally, Choudhury et al. (2016) created a metallicity map of the LMC out to  $4\text{--}5^\circ$  using the Magellanic Cloud Photometric Survey (MCPS) and Optical Gravitational Lensing Experiment (OGLE III) photometric data, calibrated with spectroscopic data of red giant branch stars.

### Small Magellanic Cloud

Figure 4.5 shows the results from 7 past studies on calculating  $[\text{Fe}/\text{H}]$  in various locations on the SMC, plotted versus radius from the center of the SMC. For this analysis, I used ( $\alpha = 13.18$ ,  $\delta = -72.82$ ) for the center of the SMC (Nidever et al., 2017). I computed on-sky distances in the same manner as in Subsection 4. The seven studies I cite calculated metallicity with different methods, stars, and locations on the sky. Larsen et al. (2000) used Stromgren photometry used to calculate metallicity for G, K giants. Piatti et al. (2001) observed six star clusters on the SMC and found metallicities with the Washington photometry method. Glatt et al. (2008) examined spectroscopy of SMC clusters and presented it with spectroscopy metallicity data from Da Costa & Hatzidimitriou (1998). Parisi et al. (2009) used near-infrared spectra covering the CaII triplet lines for a large number of stars associated with 16 SMC clusters. Dobbie et al. (2014) completed a Ca II triplet line metallicity study of 3037 field red giants. Dias et al. (2016) analyzed spectroscopy to find metallicities and compiled metallicity values from seven past studies: two using spectroscopic analysis (Dias et al. 2010 and Piatti et al. 2005a); one used CMD analysis (Mighell et al., 1998); and four used Washington photometry (Piatti et al. 2005b, Parisi et al. 2009, Da Costa & Hatzidimitriou 1998, and Glatt et al. 2008). Finally, Choudhury et al. (2018) created a photometric metallicity map of SMC, estimating metallicity using the Magellanic Cloud Photometric Survey (MCPS) and Optical Gravitational Lensing

Experiment (OGLE III) photometric data, calibrated with spectroscopic data of red giant branch stars out to  $\sim 2.5^\circ$ .

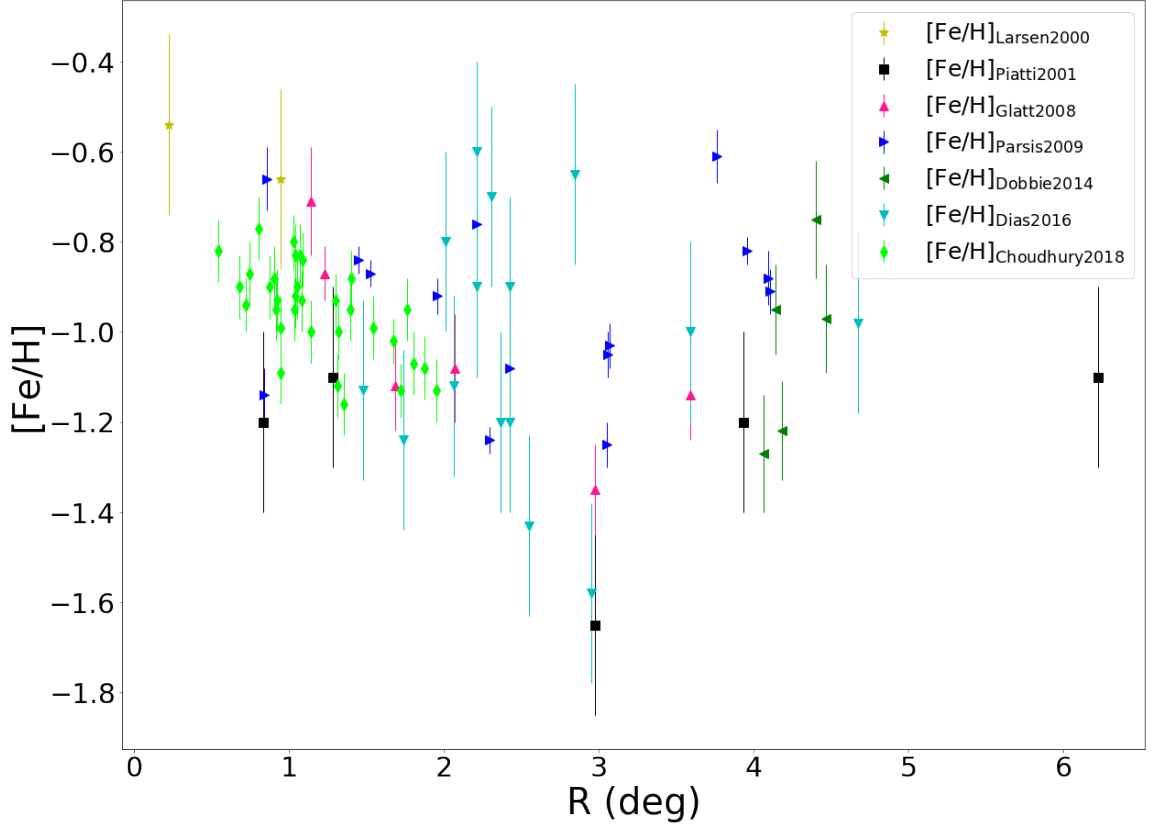


Figure 4.5: Plot of 7 past studies of metallicity values for the SMC versus radius from the center of the SMC. The subscripts in the legend denote the studies I reference.

### Magellanic Metallicity Trends

As I mentioned at the beginning of Section 4, there is apparently a large gap between ages and abundances of LMC clusters (Dirsch et al., 2000), with the bulk metallicity being pretty constant from 3–8 Gyr ago, but then around 3 Gyr the metallicity of stars increased by a factor of 6. Cole et al. (2000) also noticed the strange LMC cluster distribution, stating that of the  $\sim 4,500$  LMC clusters, less than 10 are 4–12 Gyr, but that around 2–4 Gyr ago, the rate of cluster formation increased

by  $\sim 2$  orders of magnitude and the star formation rate increased by a factor of  $2\text{--}3\times$ . They state that there are also extremely old ( $\geq 12$  Gyr) clusters substantially present. This gap is often referred to as the “age gap” and closely matches an “abundance gap”: the old ( $\geq 12$  Gyr) clusters have a mean  $[\text{Fe}/\text{H}] \sim -1/8$  and the young (1-3 Gyr) clusters have a mean  $[\text{Fe}/\text{H}] \sim -0.5$ . Hill et al. (2000) found there to be only 13 globular clusters in the LMC, and reiterated that the LMC cluster distribution is bimodal in metallicity and age, and stated that there is an age gap present between 3–4 Gyr and 10–12 Gyr. They again interpreted the bimodality as the signature of two burst of star formation: one 12–15 Gyr clusters and one some 3 Gyr ago. Looking at the location of clusters on the LMC, Kontizas et al. (2001) realized that young clusters are in the central regions of the LMC out to only  $\sim 7^\circ$  and older clusters are spread all around the LMC. Grocholski et al. (2006) also pointed out the strange age and abundance distribution in LMC clusters, and through their analysis found no evidence for the existence of a metallicity gradient in the cluster system. Studying stars out to  $\sim 8^\circ$ , Carrera et al. (2006) confidentially stated that the mean  $[\text{Fe}/\text{H}]$  of the LMC field stars decreases moving away from the central region. Feast et al. (2010) found a radial gradient of metallicity in RR Lyrae stars of the LMC. Cioni (2009) derived  $[\text{Fe}/\text{H}]$  abundances from the ratio between C and M type asymptotic giant branch stars and with their results and others, shared definitive evidence for a linear decrease in metallicity out to  $\sim 8$  kpc. They also point out the signature of two major star formation episodes in the LMC, the second of which supports an LMC origin for the Magellanic Stream. Finally, Skowron et al. (2016) also found a metallicity gradient within the LMC.

Majewski et al. (2009) studied the extended populations around the LMC and stated that the LMC disk population has a mean metallicity of  $[\text{Fe}/\text{H}] \sim -0.4$ , but the periphery changes to a different stellar population of lower metallicity at larger

radii, meaning they found definite evidence for a negative radial metallicity gradient. However, they emphasize there is a large spread in metallicity everywhere across the LMC. Expanding on the the origin of the LMC extended periphery, Majewski et al. (2009) states that clues are in the metallicity distribution. They found a mean metallicity for the outer LMC population  $[\text{Fe}/\text{H}] \sim -1$ , but with metallicity values spread out over a huge range:  $-2$  dex to  $0$  dex. They additionally note that this mean is higher than the metal-poor halos of the MW and M 31 (Kalirai et al., 2006) and that a “classical” halo of accreted satellite galaxies around the LMC would be expected to have a mean metallicity of  $-2$  dex at the most. This value is justified using  $\Lambda$ CDM paradigm that if stellar halos form from the accretion of smaller systems, and if these systems follow the linear observed relationship, so an accreted halo of the LMC would be very metal-poor (at least  $-2$  dex).

Piatti et al. (2001) emphasized that the distribution of cluster ages and abundances is very different for the SMC: the SMC clusters seemed to have formed relatively uniformly over the past 12 Gyr. Parisi et al. (2009) shared that there had been no evidence for a metallicity gradient on the SMC. They also pointed out that the orientations of the LMC and SMC have an effect on the trends that are observed in both galaxies: the LMC is seen nearly face-on from the location of the Sun so distances can be easily determined, whereas the orientation of the SMC is much more poorly understood and thought to be very elongated along the line-of-sight, making distances more difficult to accurately determine. They plotted metallicity versus distance from the SMC center and found that no trend in metallicity is present. Cioni (2009), using abundance from the ratio between C, M type asymptotic giants, found that the metallicity values of the SMC stay constant out to  $\sim 12$  kpc from the center. Therefore, they find no gradient present in the SMC. They also point out that the abundances match material in the Magellanic Bridge and that there is no

evidence for a halo population. Finally, Skowron et al. (2016) also did not observe a metallicity gradient in the SMC.

## DATA

As introduced in the Analyzing Stars Section, photometric and spectroscopic surveys have become essential tools in analyzing stellar populations. In particular, the automated data reduction, processing, and analysis of huge photometric and spectroscopic surveys have transformed the type of science astronomers are capable of performing today. In this Chapter, I will discuss the photometric and spectroscopic systems and surveys that are relevant to my study: UBV system, UBVIR system, SDSS, DECam system, DES, and SMASH.

UBV and UBVRI

I will briefly touch on the first standardized photometric system, the UBV system. It is described in Johnson & Morgan (1953), Johnson & Harris (1954), Johnson (1963), and Morgan (1988). The UBV system is a broadband photometric system originally used to classify stars according to their colors. A common extension of this system is the UBVRI system, which adds the R and I filters in redder wavelengths. There are two common versions of this system: Johnsons (Johnson et al., 1966; Moffett & Barnes, 1979; Barnes & Moffett, 1979) and Kron and Cousins (Kron et al., 1953; Cousins, 1976). The UBVRI system is shown in Figure 5.1. As I mentioned in the Metallicity Chapter, photometric metallicity historically was defined by measuring and calculating the ultraviolet excess using the either the UBV or UBVRI system. With the advent of many different photometric systems, other photometric colors can be used to calculate photometric metallicities. The studies Wildey et al. (1962b), Wallerstein & Carlson (1960), Wallerstein (1962), and Carney (1979) I discussed in Section 3 used the UBV/UBVRI systems to identify and strengthen the relationship between ultraviolet excess and metallicity.

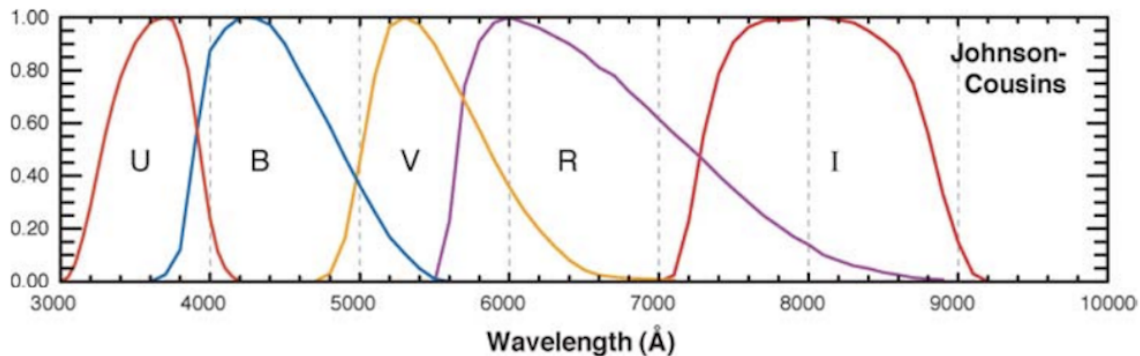


Figure 5.1: The Johnson-Cousins UBVRI photometric system.

### The Sloan Digital Sky Survey (SDSS)

The Sloan Digital Sky Survey (SDSS) began gathering photometric and spectroscopic data of galaxies, quasars and stars in the northern celestial sphere and on the celestial equator in 1998. Since I use data from the tenth data release (DR10), I will describe the survey up to that point and emphasize portions of the survey I used. SDSS revolutionized the amount and processing of photometric and spectroscopic data. Due to the unprecedented breadth of SDSS, the SDSS broadband five-filter system—written as *ugriz* and covering 3,000 to 10,000 Å—has become an important system that subsequent systems, like the DECam system, are styled in the same vein as. The SDSS photometric system is shown in Figure 5.2. The first phase of SDSS, SDSS-I, spanning the first five data releases (DR1: Abazajian et al. 2003, DR2: Abazajian et al. 2004, DR3: Abazajian et al. 2005, DR4: Adelman-McCarthy et al. 2006, and DR5: Adelman-McCarthy et al. 2007), used the 2.5 meter telescope at Apache Point Observatory in New Mexico to gather imaging and spectroscopic



data. The photometric data were gathered in strips which follow great circles; two strips together make up a stripe of  $2.5^\circ$  wide. Objects were selected from the imaging data for spectroscopy using a variety of algorithms. Spectroscopic data were then taken with exposures of overlapping tiles that are  $3^\circ$  in diameter. Spectroscopy was performed on a pair of double spectrographs with wavelength coverage from 3,800 to 9,200 Å. Both the photometric and spectroscopic data were reduced and processed with specialized software, constantly updated with new data releases. Because every SDSS data release is cumulative and comprehensive, every time a SDSS software pipeline is updated all older data is reprocessed. The fifth data (DR5) release of SDSS (Adelman-McCarthy et al., 2007) saw the completion of SDSS-I, which in total provides access to 8,000 square degrees of five-band imaging data and over one million spectra.

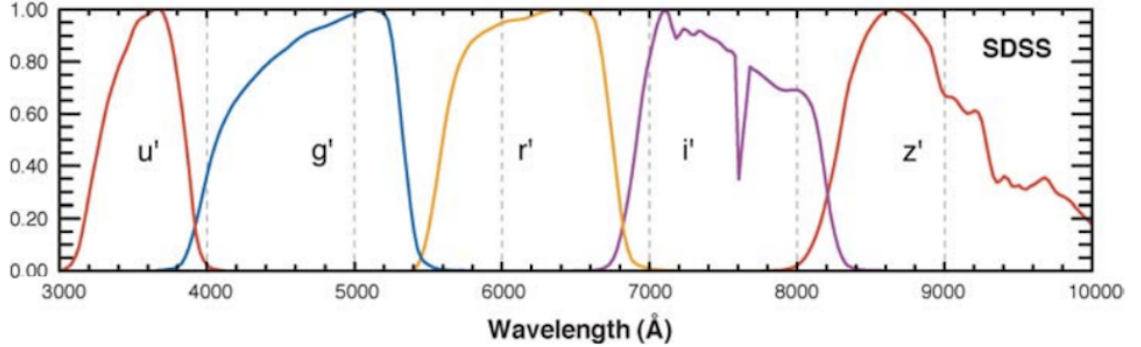


Figure 5.2: The Sloan Digital Sky Survey (SDSS)  $u'g'r'i'z'$  photometric system.

The second phase of SDSS, SDSS-II, was introduced in the fifth data release of SDSS (Adelman-McCarthy et al., 2007). This phase consists of three distinct surveys; however, only two are relevant to my study: the Sloan Legacy Survey and the Sloan Extension for Galactic Understanding and Exploration (SEGUE). The Sloan Legacy Survey is a continuation of SDSS-I and the SEGUE survey includes

3,500 square degrees of new imaging data and spectroscopy of 240,000 selected stellar targets to study the Milky Way. Additionally, the fifth data release introduced the start of deep imaging of the full equatorial stripe, Stripe 82, very important to the calibration of the SMASH survey. The sixth data release (Adelman-McCarthy et al., 2008) launched a number of improvements to the data software, one of which I will describe: the measurement and calculation of stellar atmospheric parameters. Using the spectroscopic data, the software included automatic measurement of effective temperature, surface gravity ( $\log g$ , where  $g$  is in cgs units,  $\text{cms}^{-2}$ ), and metallicity. The pipeline conducted these calculations and measured 77 atomic and molecular line indices for each object. The manner in which the quantities were calculated involved a variety of techniques and a decision tree was implemented to decide which methods or combination of methods provided the best measurements, based on the signal-to-noise ratio of the spectra and the colors of the stars. These methods include fits of spectra to synthetic photometry and continuum spectra based on model atmospheres or synthetic spectra, measurements of the equivalent widths of various metal-sensitive lines, measurements of the equivalent widths of various gravity sensitive lines, measurements of the autocorrelation function of the spectrum, and a neural network technique. Data release seven (Abazajian et al., 2009) marked the completion of SDSS-II and, therefore, the Sloan Legacy Survey and SEGUE. It includes 357 million objects in five-band photometry, repeat photometry on a  $120^\circ$  long,  $2.5^\circ$  wide strip along the celestial equator in the Southern Galactic Cap (Stripe 82), and over 1.6 million spectra, 460,000 of that stellar spectroscopy. Again, all data from previous data releases are included and were reprocessed with the new software.

SDSS-III is the third phase of SDSS and the last relevant to my study. It was introduced in data release seven (Abazajian et al., 2009). SDSS-III includes the SEGUE-2 survey, which is a continuation of SEGUE. SEGUE-2 is an extension of

the spectroscopic component of SEGUE and used the same SDSS-I/II spectrograph. The eighth data release (Aihara et al., 2011) included first data from SDSS-III, most relevantly data of 118,000 stars from SEGUE-2. It also updated the pipeline used to measure stellar atmospheric parameters. Data release nine (Ahn et al., 2012) improved even more on the stellar atmospheric parameters pipeline and released spectra from new spectroscopic instruments. Finally, data release ten (Ahn et al., 2014) included more new spectra from new instruments and a cumulative release of all data from each data release until data release ten.

SDSS data is an integral component of my study. As I described in the Metallicity Chapter, Ivezić et al. (2008) estimated photometric metallicities of 2 million Milky Way stars using SDSS imaging and spectroscopic data and is the study I follow closely and recalibrate. The SMASH survey, the main data component of my survey, uses data taken with the DECam instrument and filters, which were modeled closely after the five-band SDSS filters. SMASH also calibrated its photometry using data of stars in the SDSS. Perhaps most importantly, the majority of the spectroscopic data I use is SDSS stellar spectroscopy data in the form of the measured atmospheric stellar parameters: effective temperature, surface gravity, and metallicity. Described in more detail in the Methods and Analysis Chapter, I started with 1,843,193 SDSS spectra and crossmatched these with SMASH standards, eventually using 3,870 of the SDSS spectra with corresponding SMASH standards matches.

### Large sky Area Multi-Object Spectroscopic Telescope (LAMOST)

The Large sky Area Multi-Object Spectroscopic Telescope (LAMOST; Luo et al., 2015) survey is a spectroscopic survey that will eventually cover about half the celestial sphere and collect 10 million spectra. The spectra are collected with the LAMOST 4-meter telescope located at Xinglong Observatory northeast of Beijing,

China. The instrument has 16 low resolution spectrographs that span a range in wavelength from 3700 to 9000 Å. The general survey began in September 2012. Like SDSS, LAMOST employs a stellar parameter pipeline to automatically calculate the stellar atmospheric parameters effective temperature, surface gravity, and metallicity. Measurements of these parameters are done using two methods: Correlation Function Interpolation (CFI) and Universite de Lyon Spectroscopic analysis Software (ULySS). CFI works by studying temperature among a grid of synthetic spectra to determine effective temperature, next the code looks for  $[\text{Fe}/\text{H}]$  in metallicity space in the grid, and finally the code finds  $\log(g)$ . The CFI method is used to find coarse estimates of the parameters that are used as initial guesses in the ULySS software. ULySS improves the measurements by minimizing the squared difference between the observations and the model. The model is adjusted at the same resolution and sampling as the observation, and the fit is performed in pixel space. Importantly, ULySS determines the parameters within a single fit to manage degeneracies between parameters, such as temperature and metallicity. ULySS gives the final stellar atmospheric parameter values. Every time new data is released, all old data is reprocessed if the software pipelines are modified.

I use stellar spectra from the third data release of LAMOST, which includes 5,268,687 stellar spectra with measurements of stellar atmospheric parameters. In my study, I crossmatched 3,177,995 of these spectra with SMASH standard stars data, eventually just using 700 LAMOST spectra that have corresponding SMASH matches.

### Dark Energy Camera (DECam)

The Dark Energy Camera (DECam), described in Flaugher et al. (2015), is an imager mounted at the prime focus of the Victor M. Blanco 4-meter telescope

at Cerro Tololo Inter-American Observatory (CTIO) near La Serena, Chile. The camera consists of a five-element optical corrector, seven broadband filters, a shutter with a 60cm aperture, and a charge-coupled device (CCD). The 570-megapixel mosaic camera contains 62 imaging CCDS and 12 CCDs for guiding and focus. DECam was designed and constructed by the Dark Energy Survey (DES) collaboration (Abbott et al., 2018). The camera has a 3 square degree field of view and can take an image of an incredibly large portion of the night sky. DECam is outfitted with seven filters— $u$ ,  $g$ ,  $r$ ,  $i$ ,  $z$ ,  $Y$ , and  $VR$ —that span a wavelength range from 4000 to 10,650 Å. Although similar in name, the DECam filters are quite different from their SDSS counterparts, especially the  $u$  filter. The DECam system is shown in Figure 5.3. In 2012, DECam was completed and installed on the Blanco 4-meter telescope and received first light in September 2012. The necessity for superb photometry drove the makers to drive tight constraints on the filter uniformity. In 2015, DECam has the largest corrector optics, filters, and shutter aperture of any astronomical instrument.

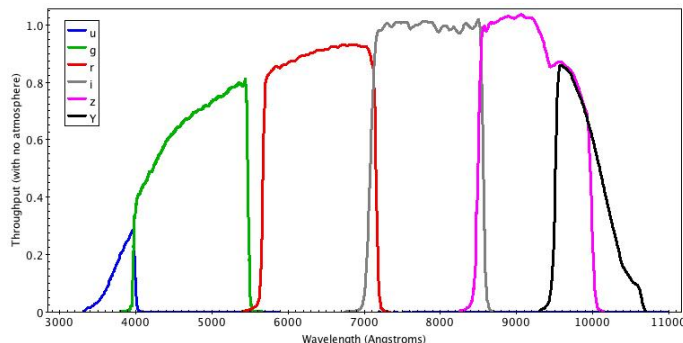


Figure 5.3: The DECam filter system total throughput with no atmosphere.

### The Dark Energy Survey (DES)

DES is a wide-field survey of 5,000 square degrees of southern sky with its first data release in 2018 (Abbott et al., 2018). To collect data, DES used five of DECams

filters:  $g, r, i, z$ , and  $Y$ . It overlaps SDSS Stripe 82 in order to perform accurate calibration. With the completion of data gathering of DES, there was an increase in volume of  $\sim 7\times$  from SDSS. It is important to mention DES because SMASH was designed to be complementary to DES and to fill in areas of the sky that DES had not imaged.

### The Survey of Magellanic Stellar History (SMASH)

The Survey of the MAgellanic Stellar History (SMASH) is a photometric survey of the Magellanic Clouds that contains approximately 360 million objects in 197 fields. These data were obtained with DECam, but only 59.5 of the 62 imaging CCDs were functional during the observing run Nidever et al. (2017). SMASH covers 480 square degrees to 24th magnitude in  $ugriz$ , encompassing a depth of  $\sim 2$  magnitudes below the oldest main-sequence turnoff stars of the Magellanic Clouds.

SMASH fields (shown in the top panel in Figure 5.4) entirely cover the main bodies of the LMC and SMC but on the Clouds peripheries, the fields are distributed as “islands” over 2,400 square degrees. The top panel of Figure 5.4 also shows the DES footprint: DES covers the northern outskirts of the Clouds as well as the Magellanic Stream. As Figure 5.4 demonstrates, the SMASH footprint was constructed to cover the rest of the LMC and SMC peripheries and the Leading Arm, but to avoid the MW midplane. Fields were chosen over the Leading Arm because models by Besla et al. (2010b) predict the existence of stars and tidal debris from the Clouds (shown in the lower panel of Figure 5.4). Although it would have been preferable to perform a fully filled survey, that was not possible with the amount of observing time available. Therefore, the SMASH fields were selected using an all-sky tiling scheme in which a uniform hex pattern of field centers (modeled in the shape of the DECam imager) with  $1.7^\circ$  separation based on an Interrupted Mollweide projection. Currently, The

DECam Local Volume Exploration (DELVE) survey is filling in the area around the Magellanic Clouds not covered by SMASH.

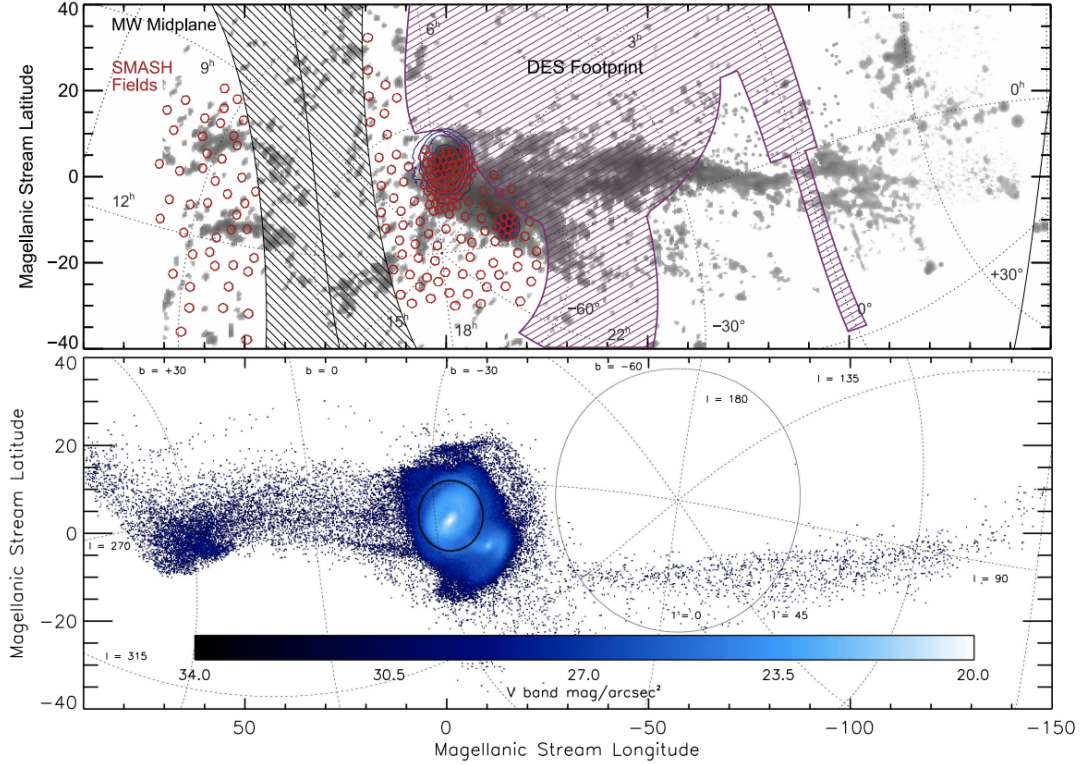


Figure 5.4: Spatial coverage of the SMASH survey using DECam.

In the planning stage, the SMASH team decided that the *ugriz* bands would give the precision needed to detect the expected faint stellar populations in the Magellanic periphery and the Leading Arm. SMASH photometry is as deep or deeper than DES in *griz* and includes the DECam *u* filter. The inclusion of the *u*-filter enabled my study into the photometric metallicities of the Magellanic main sequence stars, which aid in determining the origin of the extended stellar populations (discussed more in the Conclusion Chapter). Each night of observing, exposures of standard star fields were taken. These standards were chosen to overlap the SDSS equatorial region, including Stripe 82 (described in the SDSS section). These standards were used to calibrate

the SMASH data. SMASH was allotted 57 nights of DECam observing; 47 nights of useful data were obtained. Acceptable exposures were obtained for 197 SMASH fields, 158 of which have deep exposures. The SMASH team could've achieved their goals with 2/3 filters, but decided to include  $u$  and  $z$  to improve their ability to separate faint stars from background galaxies.

The data were reduced nightly with the automated PHOTRED pipeline first explained in Nidever et al. (2011b). PHOTRED uses point spread function (PSF) photometry.  $E(B-V)$  extinction values for each source were also included in the final catalog (Schlegel et al., 1998a). Because the southern sky that SMASH covers is not well covered with  $ugriz$  CCD imaging, the data had to be calibrated with SDSS equatorial data: Stripes 82 and 10. Data of these equatorial fields was taken every night. The processing of the standard star data was done with STDRED, a sister package to PHOTRED that uses aperture photometry. STDRED used standard star fields to derive standard star transformations for PHOTRED. After running on standard star fields where the photometry is well-established, it then used the transformation equations, and finally it calibrates the science.

SMASH is the main data component and essential to my study. I use data from version six of the calibrated catalogs. The catalogs of data I use have stars already separated from other objects and numeric values for magnitudes, right ascension (RA), declination (DEC), errors, and  $E(B-V)$  extinction values. For the calibration of my method, I use the SMASH standards from the equatorial regions because they overlap SDSS and LAMOST. I crossmatched the SMASH standards with SDSS and LAMOST using RA and DEC values. After recalibrating Ivezić et al. (2008), I calculated the photometric metallicity in over 2 million stars in the LMC, SMC, and their peripheries.

Before I could inspect the data myself, the SMASH CMDs were analyzed in



order to remove background galaxies and foreground MW stars. These processes are explained in-depth in Nidever et al. (2019a). At deep magnitudes ( $g \geq 23$ ), there are many galaxies than can pollute the SMC and LMC main-sequence (MS) and main-sequence turnoff (MSTO) regions. To remove background galaxies, cuts on the morphological parameters were first applied. Then, to further remove the unresolved galaxies, each color-color diagram was analyzed because there is a limited region of each color space that stars can occupy. This region is called the stellar “locus.” In all the color-color diagrams, bright sources were used to locate the stellar locus and its size. For each observed object, a stellar locus model is calculated using  $g-i$  color. An observed object is removed if it deviates from 0.2 magnitudes or 2.5 times more than the observational color uncertainty. Additionally, a cut is applied **SHARP** parameter. The **SHARP** quantity is a parameter in the SMASH catalogs and is a measure of an object’s spatial profile peakedness compared to the object’s point spread function. A cutoff of 0.2 is set on the **SHARP** on the brightest stars and less on fainter stars; this cut serves as a morphological cut. Another parameter in the SMASH catalogs, **PROB**, also has a cut placed on it. **PROB** is the Source Extractor stellar probability value.

Artificial star tests were also completed for every field to ascertain the completeness. Fainter stars were placed into all SMASH images and then processed with PHOTORED in the same manner as the original images. The list of images with artificial stars were then crossmatched with the final catalog of different sources. To pass the star/galaxy cut, it was required that an artificial star had to be found in at least one image in both  $g$  and  $i$  bands.

Finally, the SMASH team created their own MW model for the SMASH data (T. de Boer, in preparation). By fitting the observed distribution of stars in many CMDs, the population and spatial parameters of the MW were constrained. Best constrained parameters were fit for different components of the MW, including the

thin disk, thick disk, and halo. MW models were computed for each SMASH field using best-fit parameters. Then, most of the MW populations could be removed. The raw data of Field 55 before cuts are made is shown in the left panel of Figure 5.5.

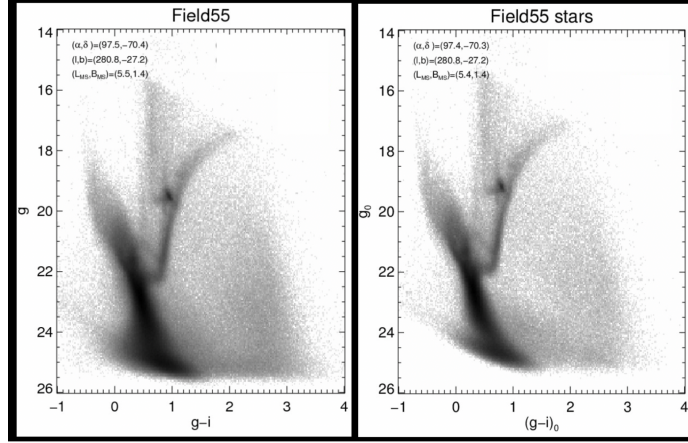


Figure 5.5: CMD of Field 55. Three different coordinates of the field are shown at the top left: equatorial coordinates, galactic coordinates, and Magellanic Stream coordinates. The left panel is the raw data, and the right panel is the data after background galaxies and foreground MW stars have been removed.

## METHODS AND ANALYSIS

In the following Chapter, I follow the Ivezić et al. (2008) methods closely (explained in detail in Chapter 3 on page 21). The steps I describe to calculate photometric metallicities are to generate a calibration sample, select SMASH data to study, and calculate photometric metallicities using different methods.

### Generate Calibration Sample

In order to effectively apply the photometric metallicity method to the SMASH data, the first step is to recalibrate the Ivezić et al. method. An important difference between their study and mine is that they use the SDSS photometric system for all their data. In contrast, the SMASH data were collected with the Dark Energy Camera (DECam) filter set, but were calibrated with SDSS data creating a “quasi-SDSS” photometric system. Therefore, in this section I create a new metallicity map to use with the SMASH data. For a thorough discussion on the data used, see Chapter 5.

The first step I completed was positionally crossmatching SMASH standard star fields—which were collected on the SDSS equatorial region—with SDSS DR10 and LAMOST DR3 spectroscopic surveys. To crossmatch, I used the `astropy` python package. Within `astropy`, I constructed three `SkyCoord` objects: an object with 64,599 SMASH standard stars, an object with 1,843,193 SDSS stars, and an object with 3,177,995 LAMOST stars. Then, I used `astropy`'s `match_catalog_sky` method to crossmatch stars within each `SkyCoord` object to within  $\leq 1$  arcsec. After crossmatching, there are 4,570 total matches: 3,870 matches between SMASH and SDSS and 700 between SMASH and LAMOST.

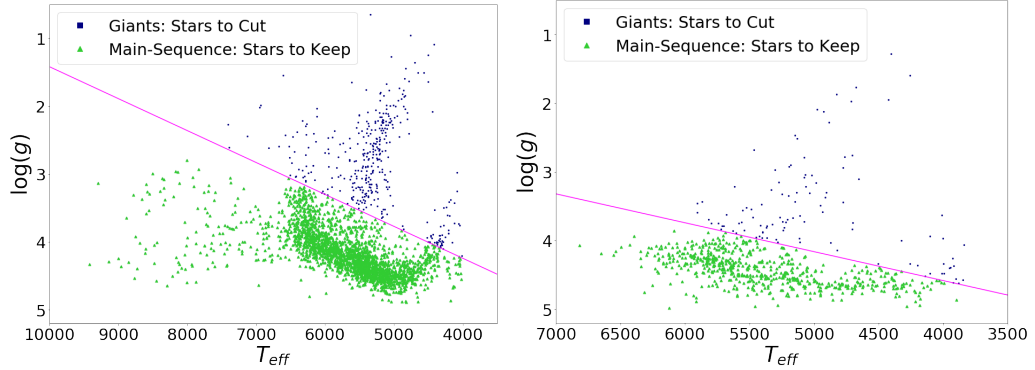


Figure 6.1: (Left) Crossmatched data between SDSS DR10 and SMASH data. Line used to remove giants shown in magenta. (Right) Crossmatched data between LAMOST DR3 and SMASH data. Line used to remove giants shown in magenta.

After crossmatching, I plotted two spectroscopic HR diagrams using the spectroscopically determined parameters surface gravity ( $\log(g)$ ) and effective temperature ( $T_{eff}$ ). Examining the stellar populations on these diagrams by eye, I fit a linear line to each spectroscopic HR diagram in order to extract the main-sequence dwarf stars (green) and exclude the giants (blue). The cuts we made are shown in the two panels of Figure 6.1. Subsequent to implementing the main-sequence cuts, my calibration sample is reduced to 2,770 total stars: 2,176 SDSS and SMASH matches and 594 LAMOST and SMASH matches.

To generate a meaningful statistic using the calibrated data, I used the `SciPy` statistic functions module, `stats`. In particular, I used the `binned_statistic_2d` class, which can compute two-dimensional binned statistics for multiple sets of data. To do this, the class takes five parameters: an array-like sequence to be binned along the first “x” dimension, an array-like sequence to be binned along the first “y” dimension, the “values” that are the data on which a statistic will be computed, the type of statistic, and the number of bins for the x and y dimension. To create an object to compute the median metallicity statistic in 2,500 bins across the entire

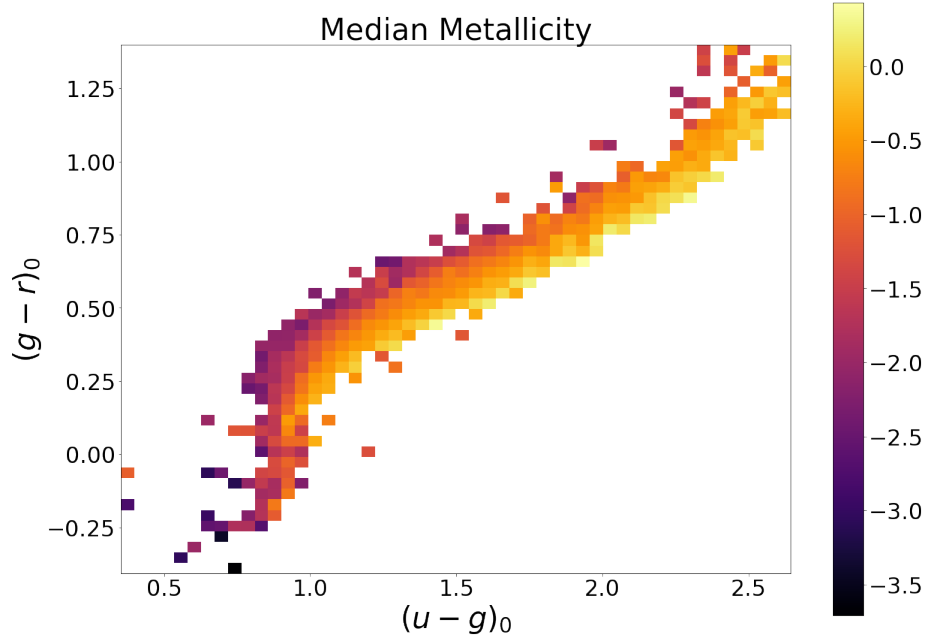


Figure 6.2: Median spectroscopic metallicity as a function of two SMASH colors. The colorbar displays median spectroscopic metallicity. Each bin has a length of 0.046 mag along the “x” dimension and a length of 0.036 along the “y” dimension.

range of  $u - g$  and  $g - r$  color range of the calibration sample, I inputted the five following parameters into the function (listing in the same order): SMASH  $u - g$  from the calibration sample, SMASH  $g - r$  from the calibrations sample, the spectroscopic metallicity values corresponding to each color from either SDSS or LAMOST, median statistic, and 50 bins in each dimension. The `binned_statistic_2d` object then returned a (50,50) array of the median metallicity statistic in each of the 2,500 bins. In bins where a statistic could not be calculated, a NAN value was put. The total number of bins that a statistic could be computed is 364 out of 2500 total bins. The bin sizes of the  $u - g$  and  $g - r$  bins (see caption of Figure 6.2) were chosen to be larger than the average of the spectroscopic metallicity error: 0.00039. I then created a figure to display the spectroscopic metallicity as a function of two SMASH colors, Figure 6.2.

### Select SMASH Data to Study

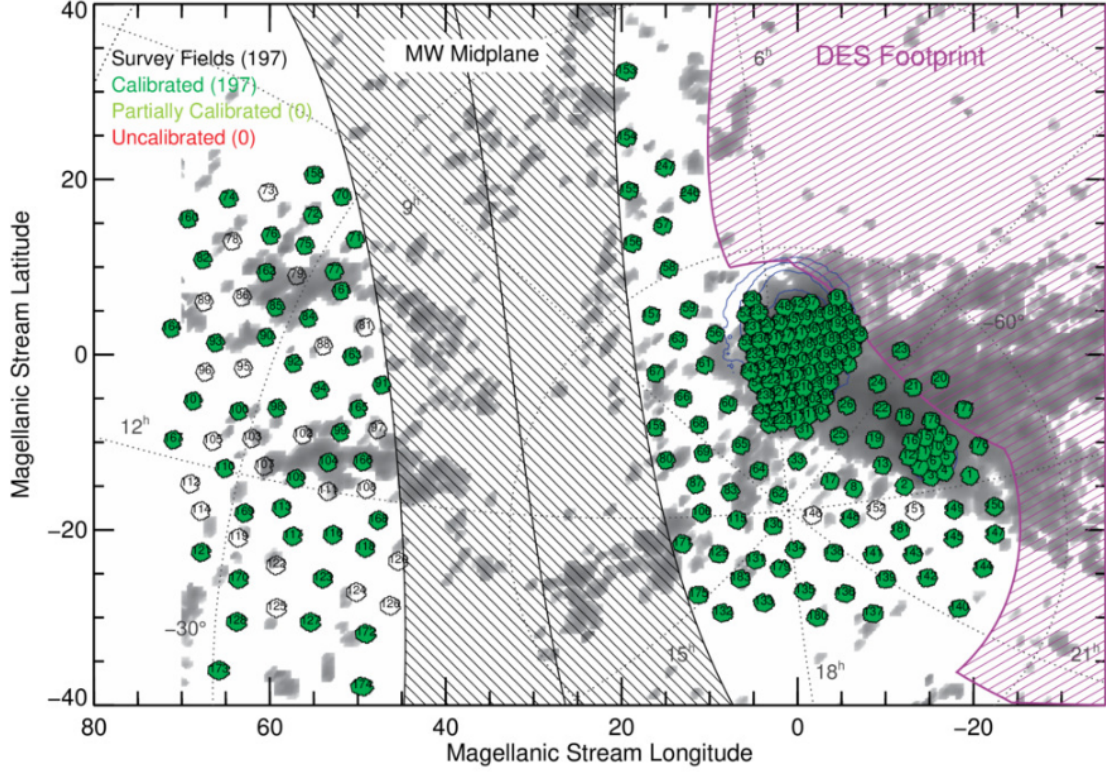


Figure 6.3: Map of the Magellanic System showing the 197 SMASH fields.

Next, I inspected the SMASH data, Figure 6.3, for appropriate fields to study. Before I could inspect the data myself, the SMASH CMDs were analyzed in order to remove background galaxies and foreground MW stars. This process is explained in Section 5 on page 56 and Figure 5.5 displays Field 55's CMD before and after source cuts. The SMASH fields that are the least explored are the periphery fields, so they were the first choice. Along with the periphery fields, I selected fields in the main bodies of both galaxies so that I could compare my results to past studies. I also only chose fields for which there were deep  $u$ -band observations.

After these fields were selected, I had to ensure they could be correctly studied

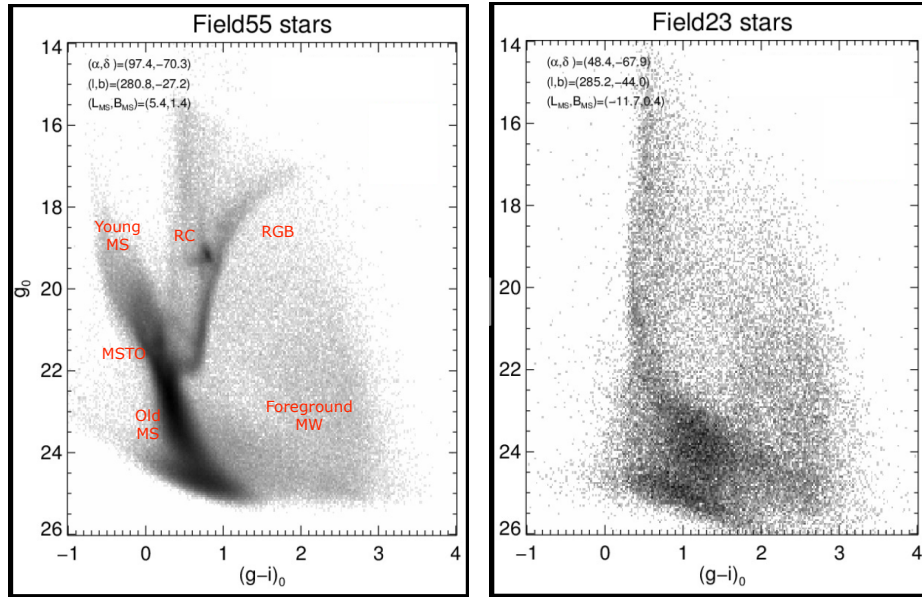


Figure 6.4: (Right) Field 55 with labeled components on its CMD: young main-sequence (MS), main-sequence turnoff (MSTO), old main-sequence (MS), red clump (RC), red giant branch (RGB), and foreground Milky Way (MW) components. Three different coordinates of the field are shown at the top left: equatorial, galactic, and Magellanic Stream coordinates. (Left) CMD of stars of Field 23. Three different coordinates of the field are shown at the top left: equatorial coordinates, galactic coordinates, and Magellanic Stream coordinates.

through two steps: (1) inspecting their CMDs to verify that they had a clear Magellanic main-sequence, and (2) checking that they were not heavily contaminated by dust by inspecting their color-color diagrams to confirm that the locus of stars overlapped that of the calibration dataset.

To inspect the CMDs, I plotted the dereddened  $(g-i)_0$  SMASH color against the dereddened  $g_0$  SMASH magnitude. Figure 6.4 shows an example dereddened CMD of Field 55. The MS and MSTO can be clearly seen, which is the region where I select stars for correct application of the photometric metallicity method, so Field 55 passed this test. An example of a SMASH field I cannot use is shown in Figure 6.4. As this figure demonstrates, Field 23 shows a swath of MW foreground stars with no discernible Magellanic MS and MSTO.

The next step I completed was checking that the data were not too contaminated by dust to use the Schlegel et al. (1998b) dust maps. The very central regions of the LMC and SMC are very dust contaminated, so I avoided those regions. Even some fields on the edges of the main bodies are extremely dust contaminated as well. On the LMC, I used the dust maps of Choi et al. (2018) as a guide for what fields to exclude from my study. Choi et al. (2018) used SMASH data to find the regions of the LMC where there is differential reddening and the Schlegel et al. (1998b) maps cannot be used. I avoided this region and choose fields on the edge of the LMC body and the periphery. There is not yet a similar study on the SMC dust, but I also chose fields on the edge of the SMC main body and on the periphery.

To further ensure the fields were not too contaminated by dust, I made density color-color plots of the bright stars in each SMASH field with density contours of the calibration sample overlaid. Figure 6.5 shows two examples. The grayscale in each of the plots is normalized by taking  $\log_{10}$  of the data. To make the calibration sample contours, I used `gaussian_kde` to create a function to perform a kernel density



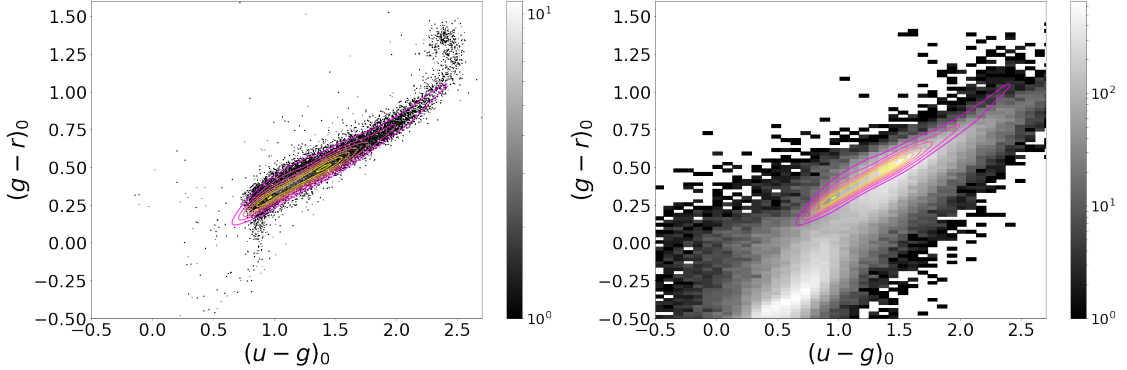


Figure 6.5: (Left) Density plot of stars of Field 91 shown in grayscale, with contours of the calibration sample overlaid. (Right) Density plot of stars of Field 50 shown in grayscale, with contours of the calibration sample overlaid.

estimation (KDE) on my calibration sample. The purpose of this test was to verify that the stars in the SMASH field overlapped with the stars of the calibration sample, so that Figure 6.2 could be used find metallicity of the field’s stars. The left panel Figure 6.5 shows how well the locus of Field 91’s stars overlaps with that of the calibration data; therefore, Field 91 is a good candidate for applying my photometric metallicity method to. In contrast, the right panel of Figure 6.5 shows how Field 50’s stars are systematically shifted redward indicating the presence of dust. The stars are also smeared out due to differential extinction, which occurs when there are different amounts of extinction along the line-of-sight to the stars in the field and, therefore, the stars get shifted by varying degrees in the color-color diagram.

After looking at the CMDs and color-color plots of the data and picking locations that weren’t too obscured by dust, I finalized the list of 53 SMASH fields to study. Figure 6.6 shows the SMASH fields used in this study shown as hexagons with their field numbers.

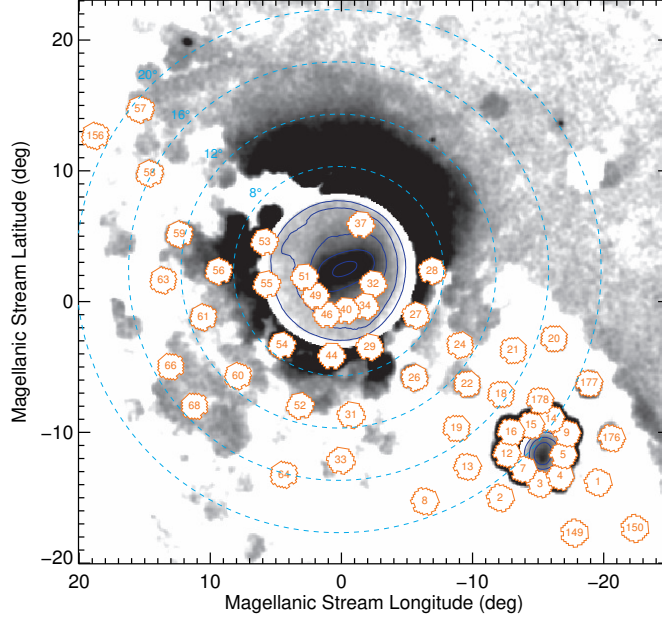


Figure 6.6: The 53 SMASH fields I chose to use in my analysis with their field numbers.

### Calculating Photometric Metallicity

The first step of calculating photometric metallicities was reading in the SMASH data and dereddening the SMASH magnitudes with the  $E(B - V)$  values in the catalogs created using the Schlegel et al. (1998b) dust maps. For the SMASH *ugir* photometry, the corrected magnitudes are:  $u_0 = u - 4.239 \times E(B - V)$ ;  $g_0 = g - 3.303 \times E(B - V)$ ;  $i_0 = i - 1.263 \times E(B - V)$  and  $r = r - 2.285 \times E(B - V)$ . The next step was making magnitude cuts to select Magellaic MSTO stars in the appropriate location of the CMD for proper application of the photometric metallicity method. F and G dwarf stars are the best candidates for this method (Ivezić et al., 2008). To select F and G dwarfs from the SMASH CMDs, I made selections on  $(g - i)_0$  and  $g_0$  in order to select SMASH F and G dwarf stars. The selections I made are  $0.44 \geq (g - i)_0 \geq 0.11$  and  $21.9 \geq g_0 \geq 22.8$ . Figure 6.7 shows SMASH Field 55 with

the selection box overlaid in red. In addition to the magnitude and color cuts, I made cuts on the DAOPHOT parameters `CHI`, `SHARP`, and `PROB`:  $\text{CHI} < 3$ ,  $|\text{SHARP}| < 1$ , and  $\text{PROB} > 0.8$ . The 53 SMASH fields and the density of MSTO off stars in the fields are shown in Figure 6.8.

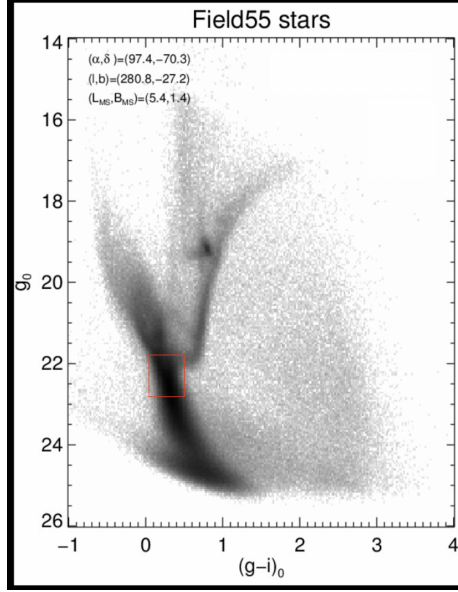


Figure 6.7: Density plot of stars of Field 55 with selection box overlaid in red.

### Measuring Metallicity from Map

Using the information contained in Figure 6.2, I constructed a method to calculate the photometric metallicity in the 53 SMASH fields in the same manner as Ivezić et al. (2008). For each star in every SMASH Field, I used the star's  $(u - g)_0$  and  $(g - r)_0$  colors to measure the metallicity value of the star from the metallicity map shown in Figure 6.2. After reading out the values for all the stars, I then calculated the median metallicity value in each field, as well as the standard deviation and formal error. Table 7.1 displays the SMASH field number, the number of total stars, the number of stars after color and magnitude cuts, the equatorial coordinates, the photometric metallicity values, and the standard deviation.

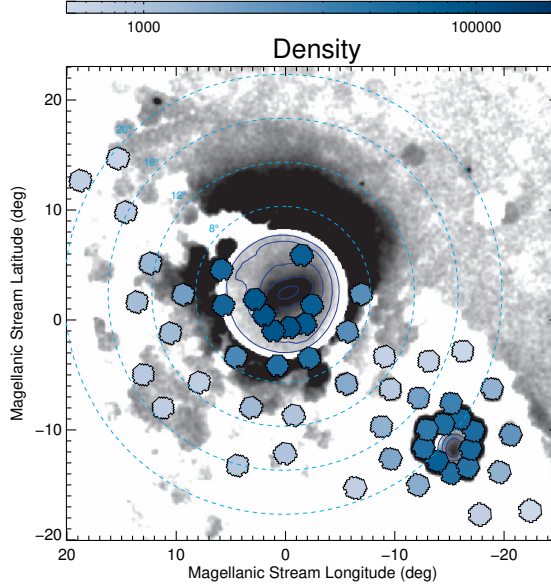


Figure 6.8: The density of MSTO stars in the 53 SMASH fields used in the current analysis.

After inspecting my raw results, I soon realized that my photometric metallicity values were systematically offset compared to previous results on the LMC and SMC. After comparing the metallicities of Field 55 with APOGEE-2S spectroscopic values of red giants (Nidever et al., 2019b, D. Nidever, private communication), I saw that my values were offset by  $\sim 0.6$  dex (too low). Table 7.2 shows the 30 LMC fields arranged in increasing distance to the LMC center with the new metallicity values, called  $[\text{Fe}/\text{H}]_{\text{Offset}}$ , with the  $+0.6$  dex offset applied. Also on the table are the metallicity values Nidever et al. (2019a) found in 14 SMASH fields by fitting isochrones to SMASH CMDs, called  $[\text{Fe}/\text{H}]_{\text{Nidever}}$ . Table 7.3 shows the same values except for the 23 SMC fields.

I will note here that we do not interpret the necessary offset of my metallicity values as meaning my method and study are flawed. It is often necessary to apply an offset in order to calibrate such studies. Therefore, my  $[\text{Fe}/\text{H}]_{\text{Offset}}$  values should be understood as calibrated metallicity values. The systematic offset that we see in

my photometric metallicities is very likely due to the different photometry methods used for the main SMASH data and the standard SMASH fields. As I explained in Section 5, the SMASH standard star fields are reduced with the STDRED pipeline using aperture photometry, whereas the main SMASH data are reduced with the PHOTRED pipeline using PSF photometry.

### RMS Error

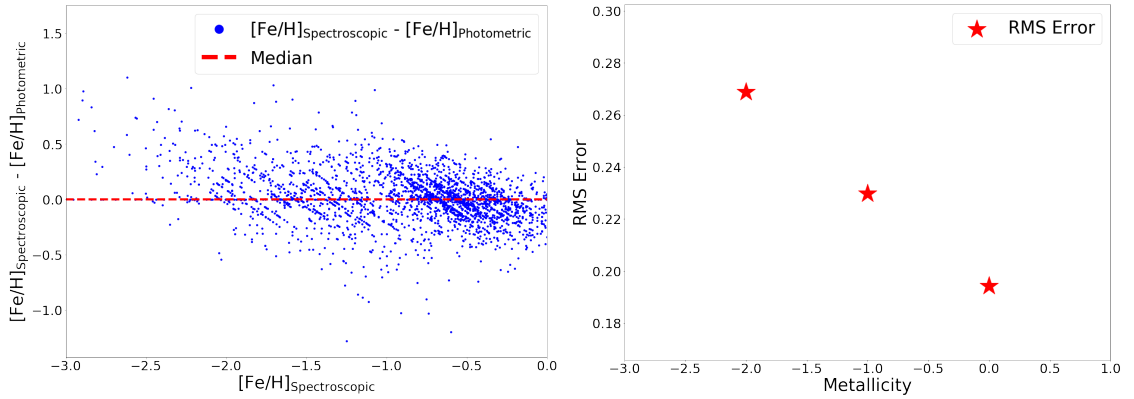


Figure 6.9: (Left) My derived photometric values ( $[\text{Fe}/\text{H}]_{\text{Photometric}}$ ) minus the spectroscopic metallicity values ( $[\text{Fe}/\text{H}]_{\text{Spectroscopic}}$ ) plotted versus spectroscopic metallicity values. This plot shows if there is systematic or random error. (Right) Computed RMS error in bins of 1 dex, plotted as red stars.

In order to generate root mean square (RMS) error, I ran my calibration sample through my photometric metallicity method. To do this, I read in the calibration data, made no color or magnitude cuts to the data, and then measured the metallicity of the 2,770 stars in the calibration sample using Figure 6.2. Next, I plotted my derived photometric values ( $[\text{Fe}/\text{H}]_{\text{Photometric}}$ ) minus the spectroscopic metallicity values ( $[\text{Fe}/\text{H}]_{\text{Spectroscopic}}$ ) plotted versus spectroscopic metallicity values (left side of Figure 6.9). This plot shows if my derived values are too high or too low. It suggests that my method suffers from random error but not systematic error. To next compute

RMS error, I used the blue points in the left of Figure 6.9, also known as the residuals, and computed RMS error in 1 dex bins, shown in the right of Figure 6.9.

### Weighted Averages

To try to improve my photometric metallicity calculation, I decided to compute a different statistic than median in each field. I used a similar method, but instead of computing median metallicity in each field, I computed the weighted average in each field. The formula for computing a weighted average is  $\frac{\sum_{i=1}^N x_i \times w_i}{\sum_{i=1}^N w_i}$ . where  $x_i$  are the measurements and  $w_i$  are the weighting factors. To compute the weighted average of my photometric metallicities in each SMASH field, I tried three methods for computing weighting factors: using  $u$ -band error, using the  $g$ -band error, and using the  $r$ -band error. I do not plan to use this statistic because it did not improve the agreement of my metallicity values with previous studies.

### Interpolating the 2D Metallicity Map

Next, I implemented three different interpolation schemes to my 2D metallicity map (Figure 6.2). One unavoidable downside of my method is that the calibration sample only has 2,770 stars. This limits the amount of metallicity measurements for different values of  $u - g$  and  $g - r$ . Therefore, preserving more values of metallicity for more pairs of  $u - g$ ,  $g - r$  points by using interpolation was a promising idea. Implementing interpolation increases the number of points in the calibration sample available for determining metallicities and can therefore increase the precision (Figure 6.2).

To implement different interpolation methods, I used the `griddata` function in the SciPy module `interpolate`. `griddata` can interpolate unstructured multi-dimensional data by taking sets of associated data points and values and then interpolating them at a given array of points. There are three methods of interpolation

I used within `griddata`: nearest, linear, and cubic. The nearest method interpolates to the value of the data point closest to the point of interpolation. The linear method computes the interpolant by triangulating the input data and then performing linear barycentric interpolation. Finally, the cubic method creates an interpolant by triangulating the input data and constructing a piecewise, cubic interpolating Bezier polynomial on each triangle, using a Clough-Tocher scheme. To run `griddata`, I first created a large grid of data points using the `mgrid` function within the `numpy` python library. `mgrid` outputs a dense multi-dimensional mesh grid, so I used it to create two (1000,1000) grids in the  $u - g$  and the  $g - r$  dimensions of my calibration sample. In both dimensions, I used the the minimum and maximum of the calibration color data as bounds for the grids. I then interpolated my calibration data to all the points on my constructed mesh grids with `mgrid`. The result for each method was 1,000,000 interpolated metallicity values corresponding to 1,000,000 pairs of  $u - g$ ,  $g - r$  values.

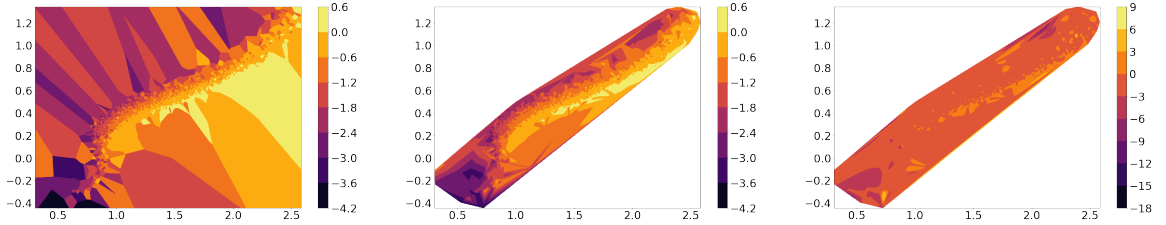


Figure 6.10: The results of using three interpolation schemes. (Left) Nearest interpolation. (Middle) Linear interpolation. (Right) Cubic interpolation.

Figure 6.10 shows the result of my interpolation for the three different methods. For the nearest method, `mgrid` was able to compute an interpolated metallicity value at every point in the mesh grid I input, that is why there is no blank space in the linear method interpolated data. Therefore, there are 1,000,000 interpolated metallicity values corresponding to 1,000,000 pairs of  $u - g$ ,  $g - r$  values for the nearest interpolation method. In contrast, for the linear and cubic methods, `mgrid`

was only able to interpolate 302,540 points closely around the original calibration data.

To calculate photometric metallicity values using these different interpolation methods, I again used the `binned_statistic_2d` function to compute the two-dimensional binned statistics. For homogeneity, I again computed the median metallicity statistic in 2,500 bins across the entire range of  $u - g$  and  $g - r$  colors. For each interpolation method, I used the following parameters: 1,000,000  $u - g$  values, 1,000,000  $g - r$  values, 1,000,000 interpolated metallicity values, median statistic, and 50 bins in each dimension. For each interpolation method, the `binned_statistic_2d` function then returned a (50,50) array of the median metallicity statistic in each of the 2,500 bins. The total number of bins with a statistic computed for the nearest method is 2,500 out of 2,500 total bins. The total number of bins with a statistic computed for the linear and cubic methods is 846 out of 2,500 total bins. The grid in the “x” and “y” dimensions were the same for my original metallicity map 6.2. Figure 6.11 shows the binned statistic for each interpolation method.

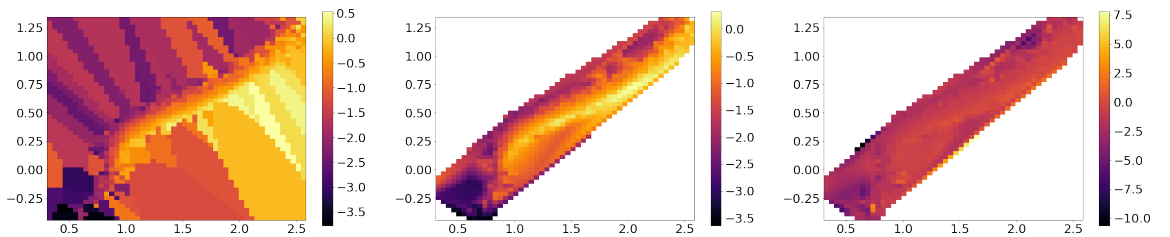


Figure 6.11: The binned median metallicity for the interpolated data. (Left) Nearest interpolation. (Middle) Linear interpolation. (Right) Cubic interpolation.

Using the information contained in Figure 6.11, I constructed methods to calculate the photometric metallicity in the 53 SMASH fields. For each star in every SMASH Field, I used the star’s  $u - g$  and  $g - r$  color indices to read out the metallicity value of the star on each subplot in Figure 6.2. After reading out the value of each star,



I then calculated the median metallicity value in each field, as well as the standard deviation and standard error. In the end, none of the three interpolated metallicity map methods improved the agreement of my metallicities with previous studies, and, therefore, I did not use them in my final results.

#### Nearest Neighbors Approximation

Next, I calculated photometric metallicities without using a 2D binned metallicity map. The method I tried is called nearest neighbors approximation, which is a supervised, regressive machine learning algorithm. This approximation can be used to predict continuous data points based on the mean of the labels of its nearest neighbors. To implement this, I used the `KNeighborsRegressor` class in the `sklearn` module `neighbors`. I created a `KNeighborsRegressor` object that takes the mean of the five neighbors, weighted equally. Then, I called the `fit` method to use the calibration data as training data. Finally, I called the `predict` method to predict metallicity values for every star in every SMASH field. Then I took the median value of all the predicted metallicity values in each field. Again, I did not use this method because it also did not improve the agreement of my metallicities with previous studies.

#### PARSEC Isochrones Tracks Method

The final method of computing photometric metallicities that I tried is using PARSEC isochrone stellar evolutionary tracks computed with the code described in Marigo et al. (2017). This code computes a set of isochrones for given stellar ages and photometric filter set, with different metallicity values for every point in the tracks. I used a set of isochrones with an input age of 3 Gyr, a large range of metallicities, and for the DECam photometric filter set. The isochrones include photometric magnitudes in the DECam filters (*ugriz*) and with associated metallicity values. In order to use

these data, the first step I needed to complete was to shift the position of the isochrone data in the  $u-g$  versus  $g-r$  plane to match the metallicities of my calibration sample. First, I plotted a color-color diagram of the isochrone data with a color-color diagram of my calibration sample. After inspecting these, I determined that I needed to apply an initial +0.3 mag shift to the isochrone  $u-g$  colors. This is shown in Figure 6.12.

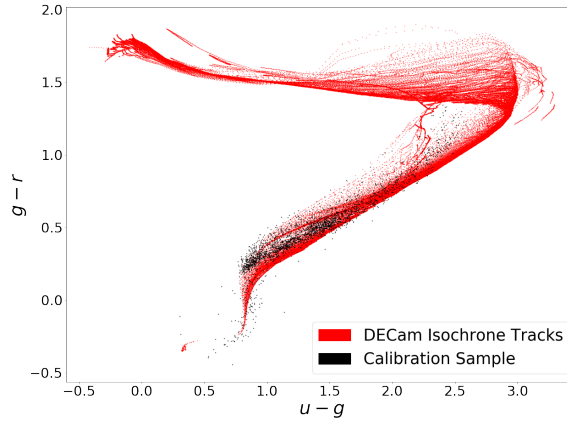


Figure 6.12: Color-color diagrams of my calibration sample in black and the PARSEC isochrone data is red.

To further optimize the position of the isochrone data in color-color space, I needed to minimize the residuals. To do this, I used `binned_statistic_2d` class again to create binned images of median metallicity. The residual in this case is the binned image of my calibration sample minus the binned image of the isochrone data. To minimize the residual matrix, I calculated the Frobenius norm of the matrix image. The Frobenius norm is defined as the square root of the absolute sum of the absolute squares of the matrix elements. By finding the position of the residual with the smallest Frobenius norm, I effectively found the matrix of the residuals with the smallest elements. The residual with the smallest elements represents a position of the shifted isochrone data that is the closest to my calibration sample. I decided to minimize the residuals in a smaller region around the values of  $u-g$  and  $g-r$  that

the SMASH stars I compute metallicity for fall into. I restricted both sample's color data to these two ranges:  $1.6 \geq u - g \geq 0.4$  and  $0.8 \geq u - g \geq -0.2$ . I then used `binned_statistic_2d` class to make two binned images with 50 bins in ranges larger than the restricted color ranges:  $2.0 \geq u - g \geq 0.1$  and  $1.1 \geq u - g \geq -0.5$ . Figure 6.13 display the calibration image and the isochrone image.

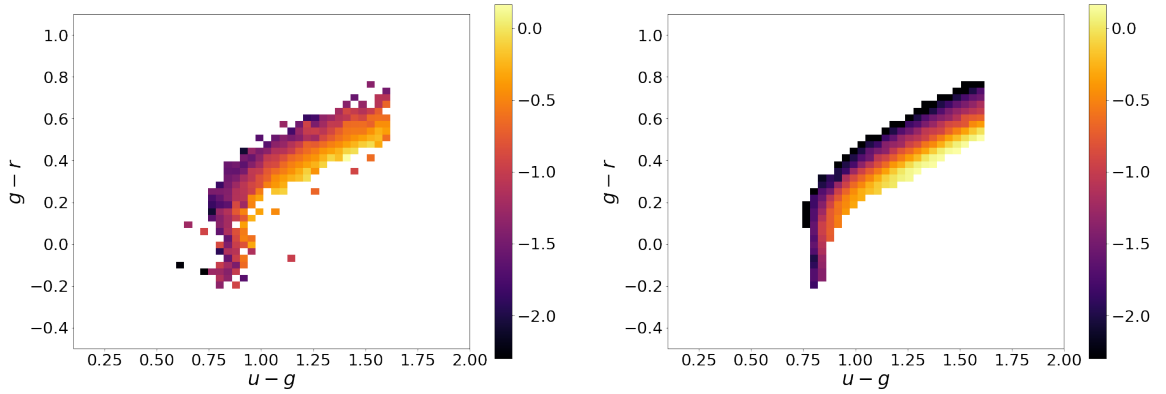


Figure 6.13: Binned metallicity for the calibration sample and the PARSEC isochrone data in restricted ranges of colors. (Left) Calibration sample. (Right) PARSEC isochrone data.

To find the best position of the left panel of Figure 6.13 to minimize the Frobenius norm of the matrix residual, I moved the restricted raw isochrone color data around a range in both  $u - g$  and  $g - r$  of -0.25 to 0.25 magnitudes in increments of 0.005 magnitudes. For each possible different position, I then created an image of the isochrone with the `binned_statistic_2d` class and calculated the resulting Frobenius norm of the residual matrix. After computing the Frobenius norm of the residuals in 10,000 different positions in the assigned range, I found the optimal position to be to be shifted in both  $u - g$  and  $g - r$  by -0.005 magnitudes. Figure 6.14 shows the Frobenius norm at each different position in color-color space.

To now compute the photometric metallicities of the 53 SMASH fields with the optimized isochrone data, I shifted the isochrone data and then used the

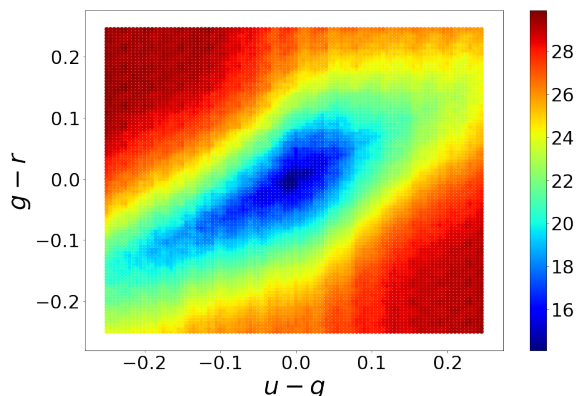


Figure 6.14: Frobenius norm in each of the 10,000 positions checked in color-color space.

`binned_statistic_2d` class to compute the two-dimensional binned statistics. For continuity, I again computed the median metallicity statistic in 2,500 bins across the entire range of  $u - g$  and  $g - r$  colors. I used the isochrone  $u - g$  values, the isochrone  $g - r$  values, the isochrone metallicities, median statistic, and 50 bins in each dimension. The total number of bins with a statistic computed was 436 out of 2,500 total bins. Figure 6.15 shows my optimized isochrone metallicity map.

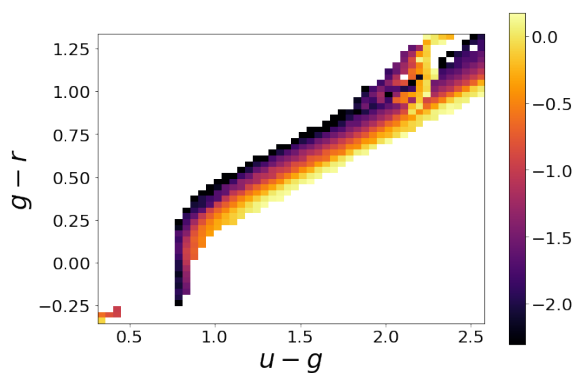


Figure 6.15: Binned metallicity for the optimized PARSEC isochrone data.

Using the information contained in Figure 6.15, I constructed a method to calculate the photometric metallicity in the 53 SMASH fields. For each star in

every SMASH Field, I used the star's  $u - g$  and  $g - r$  color indexes to read out the metallicity value of the star on Figure 6.15. After reading out the value of each star, I then calculated the median metallicity value in each field, as well as the standard deviation and standard error. Although at this time I am not using the results from this method as my main results, they are very promising and I will continue to work to improve this method in the future.

## RESULTS

In this Chapter, I will outline the results of the different methods I used to calculate photometric metallicities. For each method, I have calculated the photometric metallicities of 2,670,768 of stars in 53 SMASH fields, 30 LMC fields and 23 SMC fields. For each method, I selected SMASH F and G dwarf MSTO stars and used  $u - g$  and  $g - r$  to calculate photometric metallicities.

Original Method Results

In this section I will provide results for the original method I tried: for each star, measuring metallicity values for given  $u - g$ ,  $g - r$  values off of Figure 6.2 and then taking the median of stars in each SMASH field. Table 7.1 shows the SMASH field number, the total number of stars in the field, the number of MSTO stars in the field, the right ascension, the declination, the photometric metallicity values, and the standard deviations.

Table 7.1: SMASH Field number, initial count of all stars, number of stars after color and magnitude cuts, right ascension, declination, metallicity, and standard deviation.

| Field | Initial Star Count | Star Count After Cuts | $\alpha$ (deg) | $\delta$ (deg) | [Fe/H] | $\sigma_{[Fe/H]}$ |
|-------|--------------------|-----------------------|----------------|----------------|--------|-------------------|
| 1     | 46634              | 2849                  | 2.583          | -69.795        | -1.2   | 0.676             |
| 2     | 61991              | 3435                  | 4.741          | -77.083        | -1.377 | 0.67              |
| 3     | 847797             | 65489                 | 5.83           | -73.969        | -1.342 | 0.643             |
| 4     | 640420             | 54416                 | 6.236          | -72.386        | -1.377 | 0.635             |
| 5     | 1048414            | 92611                 | 11.028         | -71.629        | -1.543 | 0.638             |
| 7     | 1201514            | 146618                | 11.264         | -74.804        | -1.377 | 0.648             |
| 8     | 53873              | 625                   | 12.644         | -82.474        | -1.573 | 0.603             |
| 9     | 723837             | 75346                 | 15.364         | -70.718        | -1.447 | 0.637             |
| 12    | 515707             | 64007                 | 17.296         | -75.45         | -1.447 | 0.661             |
| 13    | 80790              | 4344                  | 19.393         | -78.511        | -1.447 | 0.654             |
| 14    | 776768             | 85748                 | 20.112         | -71.259        | -1.447 | 0.633             |
| 15    | 755871             | 66660                 | 21.14          | -72.825        | -1.447 | 0.652             |
| 16    | 402062             | 40929                 | 22.356         | -74.367        | -1.463 | 0.644             |
| 18    | 77413              | 5585                  | 32.301         | -73.272        | -1.447 | 0.638             |
| 19    | 43871              | 2830                  | 33.299         | -77.512        | -1.514 | 0.662             |
| 20    | 42362              | 379                   | 33.774         | -67.435        | -1.666 | 0.522             |
| 21    | 46188              | 551                   | 38.015         | -70.284        | -1.377 | 0.614             |

|     |         |        |         |         |        |       |
|-----|---------|--------|---------|---------|--------|-------|
| 22  | 59954   | 755    | 40.873  | -74.533 | -1.72  | 0.554 |
| 24  | 29599   | 560    | 48.725  | -72.489 | -1.447 | 0.708 |
| 26  | 52301   | 3767   | 55.071  | -76.415 | -1.377 | 0.652 |
| 27  | 94878   | 13883  | 62.04   | -72.038 | -1.444 | 0.668 |
| 28  | 114705  | 13946  | 62.208  | -68.417 | -1.377 | 0.659 |
| 29  | 404098  | 67384  | 71.522  | -75.374 | -1.447 | 0.642 |
| 31  | 46943   | 1132   | 73.233  | -80.748 | -1.543 | 0.645 |
| 32  | 1825281 | 152476 | 73.826  | -70.58  | -1.274 | 0.664 |
| 33  | 45996   | 1105   | 74.38   | -84.309 | -1.342 | 0.697 |
| 34  | 1421909 | 190149 | 74.825  | -72.377 | -1.447 | 0.633 |
| 37  | 1743130 | 145725 | 78.054  | -66.214 | -1.342 | 0.659 |
| 40  | 1752944 | 315218 | 79.564  | -72.869 | -1.342 | 0.647 |
| 44  | 427557  | 61749  | 83.023  | -76.389 | -1.666 | 0.557 |
| 46  | 1304849 | 240939 | 84.509  | -73.237 | -1.447 | 0.673 |
| 49  | 1763774 | 250502 | 87.254  | -71.781 | -1.248 | 0.616 |
| 51  | 1574573 | 210235 | 89.521  | -70.28  | -1.377 | 0.645 |
| 52  | 62890   | 1949   | 96.354  | -79.998 | -1.666 | 0.62  |
| 53  | 396092  | 104288 | 96.749  | -67.18  | -1.447 | 0.648 |
| 54  | 163332  | 19381  | 98.037  | -75.186 | -1.543 | 0.616 |
| 55  | 637616  | 106127 | 98.232  | -70.367 | -1.447 | 0.647 |
| 56  | 120917  | 6302   | 107.298 | -68.314 | -1.913 | 0.465 |
| 57  | 76423   | 472    | 108.637 | -54.622 | -1.656 | 0.55  |
| 58  | 77341   | 788    | 111.26  | -59.35  | -1.441 | 0.641 |
| 59  | 88849   | 2148   | 111.286 | -64.52  | -1.543 | 0.629 |
| 60  | 59324   | 664    | 114.087 | -76.191 | -1.913 | 0.57  |
| 61  | 80665   | 1745   | 114.673 | -70.992 | -1.573 | 0.624 |
| 63  | 113977  | 1575   | 118.049 | -67.009 | -1.824 | 0.578 |
| 64  | 68421   | 912    | 120.112 | -84.443 | -1.572 | 0.583 |
| 66  | 101460  | 784    | 128.154 | -72.66  | -1.447 | 0.616 |
| 68  | 90704   | 689    | 130.919 | -76.1   | -1.441 | 0.621 |
| 149 | 69283   | 616    | 351.667 | -72.086 | -1.543 | 0.614 |
| 150 | 46060   | 343    | 351.815 | -67.69  | -1.572 | 0.604 |
| 156 | 122018  | 636    | 115.387 | -54.889 | -1.377 | 0.688 |
| 176 | 111318  | 10154  | 10.651  | -67.794 | -1.447 | 0.634 |
| 177 | 98553   | 2870   | 22.459  | -67.393 | -1.342 | 0.632 |
| 178 | 233226  | 26378  | 25.12   | -71.218 | -1.447 | 0.64  |

The next values I present in this section are the values in Table 7.1 with a +0.6 dex offset applied to match past studies. For this and the following analysis, I used ( $\alpha = 81.90$ ,  $\delta = -69.87$ ) for the center of the LMC and ( $\alpha = 13.18$ ,  $\delta = -72.82$ ) for the center of the SMC (Nidever et al., 2017). For these data, I have organized two tables: one for the LMC (Table 7.2) and one for the SMC (Table 7.3). I put SMASH fields into the SMC/LMC category by eye. They both have the SMASH field number, the radius and position angle from either LMC/SMC center, and the metallicity with

the offset applied ( $[\text{Fe}/\text{H}]_{\text{Offset}}$ ). To show some motivation for applying the offset, I have also included metallicity values that Nidever et al. (2019a) derived for SMASH fields by fitting isochrones to SMASH CMDs ( $[\text{Fe}/\text{H}]_{\text{Nidever}}$ ).

Table 7.2: The 30 LMC fields used in my analysis. Field is the SMASH Field number, R. is radius, P.A. is position angle east of north the LMC's center,  $[\text{Fe}/\text{H}]_{\text{Offset}}$  are the photometric metallicity values from Table 7.1 with a +0.6 dex offset applied, and  $[\text{Fe}/\text{H}]_{\text{Nidever}}$  are metallicity values taken from Nidever et al. (2019a)

| Field | R. (deg) | P.A. (deg) | $[\text{Fe}/\text{H}]_{\text{Offset}}$ | $[\text{Fe}/\text{H}]_{\text{Nidever}}$ |
|-------|----------|------------|----------------------------------------|-----------------------------------------|
| 49    | 2.598    | 314.874    | -0.648                                 |                                         |
| 51    | 2.628    | 275.452    | -0.777                                 |                                         |
| 32    | 2.821    | 79.191     | -0.674                                 |                                         |
| 40    | 3.093    | 15.069     | -0.742                                 |                                         |
| 34    | 3.393    | 45.752     | -0.847                                 |                                         |
| 46    | 3.469    | 344.994    | -0.847                                 |                                         |
| 37    | 3.924    | 160.283    | -0.742                                 |                                         |
| 55    | 5.56     | 267.425    | -0.847                                 | -0.7                                    |
| 53    | 6.043    | 236.92     | -0.847                                 |                                         |
| 29    | 6.299    | 34.409     | -0.847                                 |                                         |
| 44    | 6.53     | 356.599    | -1.066                                 |                                         |
| 27    | 6.798    | 81.048     | -0.844                                 | -0.7                                    |
| 28    | 7.126    | 110.781    | -0.777                                 | -0.7                                    |
| 54    | 7.149    | 309.757    | -0.943                                 | -0.7                                    |
| 56    | 9.127    | 248.547    | -1.313                                 | -0.7                                    |
| 26    | 10.011   | 63.332     | -0.777                                 | -0.7                                    |
| 52    | 10.73    | 332.521    | -1.066                                 | -0.9                                    |
| 24    | 10.866   | 92.355     | -0.847                                 |                                         |
| 61    | 10.899   | 260.204    | -0.973                                 | -0.7                                    |
| 31    | 11.071   | 15.671     | -0.943                                 |                                         |
| 60    | 11.102   | 287.778    | -1.313                                 | -0.7                                    |
| 59    | 12.42    | 231.748    | -0.943                                 | -0.7                                    |
| 63    | 13.376   | 241.366    | -1.224                                 | -0.7                                    |
| 33    | 14.509   | 10.359     | -0.742                                 |                                         |
| 66    | 14.724   | 258.045    | -0.847                                 | -0.7                                    |
| 68    | 15.066   | 268.582    | -0.841                                 |                                         |
| 64    | 16.122   | 309.936    | -0.972                                 | -0.7                                    |
| 58    | 16.124   | 217.423    | -0.841                                 |                                         |
| 57    | 19.351   | 207.862    | -1.056                                 | -0.7                                    |
| 156   | 21.067   | 211.893    | -0.777                                 |                                         |

Another visual representation of these two data tables can be seen in Figure 7.1. These are plots of radii from the LMC/SMC center versus  $[\text{Fe}/\text{H}]_{\text{Offset}}$ . On both plots, the error bars represent standard error.



Table 7.3: The 23 SMC fields used in my analysis. Field is the SMASH Field number, R. is radius, P.A. is position angle east of north the SMC's center,  $[\text{Fe}/\text{H}]_{\text{Offset}}$  are the photometric metallicity values from Table 7.1 with a +0.6 dex offset applied.

| Field | R. (deg) | P.A. (deg) | $[\text{Fe}/\text{H}]_{\text{Offset}}$ |
|-------|----------|------------|----------------------------------------|
| 5     | 1.367    | 152.272    | -0.943                                 |
| 7     | 2.047    | 16.076     | -0.777                                 |
| 4     | 2.122    | 105.336    | -0.777                                 |
| 9     | 2.217    | 196.881    | -0.847                                 |
| 15    | 2.348    | 266.117    | -0.847                                 |
| 3     | 2.388    | 65.062     | -0.742                                 |
| 14    | 2.648    | 230.434    | -0.847                                 |
| 12    | 2.851    | 334.809    | -0.847                                 |
| 16    | 3.008    | 296.265    | -0.863                                 |
| 178   | 4.012    | 240.781    | -0.847                                 |
| 1     | 4.543    | 136.709    | -0.6                                   |
| 2     | 4.775    | 31.375     | -0.777                                 |
| 176   | 5.105    | 171.571    | -0.847                                 |
| 18    | 5.567    | 265.355    | -0.847                                 |
| 13    | 5.879    | 341.834    | -0.847                                 |
| 177   | 6.269    | 205.834    | -0.742                                 |
| 149   | 6.492    | 106.72     | -0.943                                 |
| 19    | 6.896    | 302.256    | -0.914                                 |
| 22    | 7.887    | 268.817    | -1.12                                  |
| 21    | 8.188    | 240.52     | -0.777                                 |
| 20    | 8.759    | 222.985    | -1.066                                 |
| 150   | 8.782    | 135.203    | -0.972                                 |
| 8     | 9.646    | 0.951      | -0.973                                 |

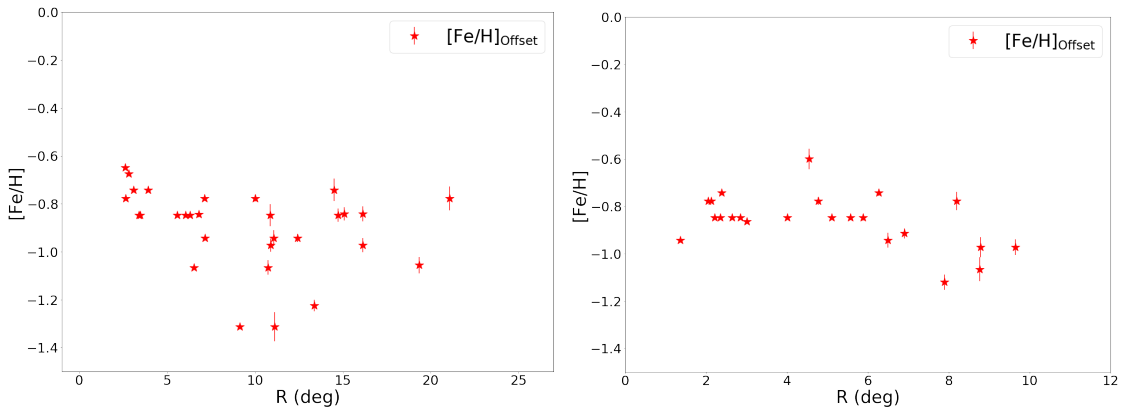


Figure 7.1: (Left) LMC radius versus  $[\text{Fe}/\text{H}]_{\text{Offset}}$  for the 30 LMC fields plotted as red stars with error bars representing standard error. (Right) SMC radius versus  $[\text{Fe}/\text{H}]_{\text{Offset}}$  for the 23 SMC fields plotted as red stars with error bars representing standard error.

### Weighted Averages Results

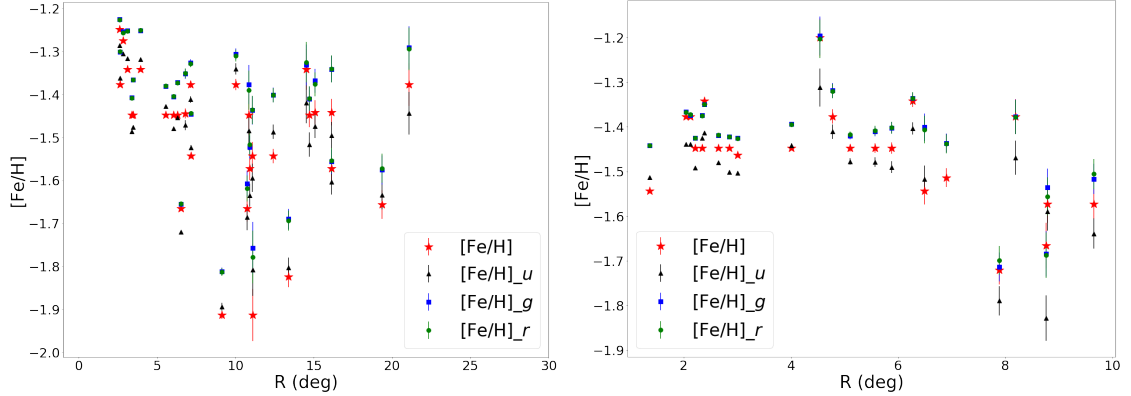


Figure 7.2: (Left) LMC radii versus original  $[\text{Fe}/\text{H}]$  (plotted as red stars),  $[\text{Fe}/\text{H}]_u$  (plotted as black triangles),  $[\text{Fe}/\text{H}]_g$  (plotted as blue squares), and  $[\text{Fe}/\text{H}]_r$  (plotted as green circles) for the 30 LMC fields. The subscripts refer to the band in which the error was used to compute the weighting factors. The errors represent standard error. (Right) SMC radii versus original  $[\text{Fe}/\text{H}]$  (plotted as red stars),  $[\text{Fe}/\text{H}]_u$  (plotted as black triangles),  $[\text{Fe}/\text{H}]_g$  (plotted as blue squares), and  $[\text{Fe}/\text{H}]_r$  (plotted as green circles) for the 30 LMC fields. The subscripts refer to the band in which the error was used to compute the weighting factors. The error bars represent standard error.

The next results are from calculating the weighted average of each SMASH field. Again I have plotted  $[\text{Fe}/\text{H}]$  values versus radii from LMC/SMC center, shown in Figures 7.2. On both plots,  $[\text{Fe}/\text{H}]_u$  represents values calculated using the  $u$ -band error to calculate the weight,  $[\text{Fe}/\text{H}]_g$  represents values calculated using the  $g$ -band error to calculate the weight, and  $[\text{Fe}/\text{H}]_r$  represents values calculated using the  $r$ -band error to calculate the weight. I also plotted the my original metallicity values in order to compare, which I write as  $[\text{Fe}/\text{H}]$ .

### Interpolated 2D Metallicity Map Results

The results in this section are from the three interpolation methods I tried: nearest, linear, and cubic. Again I have plotted  $[\text{Fe}/\text{H}]$  values versus radii from the

LMC/SMC center, shown in Figure 7.3. On both plots,  $[\text{Fe}/\text{H}]_{\text{Nearest}}$  represents the metallicity values calculated using the nearest interpolation,  $[\text{Fe}/\text{H}]_{\text{Linear}}$  represents the metallicity values calculated using the linear interpolation, and  $[\text{Fe}/\text{H}]_{\text{Cubic}}$  represents the metallicity values calculated using the cubic interpolation. I also plotted my original metallicity values in order to compare, which I write as  $[\text{Fe}/\text{H}]$ .

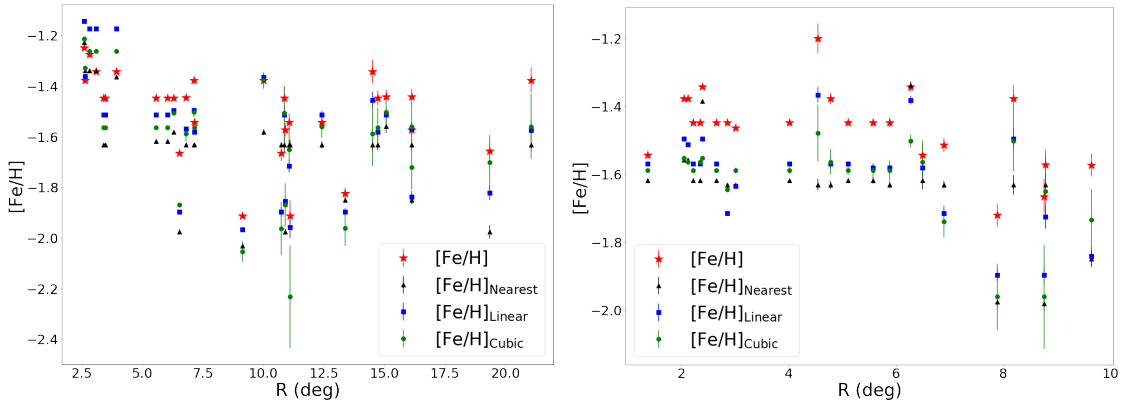


Figure 7.3: (Left) LMC radii versus original  $[\text{Fe}/\text{H}]$  (plotted as red stars),  $[\text{Fe}/\text{H}]_{\text{Nearest}}$  (plotted as black triangles),  $[\text{Fe}/\text{H}]_{\text{Linear}}$  (plotted as blue squares), and  $[\text{Fe}/\text{H}]_{\text{Cubic}}$  (plotted as green circles) for the 30 LMC fields. The subscripts refer to the type of interpolation method used. The errors represent standard error. (Right) SMC radii versus original  $[\text{Fe}/\text{H}]$  (plotted as red stars),  $[\text{Fe}/\text{H}]_{\text{Nearest}}$  (plotted as black triangles),  $[\text{Fe}/\text{H}]_{\text{Linear}}$  (plotted as green squares), and  $[\text{Fe}/\text{H}]_{\text{Cubic}}$  (plotted as green circles) for the 30 LMC fields. The subscripts refer to the type of interpolation method used. The errors represent standard error.

### Nearest Neighbor Algorithm Results

This section holds the results for the nearest neighbors approximation using a supervised, regressive machine learning algorithm. Again I have plotted  $[\text{Fe}/\text{H}]$  values versus radii from LMC/SMC center, shown in Figure 7.4. On both plots,  $[\text{Fe}/\text{H}]_{\text{Regressor}}$  represents the metallicity values calculated using the nearest neighbors approximation. I also plotted my original metallicity values in order to compare, which I write as  $[\text{Fe}/\text{H}]$ .

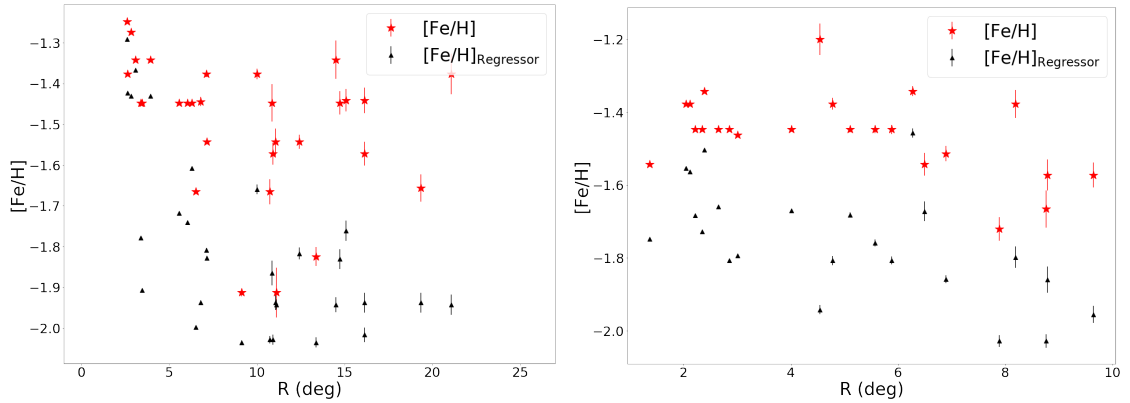


Figure 7.4: (Left) LMC radii versus original  $[\text{Fe}/\text{H}]$  (plotted as red stars) and  $[\text{Fe}/\text{H}]_{\text{Regressor}}$  (plotted as black triangles) for the 30 LMC fields. The errors represent standard error. (Right) SMC radii versus original  $[\text{Fe}/\text{H}]$  (plotted as red stars) and  $[\text{Fe}/\text{H}]_{\text{Regressor}}$  (plotted as black triangles) for the 23 SMC fields. The errors represent standard error.

### PARSEC Isochrone Method Results

Finally, in this section I display the results from using the PARSEC isochrone data to calculate photometric metallicities. Again I have plotted  $[\text{Fe}/\text{H}]$  values versus radii from LMC/SMC center, shown in Figure 7.5. On both plots,  $[\text{Fe}/\text{H}]_{\text{Isochrones}}$  represents the metallicity values calculated using the isochrone data. I also plotted the my original metallicity values in order to compare, which I write as  $[\text{Fe}/\text{H}]$ .

### Comparison to Past Studies

Figure 7.6 shows my derived metallicities ( $[\text{Fe}/\text{H}]_{\text{Offset}}$ ) overlaid on the 17 past LMC metallicity studies I cite. Figure 7.7 shows my derived metallicities overlaid on the 7 past SMC metallicity studies I cite. For more discussion these past studies and citations, see Section 4.

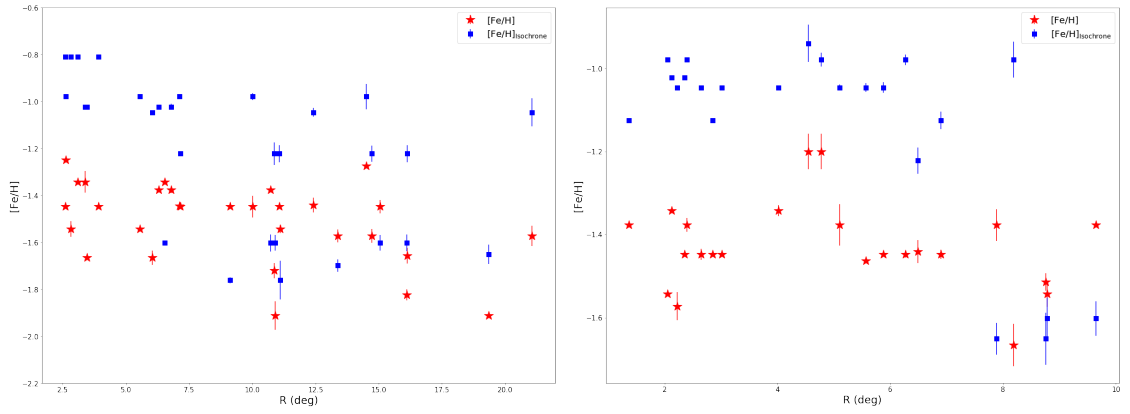


Figure 7.5: (Left) LMC radii versus original  $[\text{Fe}/\text{H}]$  (plotted as red stars) and  $[\text{Fe}/\text{H}]_{\text{Isochrone}}$  (plotted as blue squares) for the 30 LMC fields. The error bars represent standard error. (Right) SMC radii versus original  $[\text{Fe}/\text{H}]$  (plotted as red stars) and  $[\text{Fe}/\text{H}]_{\text{Isochrone}}$  (plotted as blue squares) for the 23 SMC fields. The error bars represent standard error.

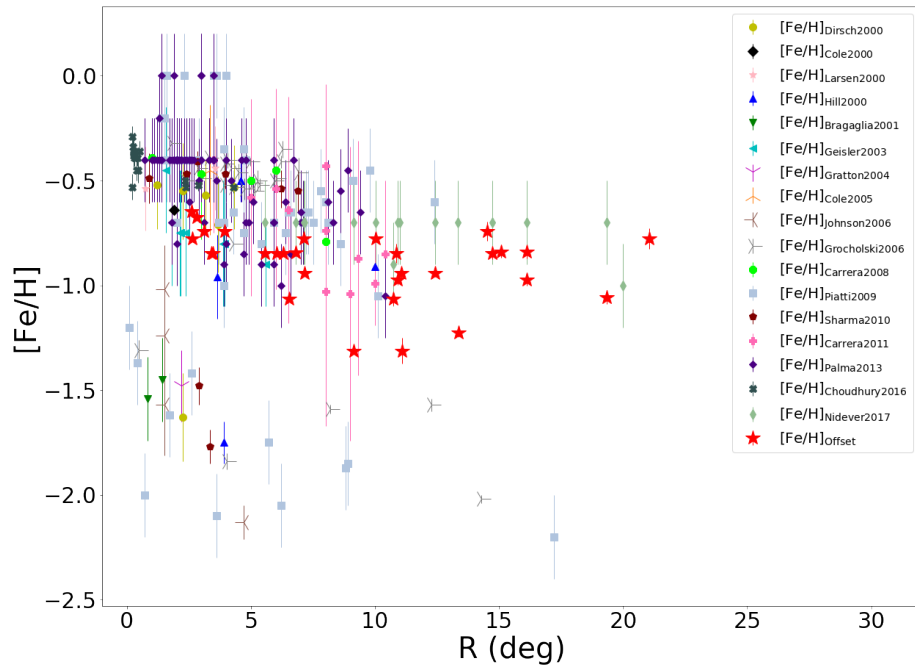


Figure 7.6: LMC radius versus  $[\text{Fe}/\text{H}]_{\text{Offset}}$  on top of the 17 past LMC metallicity studies (see section 4).

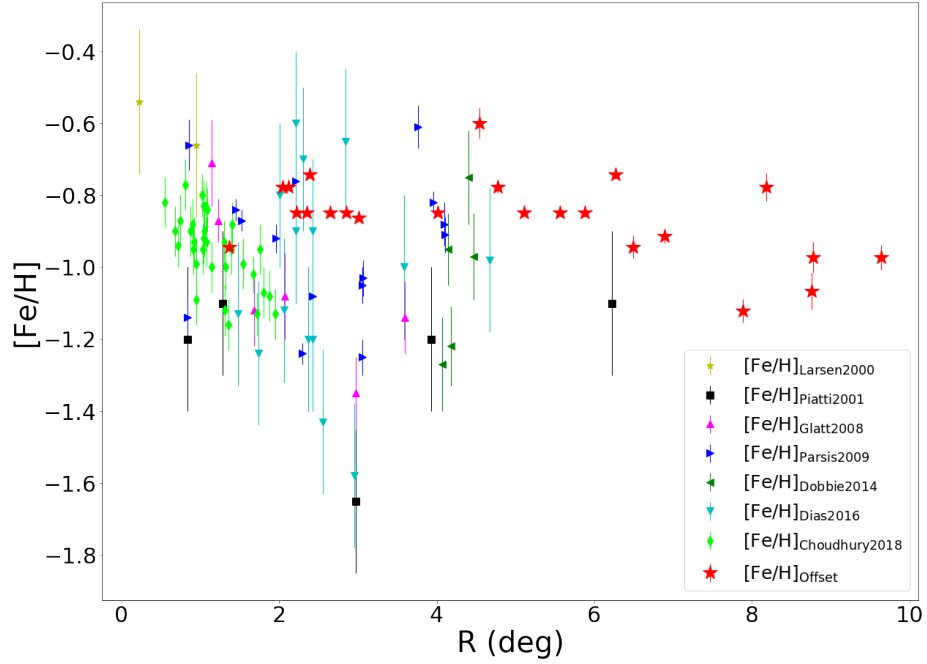


Figure 7.7: LMC radius versus  $[\text{Fe}/\text{H}]_{\text{Offset}}$  on top of the 7 past SMC metallicity studies (see section 4).

### Discussion on Data Trends

It is somewhat astonishing that for every different method I used to calculate photometric metallicities, the same trends are observed. Even for the nearest neighbor approximation, the simplest and roughest method, the same trends can be seen for both the LMC and SMC. To clearly display the trends, Figure 7.8 shows the 53 SMASH fields with the colorbar representing the values of  $[\text{Fe}/\text{H}]_{\text{Offset}}$ .

### Large Magellanic Cloud Trends

On the LMC, there is a clear, shallow, negative metallicity gradient radially outward. There are some outliers to this trend, particularly in the extended outskirts of the LMC periphery at  $R \sim 21^\circ$  from the LMC center. This indicates that there is a negative metallicity gradient in the extended disk and there are multiple populations

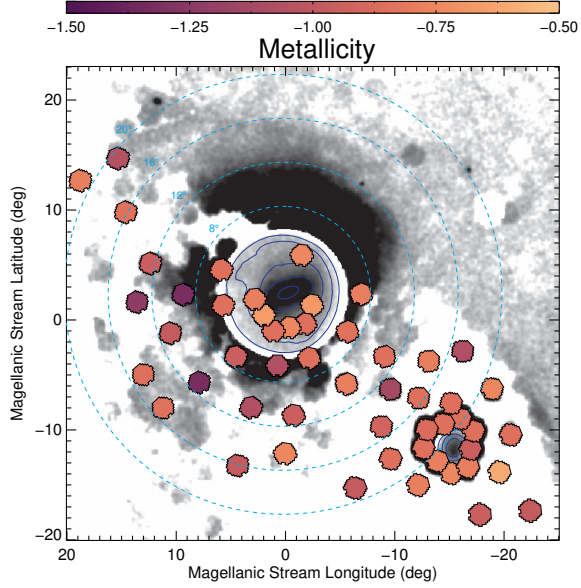


Figure 7.8:  $[\text{Fe}/\text{H}]_{\text{Offset}}$  plotted in each of the 53 SMASH fields used in my analysis.

in the extended periphery.

#### Small Magellanic Cloud Trends

The results indicate that the SMC has lower metallicity than the LMC overall. This is an expected result, as the SMC is much smaller than the LMC. In stark contrast to the LMC, the SMC metallicity values are mostly constant until  $R \sim 8.5^\circ$  from the SMC center. There is no discernible metallicity gradient on the outer main body of the SMC.

## CONCLUSION

My results can help to elucidate the origin of the enigmatic Magellanic periphery. Although I tried eight methods on top of my original calculation, at this point I believe the most accurate method is what I have called  $[\text{Fe}/\text{H}]_{\text{Offset}}$  and plotted in Figure 7.8. That I had to apply a +0.6 dex offset to match previous studies—especially those conducted by Nidever et al. (2019a) in the same regions of sky with the same SMASH data—was at first troubling to me. However, the more I contemplate the peculiarities of my calibration sample and the data sets, the more it makes sense. The calibration data was found by crossmatching SMASH standard star fields with SDSS and LAMOST data in the equatorial regions on the celestial sphere. Therefore, they are brighter stars that belong to the MW, so they are much closer. Compared to the SMASH field data on the MCs, they are in a completely different part of the sky and are attenuated by earth’s atmosphere differently. Additionally, the SMASH standard fields were reduced in a different manner compared to the SMASH field data. Furthermore, I used two different spectroscopic data sets. It is possible they could be calibrated differently and one needs an offset applied to it to be on the same metallicity scale. I have not investigate this possibility yet. Finally, my calibration sample in general could be composed of different populations compared to the SMASH data I am studying. This is complicated further by the fact that my calibration is quite small (2,400 stars) compared to Ivezić et al. (2008)’s (60,000 stars). Considering all these factors, that there is a systematic offset makes sense.

My results for the LMC indicate that there exists a shallow negative metallicity gradient radially outward. Additionally, the metallicity profile of my values farthest from the LMC center match the profile of the outer LMC disk, and follow the negative metallicity gradient that many past LMC studies have established (Cioni, 2009) and



that is well-known for larger galaxies in the Local Group (McConnachie, 2012). As I have discussed in previous sections, there are two main theories for the origin of the LMC periphery: its own halo of accreted satellite galaxies, or tidally stripped LMC material. Our results slightly favor the latter explanation because a halo is thought to be even more metal poor, at least  $-2$  dex (Majewski et al., 2009), and our lowest metallicity value on the LMC is not even  $-1.5$  dex. Moreover, given the fact that our results support the latter theory, my study supports the assertion that the two galaxies had a recent collision. This assertion is also strongly backed by recent simulations (Besla et al., 2012, 2010a). In this scenario, it is thought the SMC basically plowed through the LMC. If this occurred, there would be imprints along the outskirts of the LMC in the form of tidal LMC debris. Because the metallicity profile of my farthest metallicity values matches that of the outer disk, this is strong evidence that it is tidal debris from the collision.

In contrast to the LMC, my results show the metallicity values are relatively constant on the main body and moving radially outward to  $10^\circ$  from the SMC center. Simulations suggest this material is stars stripped from the SMC quite recently through a collision with the LMC, and our results seem to agree with that assertion (Besla et al., 2012, 2010a). The fact that there is no gradient agrees with similar findings that the smaller SMC is highly disturbed and has material all over the place. The SMC is much smaller than the LMC, so it makes sense that any metallicity gradient that might have existed in the past was basically wiped out by the recent interaction with the LMC. The outer SMC was already most loosely bound to the SMC and most susceptible to disruption. Additionally, Parisi et al. (2009) pointed out that barred galaxies display less of a metallicity gradient compared to their spiral, non-barred counterparts. Therefore, given the facts that the SMC has a subtle bar, is ten times smaller than the LMC, and many allege that the Clouds had a recent

collision, the constant metallicity values make sense.

### Future Work

Although I am satisfied that my results largely make sense and can be explained by the current, popular paradigm of the MCs first infall scenario and recent collision, there are still things I want to do to improve my study. I would like to further explore the systematic offset by running my calibration sample through my photometric metallicity method using just the photometric colors, and then compare the results to the spectroscopic metallicity values. Next, I want to crossmatch LAMOST and SDSS and explore if their metallicity values are on different scales. Finally, the metallicity values I obtained using the PARSEC isochrone tracks were very promising. In order to more effectively implement this method, I want to fit polynomials to the calibrated isochrone tracks and then use them to find a star's metallicity using SMASH  $u - g$  and  $g - r$  colors.

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