Three-dimensional Structure and Dust Extinction in the Small Magellanic Cloud

Petia Yanchulova Merica-Jones¹, Karin M. Sandstrom¹, L. Clifton Johnson², Andrew E. Dolphin³, Juliane J. Dalcanton⁴, Karl Gordon⁵, Julia Roman-Duval⁶, Daniel R. Weisz⁷, and Benjamin F. Williams⁸

¹ Center for Astrophysics and Space Sciences, Department of Physics, University of California, 9500 Gilman Drive, La Jolla, San Diego, CA 92093, USA
² Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA
³ Raytheon; 1151 E. Herrmans Road, Tucson, AZ 85756, USA
⁴ Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195, USA
⁵ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
⁶ Sterrenkundig Observatorium, Universiteit Gent, Gent, Belgium
⁷ Department of Astronomy, University of California, 501 Campbell Hall #3411, Berkeley, CA 94720-3411, USA

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Abstract

We examine the three-dimensional structure and dust extinction properties in a ~200 pc × 100 pc region in the southwest bar of the Small Magellanic Cloud (SMC). We model a deep Hubble Space Telescope optical color–magnitude diagram (CMD) of red clump and red giant branch stars in order to infer the dust extinction and galactic structure. We model the distance distribution of the stellar component with a Gaussian and find a centroid distance of 65.2 kpc (distance modulus μ = 19.07 mag) with an FWHM ≈ 11.3 kpc. This large extent along the line of sight reproduces results from previous studies using variable stars and red clump stars. Additionally, we find an offset between the stellar and dust distributions, with the dust on the near side relative to the stars by 3.22 ± 1.44 kpc, resulting in a 73% reddened fraction of stars. Modeling the dust layer with a log-normal AV distribution indicates a mean extinction ⟨AV⟩ = 0.41 ± 0.09 mag. We also calculate AV/NH = 3.2–4.2 × 10⁻²³ mag cm² H⁻¹, which is significantly lower than the Milky Way value but is comparable to previous SMC dust-to-gas ratio measurements. Our results yield the first joint dust extinction and 3D geometry properties in a key region in the SMC. This study demonstrates that CMD modeling can be a powerful tool to simultaneously constrain dust extinction and geometry properties in nearby galaxies.

Unified Astronomy Thesaurus concepts: Interstellar dust (836); Interstellar dust extinction (837); Interstellar medium (847); Magellanic Clouds (990); Small Magellanic Cloud (1468); Dwarf galaxies (416); Galaxy structure (622); Red giant clump (1370); Red giant branch (1368); Distance measure (395)

1. Introduction

Understanding dust and dust extinction at low metallicity is important for a number of reasons. Dust in galaxies attenuates starlight and affects the star formation, radiative transfer, thermodynamics, and chemistry in the interstellar medium (ISM). The amount and type of dust is likely strongly dependent on metallicity (e.g., Dwek 1998; Zubko 1999; Clayton et al. 2003; Sofia et al. 2006; Zhukovska et al. 2008; Asano et al. 2013; Rémy-Ruyer et al. 2014; Roman-Duval et al. 2014; Feldmann 2015; Chastenet et al. 2019; De Vis et al. 2019), making low-metallicity dust studies critical due to the prevalence of these conditions in the early universe.

Fundamental dust extinction properties in low-metallicity environments show distinct differences from the Milky Way. For example, the observed extinction curve of the Small Magellanic Cloud (SMC) at 1/5–1/8 Z⊙ (Dufour 1984; Russell & Dopita 1992; Kurt et al. 1999; Rolleston et al. 1999, 2003; Lee et al. 2005) shows a steep UV rise and a weak or absent 2175 Å bump (Lequeux et al. 1982; Prevot et al. 1984; Gordon & Clayton 1998; Gordon et al. 2003; Maíz Apellániz & Rubio 2012). These differences may hold clues to how the dust in such environments behaves and evolves, in turn affecting galaxy evolution.

Accounting for dust extinction at high redshift can be challenging (Somerville et al. 2001), but fortunately a great deal can be learned from nearby low-metallicity galaxies, which can be considered analogs to the high-redshift universe where galaxies must have formed at a very low metallicity (Madau & Dickinson 2014). The SMC in particular is an especially suitable target due to its proximity, with its center at ~62 kpc (de Grijs & Bono 2015; Scowcroft et al. 2016). Indeed, “SMC-like” extinction is the standard used to account for dust at high redshift and/or low metallicity (Gordon et al. 2003), thus it is a natural target for low-Z studies of dust properties.

The SMC’s proximity also allows us to study in detail its geometry, including the distance to the stars and the ISM, as well as the relative positions of these two galactic components. One of the goals of our study, named the Small Magellanic Cloud Investigation of Dust and Gas Evolution (SMIDGE; Yanchulova Merica-Jones et al. 2017, hereafter YMJ17), is to examine dust extinction and 3D geometry holistically and derive resolved maps of extinction (AV and RV) for low-metallicity dust.

Traditionally, the shapes of dust extinction curves are studied using the pair method (Trumpler 1930; Massa et al. 1983; Cardelli et al. 1992), which compares the spectra of a reddened and an unreddened star of approximately the same spectral type. However, this method relies on individual lines of sight to a select sample of UV-bright stars with high signal-to-noise data. An efficient and complementary technique to measure dust extinction and the extinction curve is to use multiband photometric observations of resolved stars to measure the average extinction properties in a galactic region. Using resolved stellar photometry to measure dust extinction, however, may require modeling the galactic geometry as well.
Interstellar dust is expected to affect all color–magnitude diagram (CMD) features. These effects depend on its distribution relative to the stars. If the dust is in a foreground screen relative to the stars, the stars will be reddened to various degrees depending on the ISM column density distribution, which is often observed to be log-normal (Hill et al. 2008; Kainulainen et al. 2009; Hennebelle & Falgarone 2012). If it is mixed with the stars, some stars will experience only a fraction of the overall reddening. If the dust is in a thin layer and the stars are in a spatially extended distribution (assuming they are not embedded in the dust layer), a part of the CMD will be foreground to the dust and unreddened, while the rest will experience the full reddening from the dust layer. In general, CMD features that are compact or perpendicular to the reddening vector are the most useful for measuring the effects of dust and geometry. CMD modeling of these effects can give clues about the relative line-of-sight depths of the dust and the stars, as well as the reddened fraction of stars. The models can then be used to produce a map of the extinction and/or the geometry. Extinction mapping of reddened stars using color–color or color–magnitude diagrams has been the subject of numerous Milky Way (Lombardi & Alves 2001; Nataf et al. 2013; Schlafly et al. 2016), M31 (Dalcanton et al. 2015), LMC (Imara & Blitz 2007; Dobashi et al. 2008; Choi et al. 2018), and SMC studies (Gardiner & Hawkins 1991; Dobashi et al. 2009, YMJ17).

Geometric effects, such as an elongation of the galaxy along the line of sight, spreads the stars in magnitude but not color. Dust, on the other hand, affects both the color and magnitude of stars in a CMD. Features that would appear narrow in the absence of dust tend to get spread out when there is dispersion in the amount of extinction due to the column density structure of the ISM. If this effect can be modeled, then we can measure the mean and the width of the extinction distribution. By finding the stars’ observed displacement in a CMD from a predicted theoretical unreddened location, we can calculate the dust extinction in magnitudes, \( \lambda s \), where \( \lambda \) is the effective wavelength of each photometric band. We can measure \( R_\lambda = A_\lambda / (A_\lambda' - A_\lambda") \) (related to the dust grain size distribution) from a single CMD color. Measuring \( R_\lambda \) across photometric bands from IR to UV allows us to sample the extinction curve shape.

The SMC, however, presents a unique challenge due to the combined effects of its extinction, relative proximity, and appreciable elongation along the line of sight (Subramaniam & Subramaniam 2009; Haschke et al. 2012; Jacyszyn-Dobrzeniecka et al. 2016). For example, in YMJ17 we found that, in order to accurately measure the SMC extinction curve from the slope of reddened red clump (RC) stars, we also needed to account for the galactic depth along the line of sight. This effect, due to the appreciable spread in spatial distances, could give the impression of a steeper RC slope because stars behind the dust layer will have fainter magnitudes at increasing distances. This observation would in turn seem to imply higher \( R_\lambda \) values. We accounted for the depth by employing a simple model for the RC, which specified a theoretical unreddened RC location based on the local star formation history (SFH), as well as a set of parameters for the extinction distribution, the extinction law, and the galactic depth along the line of sight.

In this paper, we build on our previous work and use the full RC and red giant branch (RGB) CMD to model the dust extinction, 3D geometry, and the SFH holistically. The effects of dust are ubiquitous in the SMIDGE data, and in addition to spreading the reddened RC into a streak, dust also widens the reddened RGB. The signature of the SMC’s geometry is most clearly seen in the double RGB, which is a result of the relative thicknesses along the line of sight and the absolute positions of the dust and stellar components of the galaxy. The SMC’s depth is not as immediately obvious from the CMD, but it nonetheless results in a measurable and significant spread in the magnitude of both the RC and the RGB. Analyzing the RC and the RGB simultaneously, versus only the RC, allows us to better constrain the CMD stellar number counts statistically (and thus the SFH), and to separately account for the effects of galactic geometry and dust extinction. The reason for this is that the RC reddening vector slope is a product of both the extinction curve and galactic geometry, and in YMJ17, we showed these can be degenerate without additional information. At the same time, while it would be challenging to constrain the slope of the extinction vector using the RGB alone, the RGB very strongly constrains the relative offset between the dust and the centroid of the stellar distribution. Modeling the combined effects of the RC and the RGB in theory enables one to separate these effects and better constrain the slope of the extinction vector.

Accurately modeling the CMD requires a representative SFH as a starting point. There have been numerous efforts to obtain the SFHs in the SMC by modeling CMDs of resolved stellar populations (Tosi et al. 1989; Tolstoy & Saha 1996; Harris & Zaritsky 2001; Dolphin 2002; Williams 2002; Zaritsky & Harris 2004; Cignoni et al. 2009; Weisz et al. 2013; Rubele et al. 2015; Williams et al. 2017; Rubele et al. 2018). These models commonly need to account for the initial mass function (IMF), binary fraction, stellar evolution, time resolution, metallicity, distance, extinction, and photometric noise. Typically, the distance is a parameter specified by ancillary studies. Although some approaches can also account for the extinction within a galaxy, in order to simplify the solution, most studies preferably examine regions with low internal \( A_V \), which is treated in a minimal way. Deriving the SFH itself seems to be unaffected by the presence of a significant galactic depth (Harris & Zaritsky 2004; Rubele et al. 2018).

In this paper, we forward model the SMIDGE RC and RGB CMD with realistic noise and a model which includes geometry, distance, and dust. We first create synthetic model CMDs based on a set of input SFHs and stellar evolution parameters. Next, we model the line-of-sight depth of the stellar distribution, the relative offset of the dust with respect to the stars, and the dust extinction distribution. Using a realistic model of photometric uncertainties, we then compare model CMDs to SMIDGE observations, in order to measure properties of the SMC’s 3D distribution of gas and dust.

We briefly describe the SMIDGE data in Section 2. We discuss the CMD modeling process in Section 3, including details about how we match CMDs and account for the uncertainties. Our results are presented in Section 4 and discussed in Section 5. We conclude with Section 6 and provide more relevant information in the Appendix.

2. Data

The SMIDGE survey (GO-13659) consists of eight-band Hubble Space Telescope (HST) imaging of a \( \sim 100 \) pc \( \times 200 \) pc region in the SMC southwest bar. Its location is shown in Figure 1. We refer to YMJ17 for the details of the SMIDGE
imaging footprint, HST camera and filter selections, photometry processing, and data culling. Also see the SMIDGE survey paper (K. M. Sandstrom et al. 2020, in preparation) for complete details. This work is based on the F475W − F814W versus F475W CMD shown in Figure 2 (where the units of all magnitudes are Vega magnitudes).

3. Modeling the SMIDGE Color–Magnitude Diagram

Our goal is to constrain the SMC dust extinction and 3D geometry parameters by finding the model CMDs that best match the SMIDGE observations. The best match is determined by comparing the number of stars in bins of color and magnitude between the modeled and the observed CMD. The optical CMD is ideal for this purpose, due to its high signal-to-noise (compared to other available filter combinations) and broad wavelength baseline.

The location and number of stars in the CMD are mainly determined by these factors:

1. The SFH, i.e., the star formation rate $SFR(t)$ and metallicity evolution $Z(t)$, which defines the density, unreddened position, and morphology of the stellar populations;
2. The distribution of dust extinction, which sets the additional spread in color and magnitude of the stars;
3. The extinction law, which sets the slope of the reddening vector;
4. The average distance modulus, which determines the overall apparent magnitude of the stars;
5. The line-of-sight depth, which affects the spread in magnitude of the stellar populations;
6. The dust–stellar centroid offset (which we simply call the dust–stars offset), which, along with an assumption of the relative thickness of the dust and stellar distributions, determines the fraction of reddened stars and their distance distribution.

To model these properties, we take a forward modeling approach to CMD matching by creating synthetic CMDs that include the effects of the SFH, dust extinction, galactic geometry, and observational noise, and compare the number counts in the CMD to find the best match. Versions of CMD matching have been used by several studies (see references in Section 1). The method we use is based on the approach presented in Dolphin (2002, hereafter D02), who developed a

Figure 1. The SMIDGE survey field (100 × 200 pc) in the SW bar of the SMC is overlaid on a Spitzer Space Telescope composite image in 3.6, 8, and 24 μm from the SAGE-SMC survey (Gordon et al. 2011). HST imaging footprint is shown for ACS/WFC (green), WFC3/UVIS (magenta), and WFC3/IR (blue). Cyan circle indicates the Weisz et al. (2013) SMC-2 field used in our star formation history analysis.

Figure 2. The SMIDGE F475W − F814W optical color–magnitude diagram shows the boundaries of the red clump and red giant branch region analyzed here. Dust extinction is evident from the extended reddened RC (which would theoretically be located within the red ellipse in the absence of dust) and the extended and bimodal reddened RGB (which would be represented by a single vertical sequence if unreddened). Observed bimodal RGB indicates that the dust layer is thin, relative to the stellar distribution, with few embedded stars. These combined effects cause distinct unreddened and reddened stellar populations.
widely used technique for CMD modeling (e.g., Aparicio et al. 1997; Dolphin 1997) to derive the SFHs of nearby galaxies with spatially resolved stellar populations (Tolstoy et al. 2009; Weisz et al. 2013, 2014). D02 created a maximum-likelihood CMD fitting package (MATCH) to recover the best SFH by modeling the observed stellar density in a Hess diagram (a binned CMD showing the relative density of stars). We rely on the D02 approach conceptually to search combinations of dust extinction and geometry parameters for the best-fit CMD.

Although MATCH can also model a dust extinction distribution, it is not designed to model extinction and 3D geometry (a spread of stellar distances and a dust–stars offset) simultaneously. Since the SMC geometry necessitates that we take into account all of these features at the same time, we do not use MATCH per se to find the SMIDGE SFH nor to fit the SMIDGE CMDs. Instead, we only use MATCH to generate single-distance, unreddened synthetic CMDs and we build on its foundation by developing a fitting method that facilitates our use of more complex models for distance and extinction distributions with syncmd. The syncmd code applies distance, reddening effects, and a noise model using functions available from the Bayesian Extinction and Stellar Tool (BEAST) of Gordon et al. (2016, hereafter G16) to create CMDs that we can directly compare to the data.

In principle, finding the best-fit model could involve searching through a large grid of CMD models covering all possible variables. The dimensions of this grid would be the SFH(t) and Z(t) for time bins t; the dust extinction parameters; and the 3D geometry parameters. Depending on the number of time bins in the SFH, such a calculation can become very computationally expensive. We therefore simplify the procedure by making these choices:

1. We focus only on the RC/RGB region. These populations are intrinsically narrow and most strongly display the effects of dust extinction and 3D geometry, as seen in Figure 2, where the RC is extended and the RGB is extended and doubled. We thus draw a selection box around this region. To model the dust and geometry, we do not need to include the whole RGB, nor do we have to cut the selection box at fainter magnitudes with exquisite precision. On the other hand, if the selection box is extended to fainter magnitudes, we would end up selecting main sequence stars which is not optimal. Therefore, the results should not be affected by expanding the box. We define the RC/RGB region as stars with F475W − F814W color of 1.2–2.2 mag and F475W magnitude of 18.5–22.75 mag, and obtain a CMD subset of ~12,000 stars. These ranges encompass the unreddened RC, the streak of the reddened RC, and the tip and base of the RGB.

2. We simplify the SFH because we only model the RC/RGB. Since finding the SFH is not our main goal, and the extinction and geometry parameter fitting only requires a broad knowledge of the SFH, the RC/RGB SFH can be treated coarsely with limited time bins. See Section 3.2 for details.

3. We separate the SFH and the dust/geometry grid search. We first measure the SFH by matching the stellar number counts in coarse RC/RGB bins (see Figure 3). After determining the approximate SFH, we proceed to search the full grid of dust and geometry parameters.

Using the choices above, the conceptual outline of the CMD matching process is the following, with details outlined in the rest of Section 3.

1. Fit an SFH for the SMIDGE field. (Section 3.2).

(a) First generate unreddened, single-distance synthetic CMDs according to a range of star formation rates and small metallicity offsets based on adjustments of a known SFH of a nearby region. Compare RC/RGB stellar number counts between the unreddened synthetic and the observed CMDs in coarse bins designed to be insensitive to extinction and geometry (left panel of Figure 3). Select SFHs producing CMD statistics consistent with the SMIDGE stellar number counts. (Section 3.1.1.)

(b) Refine the SFH selection by applying a fixed set of geometry, distance, and dust extinction parameters (obtained in YMJ17) to the CMDs above. Model the SMIDGE distance. Also include realistic observational noise (see Part II). Recalculate the stellar number counts in the RC/RGB coarse bins. Perform a second SFH refinement using a narrower range of the cuts. (Sections 3.1.2–3.1.5.)

(c) Select the SFH producing a best-fit coarse CMD and use it as a foundation for the analysis in Part II.

2. Fit the dust extinction and geometry model combinations. (Sections 3.1.4–3.4.)

(a) Generate model CMDs, with the SFH from step I, in a grid of combinations of dust extinction and 3D galactic geometry parameters.

(b) Add observational noise to the stars in the model CMDs as characterized using artificial star tests.

(c) Find the best-fitting model and the uncertainty in the results by measuring the probability density function (PDF) of the model grid.

3.1. Forward Modeling the CMD

3.1.1. Unreddened Single-distance CMD

We can predict the number density of a population of stars in the CMD given a SFR(t) and a Z(t). We use MATCH’s fake CMD simulation tool (D02) to generate synthetic CMD models without noise, extinction, or geometric effects, such as the one in the left panel of Figure 3. First, we create a synthetic CMD based on adjustments to the Weisz et al. (2013, hereafter W13) SMC SFH for a nearby region. Our motivation for starting with this SFH is detailed in Section 3.2, where we discuss other details of the SFH analysis. We input the following fixed parameters into fake: a Kroupa (2001) initial mass function, PARSEC stellar evolution models (Bressan et al. 2012; Tang et al. 2014; Chen et al. 2015), a binary fraction of 0.35, a foreground MW extinction of A_V = 0.18 mag derived from MW H1 foreground toward the SMIDGE field (Muller et al. 2003; Welty et al. 2012), and a distance modulus µ = 18.96 mag for the center of the SMC (de Grijs & Bono 2015; Scowcroft et al. 2016).
We then find the best SFH for the SMIDGE region in two steps (the details are in Section 3.2): (1) First, we coarsely fit synthetic unreddened, single-distance CMDs to the SMIDGE CMD, and (2) then we refine the fit by comparing to SMIDGE synthetic CMDs with simulated dust extinction and galactic geometry properties. In the process, we obtain a SMIDGE-specific distance modulus as described in the next section.

3.1.2. Modeling the SMIDGE Distance

To properly model the CMD, we must also know the average distance to the stars in the region. The SMC’s mean distance modulus varies across the galaxy, due to SMC’s three-dimensional structure. Scowcroft et al. (2016) measure a distance modulus of $\mu = 18.96 \pm 0.01$ mag for the center of the SMC using Cepheid variables, and de Grijs & Bono (2015) also find a mean SMC $\mu = 18.96 \pm 0.02$ mag. Haschke et al. (2012) find a distance modulus varying between 18.94 mag $\leq \mu \leq 19.17$ mag using RR Lyrae stars and Cepheids in the bar and wing of the SMC. Nidever et al. (2013) use RC stars to measure the SMC line-of-sight depth and find $\sim 23$ kpc for the eastern side and $\sim 10$ kpc for the western side. Rippepi et al. (2017) use classical Cepheids and find a distance spread in the SMC SW Bar of 62.5–65 kpc (18.98 $\leq \mu \leq 19.06$ mag). Models of the SMC and the LMC (Besla et al. 2007, 2012, 2016) show that the Magellanic Clouds have experienced repeated interactions with each other, causing asymmetry in the stellar structures of the galaxies. Additionally, it is well-known that the SMC has a large depth along the line of sight (Subramanian & Subramaniam 2009, 2012; Jacyszyn-Dobrzynecka et al. 2016, 2017; Subramanian et al. 2017).

We investigate the distance modulus appropriate for the SMIDGE field in the SW Bar by performing a preliminary Poisson likelihood ratio CMD matching calculation using our previous knowledge of the SFH, extinction, and geometry that we obtained in YM17: an extinction law consistent with SMC Bar Gordon et al. (2003) extinction, a log-normal median $\sim 0.32$ and width $\langle \sigma_A \rangle = 0.3$, a dust distance $D_{\text{dust}} = 60$ kpc (dust–stars offset of $\sim 2$ kpc), and a 10 kpc line-of-sight depth (resulting in a 0.65 fraction of reddened stars). Using the adjusted W13 SMC SFH, we proceed to shift the CMD in distance. The dust extinction and 3D geometry parameters are held constant as the synthetic CMDs are shifted in distance (magnitude) over the range 18.8 mag $\leq \mu \leq 19.3$ mag. Since the distance calculation relies only on shifting the CMD in magnitude, using a preliminary version of these parameters does not affect the results in terms of their sensitivity to a particular set of parameter values. Comparing to the SMIDGE observations, we find a best match at $\mu = 19.07$ mag, as shown in Figure 4. The larger distance is expected for the SMIDGE region based on models of the extended stellar distribution placing SMC’s NE regions closer than the SW regions (i.e., Haschke et al. 2012).

3.1.3. Modeling the 3D Geometry

We consider two aspects of the three-dimensional geometry which impact the SMIDGE CMD: the depth along the line of sight of the stellar component and the relative offset between the stars and a thin dust layer. We could assume that the stellar density follows one of a number of distributions, such as a Gaussian, a log-normal, an exponential, etc. Subramanian & Subramaniam (2009) find that the spread in color and magnitude of RC stars in the central region of the SMC (covering 2.5 square degrees, which includes the SMIDGE region) is best fit with a Gaussian. Using Cepheid observations to study the 3D structure of the SMC, Jacyszyn-Dobrzynecka et al. (2016) also find a Gaussian-like distance distribution for the galaxy. Our model also assumes a Gaussian stellar distribution along the line of sight (centered at a mean distance of $\mu = 19.07$ mag) with an FWHM between 3.5 and 19.8 kpc that spans the range found by previous observations. We can adapt this model to explore a variety of stellar density distributions in the future.
Table 1
Model Parameters

| Parameter                                   | Min   | Max     | Resolution |
|---------------------------------------------|-------|---------|------------|
| Galactic Line-of-sight Depth\(^1\)          | 0.05 mag (3.5 kpc) | 0.275 mag (21.3 kpc) | 0.025 mag |
| Dust–stars offset\(^2\)                     | 0.02 mag (0.6 kpc) | 0.2 mag (5.7 kpc) | 0.02 mag |
| Dust Extinction\(^3\), log-normal median ~\(A_V\) | 0.23 mag | 0.41 mag | 0.02 mag |
| Dust Extinction, width ~\(\sigma_{A_V}\)     | 0.40   | 0.95    | 0.05 |

Note. (1) The SMIDGE distance modulus is measured to be \(\mu = 19.07\) mag (see Figure 4), indicating a distance of 65.16 kpc. Galactic depth range in kpc is expressed as the FWHM of the Gaussian stellar distribution, where \(\mu = 19.07 \pm 0.05\) mag (lowest grid boundary for the galactic depth) corresponds to an FWHM = 3.53 kpc (1\(\sigma\) depth of 1.50 kpc) and \(\mu = 19.07 \pm 0.275\) mag (highest grid boundary) corresponds to an FWHM = 19.81 kpc (1\(\sigma\) depth of 8.41 kpc). (2) The dust layer is offset on the near side of the stellar distribution by the distance indicated. (3) Log-normal distribution of dust extinctions, where ~\(A_V\) is the log-normal median and dimensionless ~\(\sigma_{A_V}\) is the distribution width (see Section 3.1.4).

Figure 4. Distance modulus test for the SMIDGE field using a Poisson likelihood ratio test (see Section 3.3). SMC center is measured to be at \(\mu = 18.96 \pm 0.01\) mag by de Grijs & Bono (2015) and Scowcroft et al. (2016), while we measure the center of the SMIDGE field to be located at \(\mu = 19.07\) mag. The greater SMIDGE distance is expected from models and measurements of the extended stellar distribution.

We apply distance and geometry offsets using the \(\text{syncmd}\) and \(\text{coadd}\) code in the following way: we use the unreddened, single-distance CMD, obtained as in Section 3.1.1, and apply a random Gaussian distance distribution to the stars with a width \(\sigma_{DM}\). We then place a single thin dust layer at a specified position and find which stars are foreground and background to the dust, then redden the stars behind the dust as described in Section 3.1.4.

In our model, we assume the dust is in a thin layer relative to the stellar distribution. We can test this assumption with a population of stars that are distributed uniformly and independently of the dust layer. RGB stars can serve this purpose since they are evolved stars and would be distributed regardless of the location of the dust layer. Indeed, we do not see RGB stars covering the full range of possible extinctions, but rather we see a bimodal RGB, which indicates that stars are essentially either unreddened or reddened, placing them either in front of or behind a thin dust layer. If the dust layer had a substantial thickness relative to the stellar distribution, this clear bimodality would not be evident. From stellar counts in the reddened and unreddened RGB, we conclude that the reddened fraction is >50%. We thus consider only dust layer positions closer to us than the centroid of the stellar distribution, as specified in Table 1.

3.1.4. Modeling the Extinction

The \(\text{fake}\) routine outputs the effective temperature, surface gravity, and metallicity for each star in the CMD. We input these into \(\text{syncmd}\), which uses the BEAST to compute the associated stellar spectra in order to correctly apply extinction to the model spectra. (see Choi et al. (2020) and Van De Putte et al. (2020) for examples of using the BEAST.) We apply a G03 SMC Bar \(R_V = 2.74\) extinction law. The BEAST then extracts the integrated band fluxes and computes synthetic HST photometry that we can compare to the observations.

Following Dalcanton et al. (2015), we assume the extinction has a log-normal distribution, with median ~\(A_V\) and a dimensionless width ~\(\sigma_{A_V}\). The (normal) mean \(A_V\) is related to the median ~\(A_V\) and ~\(\sigma_{A_V}\) of the log-normal by:

\[
\langle A_V \rangle = \langle A_V \rangle e^\langle \sigma_{A_V}^2 \rangle / 2.
\]

The width of the log-normal, \(\langle \sigma_{A_V}^2 \rangle\), can be related to ~\(\sigma_{A_V}\) by:

\[
\langle \sigma_{A_V}^2 \rangle = \langle A_V \rangle^2 e^{\langle \sigma_{A_V}^2 \rangle} - 1,
\]

or in an alternate way as in Section 3.1 of Dalcanton et al. (2015). The range of extinction parameters is shown in Table 1.

It is also possible to vary the extinction curve, but since we are modeling CMDs only with the optical color F475W – F814W, we are not sensitive to the difference between an SMC and an MW extinction curve (see discussion in the Appendix). Thus, we model our CMDs with the extinction law fixed to the G03 SMC Bar extinction curve, which is one of the reasons we focus on this color combination. In future work, we plan to expand this technique to multiple color combinations and vary the extinction curve as well.

3.1.5. Observational Noise Model

Accurate simulated noise is critical to our approach, as it accounts for photometric errors, crowding, and incompleteness through artificial star tests (ASTs) performed on the SMIDGE observations. For details on how ASTs are used in our analysis, see Section 2.3.1 of Williams et al. (2014), who use the same procedures for the Panchromatic Hubble Andromeda Treasury (PHAT) survey. We employ a conservative noise model using the “toothpick” method of G16, which is used for data that are known to be correlated between photometric bands by treating the bands independently. The model is computed in equally spaced logarithmic flux bins and assumes that each AST entry corresponds to one artificial star. See Sections 4.4 and 5 in G16 for details on how ASTs are used to determine the noise model.
4.0
Note. SFR and metallicity values in each age bin are equally spaced within the range given: 4–400 Myr age bins assume five values; 400 Myr–3.2 Gyr assume four values, and bins with ages ≥3.2 Gyr assume three values. The metallicity dispersion at each time bin is 0.25.

3.2. Modeling the SMIDGE SFH

The SFH affects the RC/RGB stellar density, position of the unreddened RC, and morphology of CMD features. While finding the SFH for the SMIDGE field is not the primary goal of our study, a representative SFH is key to successfully reproducing these features in the unreddened CMD, and will ensure that our model will be sensitive to potentially subtle variations in the dust extinction and geometry properties.

The RC consists of low-mass K giants in their He-burning post-RGB phase. A K giant has a nearly constant absolute magnitude during this phase of its evolution, which places RC stars within a tight clump in the CMD. The RC is thus less affected by age variations than the RGB in terms of CMD position. However, both the RC and the RGB are sensitive to the metallicity and metallicity dispersion at a given age. We model these effects simultaneously by varying both the SFR(t) and the metallicity, Z(t), to the ranges we specify in Table 2. We assume a constant metallicity dispersion for all ages. To determine the value of the dispersion, we compare the width of the unreddened RGB in color to that of model CMDs in the following way: we define a box around the unreddened RGB in a highly reddened region where the unreddened and the reddened stars are well-separated from each other, and compare the standard deviation in color between the models and the SMIDGE data. We find that a metallicity dispersion of 0.25 dex best reproduces the unreddened RGB width.

SFH studies exist for regions near SMIDGE (W13; Rubele et al. 2015, 2018). Although those regions are close by, there are differences in the number counts of RC/RGB stars between their fields and SMIDGE. Adjustments to existing SFH results allow us to obtain a better fit to the observations because stellar number counts of RC and RGB stars are directly related to the SFR(t) over ages relevant for stars to evolve off the main sequence. For example, when modeling the unreddened RC in YMJ17, we performed a rough refinement of the SMC SFR(t) and Z(t) derived by W13 to match to first order the RC morphology and stellar positions (we neglected the stellar number counts; see Section 3.2 in YMJ17). Here, we need an additional SFR refinement because our method is sensitive to stellar number counts, the width of the unreddened RGB, and the morphology of the RC.

As a starting point, we use the results of W13, who have used deep HST photometry to study the SFH of a region in the SMC Bar near SMIDGE (shown in Figure 1) with low internal dust extinction and an RGB stellar surface density that is somewhat lower than that of the SMIDGE region. Rubele et al. (2015, 2018) have also examined the SFH of regions near and within SMIDGE. Upon an SFH and age–metallicity comparison with W13, we find that although the Rubele et al. (2015, 2018) results show higher metallicity and lower A_V, their results for older dominant RC ages compensate for these differences and show a consistency in the stellar number counts and morphology of the RC and the RGB.

The adjustments we made in YMJ17 to the W13 SFR are indicated by the dashed blue line in Figure 5 and include star formation enhancements at t = 500 Myr and 1.5 Gyr ≤ t ≤ 3 Gyr. We additionally enhance the SF in this work in order to match the total number of stars in the observed RC/RGB region (~12,300) where we increase the lower bound of the sampled SF range for ages ≥3 Gyr to 1.5 × 10^{-4} M_☉ per year. While we explore a relatively narrow metallicity range, we find that Z(t) offsets to lower values by 0.2–0.3 dex produce a better fit. We use a set of 16 logarithmic time bins (listed in Table 2) — re-binned from the original 40 time bins of W13— which range from 6.6 ≤ log(t) ≤ 10.15. We make this simplification because the RC/RGB populations consist of older ages and smoothing over the W13 bins at younger ages results in a minimal variation in the relevant areas of the CMD.

We search for a best match to SMIDGE by exploring a range around our initial estimate for SFR(t) and Z(t) illustrated by the width of the gray band in Figure 5. We define coarse diagonal CMD bins representing the upper RGB, RC & RGB, mid RGB (below the reddened RC), and lower RGB (Figure 3), and compare the stellar number counts per bin in each synthetic CMD to SMIDGE. First, we compare the unreddened, single-distance CMDs to SMIDGE, and then we use forward modeling to compare CMDs with simulated reddening and

![Figure 5](image-url)
geometry as described in the next paragraph. We search for an initial set of SFHs producing CMDs that fall within the cuts in Table 3, which are chosen to allow for a small variation around the SMIDGE counts. The diagonal bins are parallel to the extinction vector, which we know from the approximate slope of the RC reddening vector in YMJ17. They are designed to be relatively wide in color and magnitude, such that reddening, geometry, and noise would minimally affect the number counts.

To account for any subtle changes to the CMD stellar number counts due to dust and geometry as well as due to the reddening of stars with unreddened positions bluer than F475W – F814W = 1.2 mag, we refine the initial selection of models by transforming the unreddened CMDs with syncmd into models incorporating geometry, dust extinction, and observational noise effects. We use the dust extinction and geometry values we found for SMIDGE as approximate parameters and follow the process in Sections 3.1.4 and 3.1.3. Our final SFH choice is guided by a second round of narrower cuts around the SMIDGE number counts (see Table 3), which improve the fit slightly. The resulting best-fit SFR is shown in red in Figure 5.

The SFR we find to be suitable for the SMIDGE field in Figure 5 shows enhancements to the W13 SFR at almost all ages, even those where we allowed values to vary below their result. The most significant difference is at older ages (≥3 Gyr), where the SFR is enhanced by a factor of 2. The two star formation peaks at more recent times are also slightly enhanced. These differences are expected due to the higher stellar surface brightness of the SMIDGE field compared to the W13 field.

We note that the model CMDs overpredict the contribution of red horizontal branch (HB) stars, due to known challenges in modeling the HB morphology stemming from RGB mass-loss uncertainty (Catelan 2009; Gratton et al. 2010). Despite this contamination, we do not expect the HB contribution to be significant or to dominate the statistics, given that we find that the HB accounts for only about 3% of the total number of RC/RGB stars.

3.3. Comparing Model and Observed CMDs

We generate a grid of model CMDs for each dust and geometry parameter combination from Table 1, for a total of 12,000 models. To compare each model CMD to the SMIDGE observations, we calculate the probability that a model produces the observations by comparing the number of stars in the respective CMDs in a way that is sensitive to CMD features (described below). This calculation results in the probability density as a function of each dust extinction and geometry parameter, or a combinations of parameters. The PDF can in turn inform us about the confidence interval for each parameter based on a set probability threshold.

To compare the number of stars in the model and data CMDs, we bin each model CMD in an identical way to the observed CMD and calculate the probability, from a Poisson distribution, that a model with a predicted number of stars $n_i$ produces an observed $m_i$ stars in bin $i$:

$$P_i = \frac{m_i^{n_i}}{e^{m_i}n_i!}.$$  \hspace{1cm} (3)

We follow the recommendation of Dolphin (2002, 2013), who suggest that in the case of binned CMD data, the Poisson probability distribution should be used instead of the canonical Gaussian distribution, e.g., as in a $\chi^2$ minimization (Mighell 1999). The results for all CMD bins are multiplied to obtain the total probability for each model–data comparison.

The probability can be measured for any binning of the CMD in color and magnitude. There are several considerations to take into account when defining the binning. First, if there are features in the CMD that we would like to be sensitive to, we must choose binning sufficiently small such that these features are preserved. For our purposes, we want to be sensitive to features such as the unreddened and the reddened RC, the tip of the RGB, and the unreddened RGB, among others. The smallest (narrowest) of these features are the unreddened RGB (which spans ~0.1 mag in color) and the unreddened RC (spanning ~0.5 mag in magnitude). Second, we also make sure that our bins are not so small that we end up with a significant number of bins (≥5%) containing no sources. Finally, we must choose either uniform binning, where all CMD bins are of equal rectangular size, or irregular binning, to fit parts of the CMD in a bin of a special size if we have a sense for known errors or uncertainties in the data. Here, we follow D02 in choosing uniform binning. Our final bin size is 0.025 mag in color and 0.125 mag in magnitude, which finely samples the CMD features of interest while minimizing the number of empty bins. With our SFH analysis in Section 3.2, we ensure that the difference in the total number of stars in the RC/RGB region between the SMIDGE CMD and each model CMD is insignificant. The variation in this number due to noise in each model CMD is addressed in Section 3.4.

The model with the highest probability is our best-fit model. To visualize the goodness of fit per bin, it is convenient to calculate a maximum likelihood statistic based on this probability. Similarly to D02, who applied this statistic to find the best SFH for nearby galaxies, we calculate the Poisson likelihood ratio (PLR) for each model–data comparison. Many studies use the PLR for CMD fitting, primarily to analyze SFHs (Aparicio et al. 1997; Dolphin 1997, 2002; Harris & Zaritsky 2009; Weisz et al. 2011). The PLR is defined as the ratio of the probability of drawing $n_i$ stars from model $m_i$ to the probability of drawing $n_i$ stars from model $m$, and has the
following form:

$$\text{PLR} = \frac{m_1^n e^{n_1}}{n_1^n e^{m_1}}.$$  \hspace{1cm} (4)

We simulate distance, dust extinction, and observational noise simultaneously on our unreddened synthetic CMDs and then measure the degree of match. In this sense, our synthetic model CMD is stochastically sampled, and to calculate the likelihood—$$L(n_1, n_2)$$—that two samples, $$n_1$$ and $$n_2$$, come from the same underlying model, $$m$$, we use:

$$L(n_1, n_2) = \int_0^{\infty} \frac{m_1^n}{e^{m_1!}} \frac{m_2^n}{e^{m_2!}} dm = \frac{0.5^{n_1+n_2+1} (n_1 + n_2)!}{n_1!n_2!}. \hspace{1cm} (5)$$

The equivalent PLR for this expression when $$n_1$$ is the observed data and $$n_2$$ is the model is (see Section 2.3 of D02 for details):

$$-2\ln\text{PLR} = -2 \ln \frac{L(n_1, n_2)}{L(n_1, n_1)}. \hspace{1cm} (6)$$

We sum the log of the PLR for all bins to obtain a total PLR for each model–data comparison.

The best-fit maximum probability model and the corresponding PLR results per bin are shown in Figure 6. The residual significance in the lower right panel measures the fit quality by subtracting the model from the observed CMD and dividing this difference by the uncertainty in the model count, $$(n - m)/\sqrt{m}$$. This result is simply the residual in units of standard deviation (e.g., a value of +1 or −1 is a 1σ outlier).

There is a very good agreement between the overall number of stars in the RC/RGB CMD, but some weaknesses in the match are evident. The overestimated contribution of the horizontal branch (HB) discussed in Section 3.2 can be seen just below the RC in both the CMD data-to-model comparison (as a slight bulge) and in the residual significance map (as a red patch). One consequence of this HB overestimate is the appearance of a “dip” in the reddened model RC (near the location of the unreddened RGB) even though the measured RC slopes of the data and the best-fit model are nearly identical. The steeper model RGB slope is another potential consequence of this contribution. Both the PLR and the residuals maps show a poor match (an overestimation) in the number of (reddened and unreddened) RC stars, which may have to do with the overestimation of the number of stars in the HB. In the Appendix, we show examples of models that are bad fits to the data.
3.4. The PDF and Uncertainties in the Results

Each model CMD is subject to two main sources of uncertainty. One is a result of number statistics due to the small number of stars in each CMD bin. Additionally, each CMD contains an intrinsic uncertainty in the stellar positions due to the random photon noise and crowding effects (simulated by the BEAST). These effects result in an inherent variability in the model predictions when a model is generated multiple times with the same set of parameters.

We generate synthetic CMDs over a well-sampled, evenly spaced grid of models based on the ranges of geometry and dust extinction parameters in Table 1. To account for the sources of uncertainty above, we generate each CMD in the grid 50 times and calculate the average number of stars per CMD bin. Each model is fit to the data via the process in Section 3.3. The repeated trials average out the noise.

In addition to finding the best-fit model (see end of Section 3.3), we also calculate the median and the confidence intervals of the one-dimensional PDFs of each parameter. We define the 50th percentile of the cumulative probability as the PDF median, and the 16–84th percentile confidence interval threshold as a measure of the PDF width (68% around the median) or the uncertainty in our results, informing us of the range of parameter values that contains the corresponding proportion of the probability. If the probability distribution were Gaussian, then the 68% confidence interval would correspond to ±1σ uncertainty and the 50% blue line would indicate the mean. The 2D probability distribution functions show the correlation among the geometry and extinction parameters. Black contours represent the 2D 68% confidence interval threshold.
Figure 7. Observations indicate the near side of the centroid of the stellar distribution by 3.22 distribution remains compact. Lines of constant reddened fractions align with the white 68% confidence interval contours of the dust–stars offset and $\sigma_{DM}$ 2D PDF in Figure 7. Observations indicate $f_{RED} = 0.73^{+0.13}_{-0.13}$. (See Section 4.)

To obtain a 1D PDF for each parameter, we marginalize over all other parameters after one step of renormalizing. In this step, we assume that the probability of a model outside the grid is $\sim0$, thus we cover a total probability of 1 in the grid, where each model is normalized accordingly. We marginalize over various dimensions of the grid to produce 1D and 2D PDFs for each parameter and parameter pair. In this way, we can find desired confidence intervals for our parameters.

### 4. Results

The results for the 3D geometry and dust extinction parameters and their 68% confidence interval thresholds are presented in Table 4 and Figures 7 and 8. We find that the dust layer is offset on the near side of the centroid of the stellar distribution by $3.22^{+1.60}_{-1.60}$ kpc, and that the CMD is best fit with a stellar distribution along the line of sight with a 1 $\sigma$ width of $0.16^{+0.07}_{-0.06}$ mag, or an equivalent FWHM of 11.3 kpc. The reddened fraction of stars is $f_{RED} = 0.73^{+0.13}_{-0.13}$ with the dust on the near side of the stellar midplane. The log-normal of dust extinction has a median of $A_V = 0.33 \pm 0.05$ mag and width $\sigma_{A_V} = 0.67^{+0.17}_{-0.15}$. This corresponds to a mean $\langle A_V \rangle = 0.41$ mag and a width $\sigma_{A_V} = 0.097$ (where the foreground $A_V = 0.18$ mag applied to model the SFH is not a part of this result, thus it is solely attributable to SMC dust.).

There is a lack of strong correlation between the geometry and the extinction parameters in the fitting procedure. In particular, $\vec{\chi}_D$ and $\vec{\sigma}_{DM}$ do not appear correlated with the dust–stars offset or the line-of-sight depth. The interpretation of this result is that, since stars lie either in front of or behind the thin dust layer, they experience either all of the dust column or none of it (as discussed in Section 3.1.4). The geometrical arrangement of the stars and the dust is therefore independently constrained from the extinction properties of the dust layer.

Figures 7 and 9 show that all parameters are well-constrained. Figure 9 shows a slice through the multidimensional grid, with all parameters held fixed at their best-fit values from Section 3.3, aside from the value on the $x$-axis. Both figures show that small values of the line-of-sight depth, $\sigma_{DM}$, are strongly ruled out.

One of the most strongly constrained parameters from the observations is $f_{RED}$, which can be found simply from counts of RGB stars in the unreddened and reddened branches. $f_{RED}$ is a purely geometrical effect that results from the relative arrangement of the dust–stars offset and the stellar distribution along the line-of-sight ($\sigma_{DM}$). The correlation between the line-of-sight depth and the dust–stars offset is the strongest among all the parameters. $f_{RED}$ can be predicted theoretically from the relationship between $\sigma_{DM}$ and the dust–stars offset as illustrated in the right-hand panel of Figure 8. Regions of

### Table 4

| Parameter                        | PDF 50% Median and 68% Confidence Intervals |
|----------------------------------|---------------------------------------------|
| Dust–stars offset               | 0.11 $^{+0.05}_{-0.05}$ mag; 3.22 $^{+1.60}_{-1.60}$ kpc |
| Distance modulus spread, $\sigma_{DM}$ | 0.16 $^{+0.05}_{-0.04}$ mag; FWHM $\approx$ 11.3 kpc |
| Reddened fraction, $f_{RED}$    | 0.73 $^{+0.13}_{-0.13}$                      |
| Extinction Log-normal, $A_V$    | $\vec{\chi}_D = 0.33^{+0.05}_{-0.05}$ mag; mean $\langle A_V \rangle = 0.41 \pm 0.09$ mag |
| Extinction Log-normal width, $\sigma_{A_V}$ | $\vec{\sigma}_{A_V} = 0.67^{+0.17}_{-0.15}$ mean $\langle \sigma_{A_V} \rangle = 0.097 \pm 0.003$ |

Note. The dust layer is on the near side of the stars. The log-normal median $\vec{\chi}_D$ and $\vec{\sigma}_{A_V}$ are converted into the mean (normally distributed) $\langle A_V \rangle$ and $\langle \sigma_{A_V} \rangle$ using Equations (1) and (2).
constant $f_{\text{RED}}$ indicate that the closer the dust layer is to the centroid of the stellar distribution, the smaller the line-of-sight depth required to preserve the same reddened fraction. Indeed, the 68% confidence intervals of the 2D PDF of the dust–stars offset—$\sigma_{\text{DM}}$—trace lines of constant $f_{\text{RED}}$. Our results for $f_{\text{RED}} = 0.73^{+0.13}_{-0.13}$ are consistent with the 68% confidence interval.

5. Discussion

Our two main findings about the SMC galactic structure are that the SW bar of the galaxy shows a significant spread in the distribution of stars along the line of sight of more than 10 kpc FWHM, and also that the dust layer, which is clearly observed from its extinction effects, is offset from the centroid of the stars on the near side of the SMC. We obtained a similar result for the line-of-sight depth ($10 \pm 2$ kpc) in YMJ17 by employing a simple model for the reddened RC, which helped explain the observed offset in the extinction curve in the SMC and the LMC.

Our line-of-sight depth finding is consistent with a number of other studies of the SMC structure employing various methods that generally suggest the SMC to be significantly elongated along the line of sight. Depending on the region studied and the method used, results vary and indicate galactic depths of less than 10 kpc and up to $\sim23$ kpc in the outer regions of the galaxy (Hatzidimitriou & Hawkins 1989; Gardiner & Hawkins 1991; Harris & Zaritsky 2004; Subramanian & Subramaniam 2009, 2012; Nidever et al. 2013; Muraveva et al. 2018; Rubele et al. 2018).

Distance tracers show a number of features in the SMC, such as a distance gradient, galactic depth, and a distance bimodality. The distance gradient observed generally suggests that the eastern regions are closer than the western ones (Subramanian & Subramaniam 2012; Jacyszyn-Dobrzeniecka et al. 2016; Ripepi et al. 2016; Subramanian et al. 2017; Muraveva et al. 2018). The galactic depth has been observed by finding the distribution of RR Lyrae and Cepheid variables (Harris & Zaritsky 2004; Haschke et al. 2012; Kapatos & Hatzidimitriou 2012; Jacyszyn-Dobrzeniecka et al. 2016; Muraveva et al. 2018) and the luminosity dispersion of RC stars (Gardiner & Hawkins 1991; Nidever et al. 2013; Subramanian et al. 2017). Using the latter also shows a distance bimodality (Subramanian et al. 2017) with two distinct bodies of stellar structures in the eastern regions of the galaxy. Although we do not study the distance gradient here, we
note that the distance modulus we find via CMD matching discussed in Section 3.2 of $\mu = 19.07$ mag indicates that the SMIDGE region in the SMC’s SW Bar is offset from the center of the SMC (found to be at a distance modulus of $\mu = 18.96$ mag (Scowcroft et al. 2016)), consistent with the studies above in that it indicates the western region is farther away.

A significant line-of-sight depth is also consistent with an LMC/SMC interaction. Numerical models for the SMC and the LMC indicate that the SMC geometric features, as well as the internal kinematics of the Magellanic Clouds, can be explained by repeated interactions between the two galaxies (Besla et al. 2012, 2016). The models of Besla et al. (2012) show that ram pressure decreases the velocity of the SMC’s ISM and plays a role in modifying the properties of the ISM distribution, such as its location and velocity. Our observations that the dust layer is thin and results that the dust is positioned on the near side of the SMC relative to the stellar centroid (therefore placing the dust nearer to the LMC as well) may be an expected consequence of such a ram pressure effect. Choi et al. (2018) measured the dust reddening and 3D structure of the LMC using RC stars and discovered a new stellar warp toward the SMC in the outer disk (and an LMC line-of-sight depth of $\sim 7$ kpc). It is clear from our study and others that the line-of-sight geometry of both Magellanic Clouds is complicated, due to their interactions.

We compare our CMD fitting result for the average SMIDGE dust extinction with $A_V$ based on dust mass surface densities, $\Sigma_{Md}$, derived from IR emission observations by the HERschel Inventory of The Agents of Galaxy Evolution (Gordon et al. 2014). We fit the IR dust SED with a modified blackbody dust emission model as in Chiang et al. (2018) to extract the average dust mass surface density in the SMIDGE footprint, and find $\Sigma_{Md} = 1 \times 10^{5} M_{\odot}$ kpc$^{-2}$. Using $A_V / \Sigma_{Md} = 0.7394$ mag/10$^{5} M_{\odot}$ kpc$^{-2}$ from the Draine & Li model and from Draine et al. (2014), the IR-derived extinction is $A_V \approx 0.75$. This overprediction of the observed extinction—here by a factor of $~1.8$—is consistent with other comparisons between IR-derived optical extinction results using the Draine & Li dust model and alternative extinction methods. Dalcanton et al. (2015), who use CMD fitting of RGB stars to derive the distribution of dust in M31, find that the dust model $A_V$ estimates are too high by a factor of $\sim 2.5$ when comparing their results to those of Draine et al. (2014). Similarly, Planck Collaboration et al. (2016) show a discrepancy of a factor of 1.9 in $A_V$ estimates from all-sky Milky Way optical photometry of quasi-stellar objects. This discrepancy can be attributed to the Draine & Li model overestimating the dust mass from IR emission, which would imply that dust grains are more emissive than the model assumes. However, it is notable that M31 and the Milky Way are both at relatively high metallicity. Our comparison is among the first of its kind for a low-metallicity environment containing dust that potentially has very different properties.

Further, an SMC $A_V$ comparison can be made with the work of Hagen et al. (2017) who use UV, IR, and optical observations integrated into 200$^3$ regions to model the SMC SED and map $A_V$ for the galaxy. Half of their SMC regions have a mean $\langle A_V \rangle < 0.25$, with results for the SMIDGE region varying between $A_V = 0.2–0.75$ mag. Our results of mean $\langle A_V \rangle = 0.41$ are at the high end, which is expected since the SMIDGE field was specifically picked as one of the dustiest spots in the SMC. Our upcoming study will resolve the SMIDGE field into smaller regions, which will allow for a better comparison with Hagen et al. (2017).

Dalcanton et al. (2015) studied the distribution of dust in M31 by modeling the NIR CMD of RGB stars to obtain results for the same set of dust and geometry parameters as the ones we explore here—$A_V$, $\Sigma_{Md}$, and $f_{\text{RED}}$. Although they approach modeling the RGB and RC quite differently for a number of reasons, they also observe an RGB broadening and a bimodality due to the combined effects of dust extinction and geometry, and rely on modeling these observed effects to form the basis of their conclusions. Their study explores regions in the star-forming disk of M31, which generally have a more widely varying and a higher $A_V$ than SMIDGE. They do not observe a correlation between $A_V$ and $f_{\text{RED}}$ at high extinctions (median $A_V \gtrsim 1$ mag). A correlation between the two at lower extinctions is interpreted not as a physically driven result, but rather as a result expected from their fitting approach (which relates $f_{\text{RED}}$ to $A_V$ through a “filling factor” describing the areas of the gas cloud and the analyzed pixel such that an increasingly smaller filling factor for dusty gas is due to a decreasing median extinction and also contributes to a decreasing geometric reddened fraction). At the lowest extinctions they observe, which are comparable to the extinctions we find in SMIDGE, (median $A_V \lesssim 0.3$ mag), the broadening of the RGB in their NIR CMDs is not significant, thus they do not have a strong constraint on $f_{\text{RED}}$.

The LMC, also known to have an appreciable depth along the line of sight (Subramaniam & Subramaniam 2009) and a relatively low metallicity at 1/2 solar (Russell & Dopita 1992), is another suitable target for this RC/RGB dust and geometry modeling technique. Our goal is to apply this same approach to data from the LMC METAL survey (Roman-Duval et al. 2019) to study dust extinction and geometry properties probing the LMC extinction curve, extinction distribution, and 3D structure.

5.1. Calculating $A_V/N_H$

We measure the average H column density in the SMIDGE field via H I observations from Stanimirovic et al. (1999) using the ATCA and Parkes telescopes and $^{12}$CO $J = (2-1)$ observations of the SW Bar with the APEX telescope (M. Rubio et al. 2020, in preparation). We extract the average integrated intensities of the H I and CO lines over the full coverage of the ACS imaging from SMIDGE. We convert the HI line integrated intensity to column density assuming no opacity correction. For H$_2$, we must adopt a CO-to-H$_2$ conversion factor. The behavior of the conversion factor as a function of metallicity is the subject of much investigation (Bolatto et al. 2013). For the SMC, $X_{\text{CO}}$ has been found to be larger than the MW value of $X_{\text{CO}} = 2 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$) by a variety of studies (Leroy et al. 2011; Roman-Duval et al. 2014). The SMIDGE field is dominated by atomic gas, so for a wide range of conversion factors, $N_H$ does not change dramatically depending on the conversion factor choice. We convert the CO (2-1) line to (1-0) using an $R_{21} = (2-1)/(1-0) = 0.7$ and we use $X_{\text{CO}}$ values between the MW and 10 times the MW value to obtain $N_{\text{H}}$, which we multiply by 2 to obtain $N_H$. We calculate a mean $\langle A_V \rangle = 0.41 \pm 0.09$ mag. The final range of $N_H$ for SMIDGE is $9.7 \times 10^{21}$ to $1.3 \times 10^{22}$ cm$^{-2}$. This yields $\langle A_V \rangle / N_H = 3.2 - 4.2 \times 10^{23}$ mag cm$^2$ H$^{-1}$. These values are substantially lower than the canonical MW $\langle A_V \rangle / N_H = 5.3 \times 10^{22}$ (Bohlin et al. 1978; Rachford et al. 2009) by more than an order of magnitude. G03 measure the H I column density from the UV L$_{\text{Ly}}$ absorption profile for four sightlines in the SMC Bar and find $A_V / N_H = 7.7 \times 10^{23}$ mag cm$^{-2}$ H$^{-1}$, which is only a factor of $\sim 2$ higher than our result. Roman-Duval et al. (2014) measure a comparable ratio in the SMC using Herschel IR observations, where they find the gas-to-dust ratio to be between 4 and $\sim 10$.
times the MW value in the diffuse and dense ISM, respectively, depending on the methodology used.

6. Conclusions and Further Work

We model the dust extinction and 3D geometry properties of the SMIDGE field in the SW Bar of the SMC using the optical F475W – F814W CMD of RC and RGB stars. We find the following:

1. The distance modulus for the midpoint of the stellar distribution within the SMIDGE region is 65.2 kpc ($\mu = 19.07$ mag).
2. The CMD is best fit with a 1σ line-of-sight depth $\sigma_{\text{DM}} = 0.16^{+0.07}_{-0.06}$ mag or an equivalent FWHM of 11.3 kpc.
3. The dust layer is offset on the near side of the stars by $3.22^{+1.69}_{-1.44}$ kpc and is located at a distance modulus of $\mu = 18.96$ mag (61.94 kpc).
4. The combination of dust position and stellar distribution results in a 73–0.13% reddened fraction of stars.
5. The distribution of dust extinction has a mean $\langle A_V \rangle = 0.41 \pm 0.09$ mag and width $\sigma_{A_V} = 0.097 \pm 0.003$ mag (log-normal median $\tilde{A}_V = 0.33^{+0.05}_{-0.05}$ mag and dimensionless width $\tilde{\sigma}_{A_V} = 0.67^{+0.17}_{-0.13}$).

The SMC’s dust extinction curve is notably different from that of the Milky Way, in terms of the lack of a strong 2175 Å bump and a steep rise in the UV (G03). Here, we base our model grid on the G03 SMC Bar extinction law ($R_V = 2.74$) as discussed in Section 3.1.4, because our 2017 work (YMJ17) showed consistency with the G03 results. To probe different extinction laws, including a potential extinction law mixture of SMC and Milky Way extinction curves (see Appendix), in subsequent work we will use multiple color combinations for a similar analysis, fixing the geometric parameters of the SMC at the values found here.

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Appendix

We perform tests to determine the sensitivity of our technique to a number of physical and technique-specific factors in our attempt to measure quantities of interest.

Our sensitivity to the extinction law is limited because extinction curve differences in the optical part of the spectrum are small and our analysis is based only on optical CMDs. We test how sensitive we are to differentiating between an SMC and an MW extinction curve by simulating CMDs with a mixture of an SMC-like G03 $R_V = 2.74$ law and a Milky Way-like Fitzpatrick (1999) $R_V = 3.1$ law. We do this by varying $f_s$, which is the fraction corresponding to the mixture between the

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Figure 10. Examples of bad model fits where all but one of the parameters are at their best-fit value listed in Section 4. Top panels: dust layer is aligned with the center of the stellar distribution, causing a 50% reddened fraction. Middle panels: spread of the stellar distribution is 1/2 of its best-fit value ($\sigma_{\text{DM}} = 2.25$ kpc), which results in a distribution with an FWHM = 5.3 kpc. Bottom panels: mean of the log-normal distribution of dust extinctions is $A_V = 0.1$ mag.
two extinction laws (see Section 3.2 of G16). Although we see a trend of increasing PLR (worse match) as the model moves away from an SMC-like extinction, a pure Milky Way–like law is within the SMC noise model uncertainties. Thus, we are not sensitive to the extinction law to a sufficient degree when using the optical CMD only.

While Figure 6 shows our best-fit model, here we show examples of bad model fits where all parameters are held fixed at their minimum-PLR values, except for one parameter that is fixed at a bad-fit value. The PLR and the residual significance plots clearly show the mismatch. The top panel of Figure 10 shows the result of placing the dust layer in the middle of the stellar distribution, causing a ~50% reddened fraction. We can see that both the RC and the RGB have an overdensity of stars, which we do not see in the data.

The middle panel shows a model that underestimates the spread of the stars along the line of sight (FWHM = 3.3 kpc), while our results point to an FWHM ~ 11.3 kpc. We clearly see that the model lacks a sufficient number of unreddened stars extending to brighter magnitudes (which would result from a higher line-of-sight depth). Correspondingly, the model overestimates the number of reddened stars (calculated to be $f_{\text{RED}}$), because the smaller spread in the stellar distribution places a higher fraction of stars behind the dust (see Figure 8).

It can be also seen that the slope of the reddened portion of the RC is incorrect because a smaller galactic depth produces a shallower RC slope, and in our case a mismatch to the data. Indeed, the main measurement of our previous work (YM17), which used the slope of the reddened RC across multiple-color CMD combinations to measure the shape of the SMIDGE extinction curve, showed an offset from previous extinction curve measurements. This result was due to the measured steepness of the RC reddening vector, which resulted in higher extinction values across all CMD combinations. Using a toy RC model to simulate an SMC depth, we showed that the offset was consistent with a stellar distribution with an FWHM = 10 ± 2 kpc along the line of sight.

The bottom panel of Figure 10 shows a model that underestimates the amount of dust by incorporating a distribution of dust extinctions with $A_V = 0.1$ (contrasted with our result of $A_V = 0.3$). This model also results in a reddened fraction $f_{\text{RED}} = 0.7$, because the extinction has no bearing on the dust-stars geometry (and vice versa) as discussed in Section 5. However, because $A_V$ changes both the color and magnitude of stars, we can see the effect in both CMD dimensions for the RC and the RGB, as they tend to be closer to their unreddened positions (see the left panel of Figure 3).
