The Most Metal-poor Stars in the Magellanic Clouds Are \( r \)-process Enhanced*

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Abstract

The chemical abundances of a galaxy’s metal-poor stellar population can be used to investigate the earliest stages of its formation and chemical evolution. The Magellanic Clouds are the most massive of the Milky Way’s satellite galaxies and are thought to have evolved in isolation until their recent accretion by the Milky Way. Unlike the Milky Way’s less massive satellites, little is known about the Magellanic Clouds’ metal-poor stars. We have used the mid-infrared metal-poor star selection of Schlaufman & Casey and archival data to target nine LMC and four SMC giants for high-resolution Magellan/MIKE spectroscopy. These nine LMC giants with \( [\text{Fe}/\text{H}] \lesssim -1.5 \) and four SMC giants with \( -2.6 \lesssim [\text{Fe}/\text{H}] \lesssim -2.0 \) are the most metal-poor stars in the Magellanic Clouds yet subject to a comprehensive abundance analysis. While we find that at constant metallicity these stars are similar to Milky Way stars in their \( \alpha \), light, and iron-peak elemental abundances, both the LMC and SMC are enhanced relative to the Milky Way in the \( r \)-process element europium. These abundance offsets are highly significant, equivalent to 3.9\( \sigma \) for the LMC, 2.7\( \sigma \) for the SMC, and 5.0\( \sigma \) for the complete Magellanic Cloud sample. We propose that the \( r \)-process enhancement of the Magellanic Clouds’ metal-poor stellar population is a result of the Magellanic Clouds’ isolated chemical evolution and long history of accretion from the cosmic web combined with \( r \)-process nucleosynthesis on a timescale longer than the core-collapse supernova timescale but shorter than or comparable to the thermonuclear (i.e., Type Ia) supernova timescale.

Unified Astronomy Thesaurus concepts: Galaxy accretion (575); Galaxy chemical evolution (580); Galaxy environments (2029); Magellanic Clouds (990); Population II stars (1284); Stellar abundances (1577)

Supporting material: machine-readable table

1. Introduction

A common goal of Local Group galactic archeology is the use of the elemental abundances of a galaxy’s metal-poor stars to constrain its formation and early chemical evolution (e.g., Beers & Christlieb 2005; Tolstoy et al. 2009; Frebel & Norris 2015; Simon 2019). The formation and early chemical evolution of massive spiral galaxies like the Milky Way and M31 with \( M_{\text{vir}} \sim 10^{12} M_\odot \) (e.g., Kafle et al. 2018; Wang et al. 2020) resulted from complex interactions between inflows, star formation, stellar evolution, nucleosynthesis, and outflows (e.g., Kobayashi et al. 2006, 2020). In the metallicity range \(-3 \lesssim [\text{Fe}/\text{H}] \lesssim -1 \), stars in both the Milky Way and M31 have supersolar abundances relative to iron of titanium and the \( \alpha \)-elements magnesium, silicon, and calcium (e.g., McWilliam et al. 1995a, 1995b; Escala et al. 2019, 2020a, 2020b; Gilbert et al. 2020). The supersolar \( \alpha/\text{Fe} \) abundance ratios observed in these stars are thought to result from nucleosynthesis in core-collapse supernovae that start enriching a galaxy’s interstellar medium just a few Myr after the onset of star formation (e.g., Woosley & Weaver 1995; Heger & Woosley 2010; Sukhbold et al. 2016). The eventual prolife nucleosynthesis of iron-peak elements in thermonuclear (i.e., Type Ia) supernovae starting a few tens to 100 Myr after the onset of star formation causes the \( [\alpha/\text{Fe}] \) abundance ratio to approach solar as \( [\text{Fe}/\text{H}] \) approaches zero (e.g., Maoz et al. 2014). The \( [\text{Fe}/\text{H}] \) value at which \( [\alpha/\text{Fe}] \) begins to decline (sometimes called the “knee”) therefore corresponds to a point in time a few tens to 100 Myr after the onset of star formation in a stellar population (e.g., Tinsley 1979). The implication is that both the Milky Way and M31 transitioned from forming stars with \( [\text{Fe}/\text{H}] \sim -3 \) to forming stars with \( [\text{Fe}/\text{H}] \sim -1 \) in less than about 100 Myr. The Milky Way’s and M31’s high masses and star formation rates necessary to drive chemical evolution from \( [\text{Fe}/\text{H}] \sim -3 \) to \( [\text{Fe}/\text{H}] \sim -1 \) in less than 100 Myr suggest that even rare classes of supernovae should contribute to their chemical evolution.

1.1. Metal-poor Star Formation in Classical and Ultrafaint Dwarf Spheroidal Satellites

The formation and chemical evolution of the Milky Way’s satellite classical and ultrafaint dwarf spheroidal (dSph) galaxies\(^8\) with masses enclosed inside their half-light radii \( M_{1/2} \) in the range \( 10^{8} M_\odot \lesssim M_{1/2} \lesssim 10^{9} M_\odot \) appear to have been simpler.\(^9\) The Milky Way’s classical dSph galaxies with \( 10^{7} M_\odot \lesssim M_{1/2} \lesssim 10^{8} M_\odot \) have extended star formation histories, broad metallicity distributions, and no discernible downturns in \( [\alpha/\text{Fe}] \) with increasing \( [\text{Fe}/\text{H}] \) in the range

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\(^*\) This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.

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\(^{8}\) From here all references to classical and dSph refer to satellite galaxies.

\(^{9}\) While the distances to M31’s dSph galaxies make them more challenging to study, at constant mass they are generally similar to the Milky Way’s satellites (e.g., Wojno et al. 2020).
while simple chemical evolution models are unable to explain all of their observed properties, significant inflows of unenriched gas are usually necessary. Moreover, the importance of unenriched gas inflow relative to gas outflows appears to increase with galaxy luminosity.

Like the Milky Way’s more massive classical dSph galaxies, its ultrafaint dSph galaxies with $10^5 M_\odot \lesssim M_{\ast, z} \lesssim 10^7 M_\odot$ have extended star formation histories and broad metallicity distributions (e.g., Brown et al. 2012, 2014; Vargas et al. 2013; Weisz et al. 2014). In contrast to their more massive counterparts, the Milky Way’s ultrafaint dSph galaxies stopped forming stars after only a few Gyr. When considered as a population, stars in the Milky Way’s ultrafaint dSph galaxies show a decline in $\alpha/Fe$ with increasing $Fe/H$ in the range $-3 \lesssim [Fe/H] \lesssim -1$ as expected if star formation persisted for more than about 100 Myr and thermonuclear supernovae had an opportunity to contribute to their chemical evolution (e.g., Vargas et al. 2013). Chemical evolution models for ultrafaint dSph galaxies have suggested that they were an order of magnitude less efficient than classical dSph galaxies at turning their cosmological complement of baryons into stars (e.g., Vincenzo et al. 2014). When combined with their low masses, the low star formation efficiencies realized in ultrafaint dSph galaxies indicate that the probability of a rare class of supernovae occurring in a single ultrafaint dSph galaxy is small (e.g., Ji et al. 2016a, 2016b).

The formation of metal-poor stars with $[Fe/H] \lesssim -2$ will persist while a galaxy’s star formation rate is small compared to the inflow rate of unenriched gas from the cosmic web. Alternatively, a galaxy will cease forming metal-poor stars when its star formation rate is large relative to the inflow rate of unenriched gas from the cosmic web. The interplay between star formation and the accretion of unenriched gas is therefore the key determinant of the duration of metal-poor star formation. The available data described above suggest that the chemical evolution of the Milky Way and M31 advanced rapidly through the range $-3 \lesssim [Fe/H] \lesssim -1$. In contrast, the chemical evolution of the Milky Way’s classical and ultrafaint dSph galaxies moved slowly through the range $-3 \lesssim [Fe/H] \lesssim -1$. While the physical processes that halted the inflow of unenriched gas from the cosmic web and therefore ended the era of metal-poor star formation are not directly observable, it is possible to directly study the quenching of metal-rich star formation in nearby galaxies.

### 1.2. Quenching Metal-poor Star Formation

Galaxies can be roughly categorized using their morphologies and rest-frame optical colors into two classes: spiral or irregular galaxies that are part of a “blue cloud,” and elliptical galaxies that are part of a “red sequence” (e.g., Strateva et al. 2001; Blanton et al. 2003; Baldry et al. 2004; Wyots et al. 2011; van der Wel et al. 2014). While both morphologies and rest-frame optical colors are manifestations of galaxies’ star formation rates, the physical processes responsible for quenching star formation and therefore moving galaxies from the blue cloud to the red sequence are complex and uncertain. It has been shown that both galaxy mass and environment contribute to quenching star formation (e.g., Peng et al. 2010). The implication is that processes both intrinsic and extrinsic to individual galaxies play some role in heating and/or removing cold gas from halos and therefore quenching star formation.

Possible processes responsible for intrinsic quenching are stellar winds and supernova explosions (e.g., Webster et al. 2014, 2015; Bland-Hawthorn et al. 2015), AGN feedback (e.g., Fabian 2012), or the shock heating of cold gas falling onto a galaxy from the cosmic web (e.g., Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006). The first is expected to be important for lower-mass galaxies with shallower gravitational potentials, while the latter two are expected to be important for massive galaxies with deeper gravitational potentials. Extrinsic quenching of star formation is thought to result from the removal of a galaxy’s cold gas by the reionization of the universe (e.g., Bullock et al. 2000; Benson et al. 2002a, 2002b; Somerville 2002), ram pressure stripping (e.g., Gunn et al. 1972), or the interdiction of its supply of cold gas in a process called “ strangulation” (e.g., Larson 1980; van den Bosch et al. 2008; Putman et al. 2021).

### 1.3. The Magellanic Clouds

The Magellanic Clouds occupy a mass range between the Milky Way’s lower-mass ultrafaint and classical dSph galaxies and the higher-mass Milky Way and M31. Before their interactions with the Milky Way, the Large and Small Magellanic Clouds had masses $M_{\ast, \alpha} \sim 10^{11} M_\odot$, and $M_{\ast, \beta} \sim 10^{10} M_\odot$, respectively (e.g., van der Marel & Kallivayalil 2014; Bekki & Stanimirović 2009; Di Teodoro et al. 2019; Ėrkal et al. 2019). Unlike most of the Milky Way’s classical and ultrafaint dSph galaxies that have well-defined apocenters and therefore have been inside the Milky Way’s virial radius for a few orbital periods and thus several Gyr (e.g., Fritz et al. 2018; Gaia Collaboration et al. 2018; Simon 2018), the orbits of the LMC and SMC support the idea that they only recently entered the Milky Way’s virial radius. This recent infall inference is especially robust if the Magellanic Clouds have been part of a bound pair for several Gyr (e.g., Besla et al. 2007, 2010; Kallivayalil et al. 2013).

The idea that the Magellanic Clouds evolved in isolation for most of their histories is supported by their inferred star formation and chemical evolution histories. Models of the Magellanic Clouds’ star formation histories suggest initial surges of star formation followed by relatively low levels of star formation until bursts a few Gyr in the past (e.g., Harris & Zaritsky 2004, 2009). These bursts of star formation are plausibly associated with the Magellanic Clouds’ first interaction with the Milky Way. Masses in excess of $M_{\ast, \text{tot}} \sim 10^{10} M_\odot$, combined with flat age–metallicity relations for both the LMC at $[Fe/H] \approx -1.2$ between 12 and 5 Gyr in the past and the SMC at $[Fe/H] \approx -1$ between 8 and 3 Gyr in the past, require the accretion of significant amounts of unenriched gas. Nidever et al. (2020) have suggested that $\alpha/Fe$ begins to decline in the Magellanic Clouds at $[Fe/H] \approx -2.2$ as well, implying that the chemical evolution of both the LMC and SMC had advanced no further than $[Fe/H] \approx -2.2$ after about 100 Myr. While the chemical evolution of the SMC has not yet been studied in detail, models of the LMC’s chemical evolution confirm the importance of the accretion of low-metallicity gas (e.g., Bekki & Tsujimoto 2012).

All of these data are consistent with a scenario in which the Magellanic Clouds spent the majority of their histories beyond the Milky Way’s virial radius. They were therefore able to accrete gas from the cosmic web because of their intermediate masses and relative isolation. They were then able to retain that gas against stellar and supernova feedback because of their
intermediate-depth potential wells (e.g., Jahn et al. 2019; Santos-Santos et al. 2021). Indeed, Geha et al. (2012) have shown that in the mass range of the Magellanic Clouds internal processes appear to be unable to quench star formation. At the same time, they were not massive enough to be significantly affected by AGN feedback or the shock heating of infalling unenriched gas. The net result is that metal-poor star formation at rates high enough to realize even rare supernovae likely extended for a longer time in the Magellanic Clouds than in the Milky Way, M31, or most of their satellite dSph galaxies.

1.4. The Origin of r-process Elements

The Magellanic Clouds’ high rates (relative to the Milky Way’s dSph satellite galaxies) and extended durations of metal-poor star formation (relative to the Milky Way and M31) provide an opportunity to identify the astrophysical origin of the rapid neutron-capture process or r-process nucleosynthesis. While some small amount of r-process nucleosynthesis probably occurs in ordinary core-collapse supernovae (e.g., Ji et al. 2016b; Casey & Schlaufman 2017), a rare class of explosive event is thought to be responsible for most r-process nucleosynthesis. Evidence for a rare but prolific astrophysical origin for r-process nucleosynthesis comes from sea floor $^{244}$Pu (e.g., Horikawa et al. 2015; Wallner et al. 2015), early solar system $^{244}$Pu and actinide abundances (Bartos & Marka 2019), the r-process abundances of stars in ultrafaint dSph galaxies (e.g., Ji et al. 2016a), and models of galactic chemical evolution (e.g., Shen et al. 2015; van de Voort et al. 2015; Macias & Ramirez-Ruiz 2018; Naiman et al. 2018). Three types of models have been suggested to explain the existence of r-process-enriched metal-poor stars: (1) unusual core-collapse supernovae like collapsars or magnetorotationally driven supernovae (e.g., Pruet et al. 2004; Fryer et al. 2006; Winteler et al. 2012; Siegel et al. 2019), (2) compact object mergers involving a neutron star (e.g., Lattimer & Schramm 1974; Symbalisty & Schramm 1982), and (3) Common envelope process enhancements in rare events, in the unusual core-collapse supernova model r-process nucleosynthesis should be prompt on a timescale comparable to the core-collapse supernova timescale. On the other hand, in the neutron star merger model r-process nucleosynthesis events should occur only after some delay of uncertain duration from the onset of star formation.

One way to evaluate both the reality and duration of a delay in the onset of r-process nucleosynthesis would be to compare the relative occurrence of r-process-enhanced stars in both the Milky Way and the Magellanic Clouds at $[\text{Fe/H}] \sim -2$ and $[\alpha/\text{Fe}] \approx 0.4$. Both galaxies are massive enough and experience sufficient metal-poor star formation for rare supernovae to occur. The key difference is that chemical evolution in the Milky Way moved through the range $-3 \lesssim [\text{Fe/H}] \lesssim -1$ before thermonuclear supernovae could become significant contributors to its chemical evolution. In the same amount of time, chemical evolution in the Magellanic Clouds advanced no further than $[\text{Fe/H}] \approx -2.2$. If the occurrence of r-process-enhanced metal-poor stars is the same in both the Milky Way and the Magellanic Clouds, then r-process nucleosynthesis occurs on a timescale comparable to the core-collapse supernova timescale. If r-process-enhanced metal-poor stars are more common in the Magellanic Clouds, then r-process nucleosynthesis occurs with a delay between the core-collapse supernova and thermonuclear supernova delay timescales in the range of a few to 100 Myr.

In this paper, we isolate and then study the stellar parameters and detailed elemental abundances of the most metal-poor stars yet subject to comprehensive abundance analyses in both the Large and Small Magellanic Clouds. We describe in Section 2 our sample selection and high-resolution follow-up observations. We then infer stellar parameters from those spectra and all available photometric data in Section 3. We report each star’s detailed elemental abundances in Section 4. We review our results and their implications in Section 5. We conclude by summarizing our findings in Section 6.

2. Sample Selection and Observations

We selected our initial list of candidate metal-poor giants using a variant of the Schlaufman & Casey (2014) infrared metal-poor star selection on Two Micron All Sky Survey (2MASS) near-infrared and Spitzer SAGE or AllWISE mid-infrared photometry (Meixner et al. 2006; Skrutskie et al. 2006; Wright et al. 2010; Mainzer et al. 2011). We required $[\text{Fe/H}] \equiv \left[\frac{\text{Fe}}{\text{H}}\right] < -3.6 - 4.5 < 0.04$ in Spitzer SAGE or $|W1 - W2| < 0.04$ in AllWISE. While we used a near-infrared color cut 0.45 < $J - H < 0.60$ in Schlaufman & Casey (2014), we extended that color cut to 0.45 < $J - H < 0.70$ in the Magellanic Clouds to include metal-poor giants closer to the tip of the red giant branch. The only Spitzer SAGE data quality cut we imposed was closeflag $= 0$ to require all sources to have no detected sources within 3 of our candidates. Because we were confident that we could exclude LMC and SMC variable stars identified as such by the Optical Gravitational Lensing Experiment (OGLE),$^{10}$ we did not use in our selection the AllWISE var_flag metadata. We also ignored AllWISE moon Lev metadata.

The procedure described above produced an initial candidate list that we then examined using SIMBAD. We found literature data for five of our candidates from Cole et al. (2005; 2MASS J05224088−6951471 and 2MASS J05242020−6945073), Carrera et al. (2008; 2MASS J05141665−6454310), Pompéia et al. (2008)/Van der Swaalmnen et al. (2013; 2MASS J05135097−7109322), or Dobbie et al. (2014; 2MASS J00263959−7122102). We prioritized for high-resolution follow-up our candidates with low inferred metallicities from those sources. We also confirmed the metal-poor nature of four of our candidates (2MASS J00251849−7140074, 2MASS J00262394−7128549, 2MASS J00263959−7122102, and 2MASS J00273753−7125114) using data described in Maciarella (2014) collected with UT2 of the Very Large Telescope and its GIRAFFE instrument fed by the Fibre Large Array Multi Element Spectrograph (FLAMES; Pasquini et al. 2002) in a field centered on the ancient SMC globular cluster NGC 121. $^{11}$ NGC 121 has heliocentric radial velocity $v_r = 138 \pm 4 \text{ km s}^{-1}$, $[\text{Fe/H}] = -1.41 \pm 0.04$, and distance $d = 63.4 \pm 0.8 \text{ kpc}$ (e.g., Da Costa & Hatzidimitriou 1998; Johnson et al. 2004; Glatt et al. 2008). These four metal-poor giants have positions well beyond the cluster’s tidal radius and, as we will

$^{10}$ The OGLE survey and its variable star discoveries in the Magellanic Clouds have been described in Udalski et al. (2008, 2015). Soszyński et al. (2015, 2016, 2017, 2018), and Pawlak et al. (2016).

$^{11}$ Based on observations collected at the European Southern Observatory under ESO program 086.D-0665(A) obtained from the ESO Science Archive Facility under request No. 284138.
show, have radial velocities, metallicities, and/or distances that rule out an association with NGC 121. We supplemented our mid-infrared selected candidates with an additional three candidates from Carrera et al. (2008) with low Ca II-inferred metallicities (2MASS J05121686−6517147, 2MASS J05143154−6505189, and 2MASS J05150380−6647003).

We subsequently found that these seven LMC and four SMC stars all have metallicities in the range $-2.6 \lesssim [\text{Fe/H}] \lesssim -1.7$, leaving a significant metallicity gap between the most metal-rich LMC stars in our sample and the metal-poor LMC stars analyzed by Van der Swaelmen et al. (2013). To close that gap, we selected two LMC stars from the fourth phase of the Sloan Digital Sky Survey’s extension of the Apache Point Observatory Galactic Evolution Experiment to the southern sky (APOGEE-2; Blanton et al. 2017; Majewski et al. 2017; Zasowski et al. 2017; Wilson et al. 2019). These stars had Sloan Digital Sky Survey (SDSS) Data Release 16 APOGEE Stellar Parameters and Chemical Abundances Pipeline (ASPCAP; García Pérez et al. 2016; Ahumada et al. 2020) inferred metallicities in the range $-1.7 \lesssim [\text{Fe/H}] \lesssim -1.5$ (2MASS J05160009−6207287 and 2MASS J06411906−7016314). We plot the locations of these 13 stars on Digitized Sky Survey images of the LMC and SMC in Figure 1.

We followed up on these 13 stars with the Magellan Inamori Kyocera Echelle (MIKE) spectrograph on the Magellan Clay Telescope at Las Campanas Observatory (Bernstein et al. 2003; Shectman & Johns 2003). We used either the 0.75 or 1.0 slits and the standard blue and red grating azimuths, yielding spectra between 335 and 950 nm with resolution $R \approx 40,000/28,000$ in the blue and $R \approx 31,000/22,000$ in the red for the 0.75/1.0 slits. We collected all calibration data (e.g., bias, quartz and “milky” flat field, and ThAr lamp frames) in the afternoon before each night of observations. We present a log of these observations in Table 1. We reduced the raw spectra and calibration frames using the CarPy12 software package (Kelson et al. 2000, 2014; Kelson 2003). We used iSpec13 (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019) to calculate radial velocities and barycentric corrections and normalized individual orders using IRAF14 (Tody 1986, 1993).

12 http://code.obs.carnegiescience.edu/mike
13 https://www.blancocuaresma.com/s/ISpec
14 https://iraf-community.github.io/
15 https://github.com/vmplacco/linemake

3. Stellar Properties

We use both the classical excitation/ionization balance approach and isochrones to infer photospheric stellar parameters for the 13 stars listed in Table 1. Isochrones are especially useful for effective temperature $T_{\text{eff}}$ inferences in this case, as high-quality multiwavelength photometry from the ultraviolet to the mid-infrared is available for both the LMC and SMC. Similarly, the known distances of the Magellanic Clouds make the calculation of surface gravity $\log g$ via isochrones straightforward. With both $T_{\text{eff}}$ and $\log g$ available via isochrones, the equivalent widths of iron lines can be used to self-consistently determine metallicity [Fe/H] and micro-turbulence $\xi$.

We follow the algorithm outlined in Reggiani et al. (2020). Using atomic absorption-line data from Ji et al. (2020) based on the linemake code15 (Placco et al. 2021, Sneden et al. 2009, 2016) maintained by Vinicius Placco and Ian Roederer, we first measure the equivalent widths of Fe II atomic absorption lines by fitting Gaussian profiles with the splplot task in IRAF to our continuum-normalized spectra. We use only Fe II lines with equivalent widths smaller than 150 mÅ in our photospheric stellar parameter inferences to avoid the possibly important effects of departures from local thermodynamic equilibrium (LTE) on Fe I-based inferences. Whenever necessary, we use the deblend task to disentangle absorption lines from adjacent spectral features. We report our input atomic data, measured equivalent widths, and inferred abundances in Table 2.

To evaluate the relative importance of departures from LTE on Fe I- and Fe II-based metallicity inferences, we used the grid of corrections to abundances derived under the assumptions of LTE for departures from LTE (i.e., non-LTE corrections) from Amarsi et al. (2016) for stars with $\log g = 1.5$. For all of our stars, the non-LTE corrections to our inferred Fe II-based metallicities were less than 0.1 dex and therefore smaller than...
the overall metallicity uncertainties we adopted. On the other hand, corrections for individual Fe I lines can be as large as 0.3 dex. We therefore argue that the metallicity inference approach we followed based on Fe II lines is likely to be more accurate and precise than one based on Fe I lines.

We use 1D plane-parallel α-enhanced ATLAS9 model atmospheres (Castelli & Kurucz 2004), the 2019 version of the MOOG radiative transfer code (Sneeden 1973), and the q2 MOOGwrapper16 (Ramírez et al. 2014) to derive with the classical excitation/ionization balance approach an initial set of photospheric stellar parameters Teff, log g, [Fe/H], and ξ. Since photospheric stellar parameters inferred via the classical excitation/ionization balance approach differ from those derived using photometry and distance information (e.g., Korn et al. 2003; Mucciarelli & Bonifacio 2020), we then use the isochrones package17 (Morton 2015) in an iterative process to self-consistently infer photospheric and fundamental stellar parameters for each star using the following as input:

1. photospheric stellar parameters from the classical excitation/ionization balance approach (on the first iteration) or the reduced equivalent width balance approach (on all subsequent iterations);

2. g, r, i, and z magnitudes and associated uncertainties from Data Release (DR) 2 of the SkyMapper Southern Sky Survey (Onken et al. 2019);

3. J, H, and Ks magnitudes and associated uncertainties from the 2MASS Point Source Catalog (Skrutskie et al. 2006);

4. W1 and W2 magnitudes and associated uncertainties from the Wide-field Infrared Survey Explorer (WISE) AllWISE Source Catalog (Wright et al. 2010; Mainzer et al. 2011);

5. reddening inferences from Skowron et al. (2021);

6. distances inferred via the surface brightness–color relation for eclipsing binaries in the LMC (Pietrzyński et al. 2019) and SMC (Graczyk et al. 2014). For the SMC, we account for a possibly significant line-of-sight depth inferred by Scowcroft et al. (2016) using the mid-infrared period–absolute magnitude relation for Cepheids (i.e., the Leavitt Law).

We use isochrones to fit the MESA Isochrones and Stellar Tracks (MIST; Paxton et al. 2011, 2013, 2015, 2018, 2019; Choi et al. 2016; Dotter 2016) library to these data using MultiNest18 (Feroz & Hobson 2008; Feroz et al. 2009, 2019). We restrict the MIST library to stellar ages τ in the range 8.0 Gyr ≤ τ ≤ 13.721 Gyr and distances d to the 3σ

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16 https://github.com/astroChasqui/q2
17 https://github.com/timothydmorton/iscochrones
18 https://ccpforge.cse.rl.ac.uk/gf/project/multinest/
ranges including both statistical and systematic uncertainties for the LMC and SMC from Pietrzyński et al. (2019) and Graczyk et al. (2014), respectively, accounting for the possibly significant line-of-sight depth for the SMC advocated by Scowcroft et al. (2016). We also restrict our analysis to extinctions $A_V$ in the ranges proposed by Skowron et al. (2021) at the location of each candidate. While the metal-poor stars in our sample generally have supersolar $\alpha$-element abundances, the current versions of the MIST isochrones were calculated using solar-scaled abundances. While this potential inconsistency can affect fundamental stellar parameter inferences like mass and age, the uncertainties due to this effect are usually smaller than the uncertainties resulting from other sources (e.g., Grunblatt et al. 2021).

For the first isochrones calculation, we use in the likelihood the initial set of photospheric stellar parameters inferred from the classical excitation/ionization balance analysis of each spectrum along with the photometric, extinction, and distance information described above. We then use isochrones to calculate a new set of photospheric and fundamental stellar parameters that is both self-consistent and physically consistent with stellar evolution. We next impose the $T_{\text{eff}}$ and $\log g$ inferred in this way on an iteration of the reduced equivalent width balance approach to derive [Fe/H] and $\xi$ values consistent with our measured Fe II equivalent widths and our isochrones-inferred $T_{\text{eff}}$ and $\log g$. We then execute another isochrones calculation, this time using this updated set of photospheric stellar parameters in the likelihood.

We iterate this process until the metallicities inferred from both the isochrones analysis and the reduced equivalent width balance approach are consistent within their uncertainties (typically a few iterations). For our final photospheric stellar parameters, we adopt $T_{\text{eff}}$ and $\log g$ from the final isochrones iteration. We infer $A_V \approx 1.6$ mag for the two stars coincident with the bar of the LMC 2MASS J05224088−6951471 and 2MASS J05242202−6945073, possibly suggesting that they are on the far side of the LMC. We prefer stellar parameters inferred using both isochrones and spectroscopy to stellar parameters derived from spectroscopy alone. Isochrone analyses can make use of constraints from multi-wavelength photometry as well as distance and extinction information impossible to leverage with the classic spectroscopic method. All of these data are available for the stars in our sample. Unlike $T_{\text{eff}}$ and $\log g$ values derived from spectroscopy alone, $T_{\text{eff}}$ and $\log g$ values deduced from isochrone analyses are guaranteed to be self-consistent and in principle realizable during stellar evolution (to the degree of accuracy achievable by the stellar models). It has long been known that photospheric stellar parameters inferred for metal-poor giants using the classical approach differ from those derived using photometry and parallax information (e.g., Korn et al. 2003; Frebel et al. 2013; Mucciarelli & Bonifacio 2020). Since LTE is almost always assumed in the calculation of the model atmospheres used to interpret equivalent width measurements, these differences are often attributed to the violation of the assumptions of LTE in the photospheres of metal-poor giants.

We derive the uncertainties in our adopted [Fe/H] and $\xi$ values due to the uncertainties in our adopted $T_{\text{eff}}$ and $\log g$ values using a Monte Carlo simulation. We randomly sample self-consistent pairs of $T_{\text{eff}}$ and $\log g$ from our isochrones posteriors and calculate the values of [Fe/H] and $\xi$ that produce the best reduced equivalent width balance given our Fe II equivalent width measurements. We save the result of each iteration and find that the contributions of $T_{\text{eff}}$ and $\log g$ uncertainties to our final [Fe/H] and $\xi$ uncertainties are small: about 0.01 dex for both the LMC and SMC. We derive our adopted metallicities and uncertainties using a final reduced equivalent width balance calculation imposing the adopted $T_{\text{eff}}$ and $\log g$ values described above. The result of this calculation agrees well with the result of the Monte Carlo simulation. We report our adopted photospheric stellar parameters both by themselves in Table 3 and together with all of our derived stellar parameters in the comprehensive Table 4.

We define the line-by-line dispersion of our inferred iron abundances as the standard deviation of the Fe II abundances inferred from individual Fe II lines. The uncertainties in our metallicity inferences are dominated by this line-by-line dispersion. We provide in Tables 3 and 4 our adopted Fe II-based metallicities with uncertainties derived by adding in quadrature the relatively large uncertainties from our line-by-line abundance dispersions and the relatively small uncertainties that can be attributed to $T_{\text{eff}}$ and $\log g$ uncertainties. We also present in Table 4 a detailed view of our adopted

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### Table 3

**Adopted Photospheric Stellar Parameters**

| 2MASS Designation | $T_{\text{eff}}$ (K) | $\log g$ | [Fe/H] | $\xi$ (km s$^{-1}$) |
|-------------------|-----------------|--------|-------|------------------|
| J00251849−7140074 | 4372$^{+5}_{-3}$ | 0.65 ± 0.01 | −2.33 ± 0.30 | 2.71 ± 0.50 |
| J00262394−7128549 | 4388$^{+5}_{-6}$ | 0.87 ± 0.01 | −2.02 ± 0.32 | 2.51 ± 0.80 |
| J00263959−7122120 | 4481$^{+7}_{-3}$ | 0.73 ± 0.01 | −2.60 ± 0.39 | 3.01 ± 0.45 |
| J00273751−7125114 | 4326 ± 10 | 0.61 ± 0.01 | −2.27 ± 0.26 | 3.83 ± 0.95 |
| J01214686−651747 | 4247 ± 1 | 0.55 ± 0.01 | −2.32 ± 0.36 | 2.91 ± 0.50 |
| J0133509−7109322 | 4520$^{+26}_{-18}$ | 1.06 ± 0.02 | −2.15 ± 0.38 | 2.55 ± 0.75 |
| J0141665−6454310 | 4761$^{+18}_{-15}$ | 1.43 ± 0.02 | −2.42 ± 0.23 | 2.45 ± 0.62 |
| J0143154−6505189 | 4361$^{+12}_{-14}$ | 1.06 ± 0.01 | −1.65 ± 0.35 | 2.74 ± 0.83 |
| J0150380−6647003 | 4139$^{+14}_{-14}$ | 0.64 ± 0.02 | −1.83 ± 0.46 | 3.31 ± 0.91 |
| J0160609−6207287 | 4151 ± 17 | 0.60 ± 0.02 | −1.62 ± 0.24 | 3.25 ± 0.54 |
| J05224088−695147 | 4619$^{+25}_{-21}$ | 1.24 ± 0.03 | −2.14 ± 0.32 | 3.16 ± 0.45 |
| J05242202−6945073 | 4903$^{+16}_{-16}$ | 1.61 ± 0.03 | −1.99 ± 0.47 | 2.38 ± 0.78 |
| J06411906−7016314 | 4093$^{+5}_{-5}$ | 0.53 ± 0.01 | −1.54 ± 0.14 | 3.28 ± 0.47 |

**Note.** We give our adopted photospheric stellar parameters both by themselves here and in our comprehensive table of stellar parameters in Table 4.

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### Table 4
Stellar Properties and Adopted Parameters

| Property                        | J00251849 | J00262394 | J00263959 | J00273753 |
|--------------------------------|-----------|-----------|-----------|-----------|
|                                | Units     | Units     | Units     | Units     |
| SKYMAPPER  g                   | 16.575 ± 0.036 | 17.604 ± 0.016 | 16.801 ± 0.025 | 16.987 ± 0.028 |
| SKYMAPPER  r                   | 16.917 ± 0.020 | 16.980 ± 0.014 | 16.172 ± 0.013 | 16.107 ± 0.013 |
| SKYMAPPER  i                   | 15.356 ± 0.003 | 16.403 ± 0.017 | 15.576 ± 0.040 | 15.475 ± 0.004 |
| SKYMAPPER  z                   | 15.171 ± 0.009 | 16.232 ± 0.017 | 15.407 ± 0.009 | 15.208 ± 0.003 |
| 2MASS  J                       | 13.938 ± 0.026 | 15.076 ± 0.045 | 14.236 ± 0.030 | 14.038 ± 0.029 |
| 2MASS  H                       | 13.327 ± 0.035 | 14.519 ± 0.060 | 13.580 ± 0.026 | 13.351 ± 0.030 |
| 2MASS  K                       | 13.119 ± 0.037 | 14.295 ± 0.078 | 13.462 ± 0.051 | 13.242 ± 0.040 |
| WISE  W1                       | 13.106 ± 0.024 | 14.247 ± 0.026 | 13.423 ± 0.024 | 13.092 ± 0.024 |
| WISE  W2                       | 13.104 ± 0.026 | 14.268 ± 0.038 | 13.451 ± 0.028 | 13.064 ± 0.025 |

#### Photometric properties

**SkyMapper g**

Luminosity

| Property                        | J05121868 | J05133509 | J05141665 | J0514154 | J05150380 |
|--------------------------------|-----------|-----------|-----------|-----------|-----------|
|                                | Units     | Units     | Units     | Units     | Units     |
|                                | J0517147  | J0710932  | J0654310  | J0650189  | J0647003  |
| LMC                            | Units     | Units     | Units     | Units     | Units     |
|                                | J05160009 | J05224088 | J05242202 | J0641906  | J0616314  |

#### Photometric properties

**SkyMapper g**

Luminosity

| Property                        | J05121868 | J05133509 | J05141665 | J0514154 | J05150380 |
|--------------------------------|-----------|-----------|-----------|-----------|-----------|
|                                | Units     | Units     | Units     | Units     | Units     |
|                                | J0517147  | J0710932  | J0654310  | J0650189  | J0647003  |
| LMC                            | Units     | Units     | Units     | Units     | Units     |
|                                | J05160009 | J05224088 | J05242202 | J0641906  | J0616314  |

#### Photometric properties

**SkyMapper g**

Luminosity

| Property                        | J05121868 | J05133509 | J05141665 | J0514154 | J05150380 |
|--------------------------------|-----------|-----------|-----------|-----------|-----------|
|                                | Units     | Units     | Units     | Units     | Units     |
|                                | J0517147  | J0710932  | J0654310  | J0650189  | J0647003  |
| LMC                            | Units     | Units     | Units     | Units     | Units     |
|                                | J05160009 | J05224088 | J05242202 | J0641906  | J0616314  |
4. Elemental Abundances

To infer the elemental abundances of several $\alpha$, light odd-Z, iron-peak, and neutron-capture elements, we first measure the equivalent widths of atomic absorption lines of Na I, Mg I, Si I, Ca I, Sc II, Ti I, Ti II, Cr I, Mn I, Co I, Ni I, Y II, Ba II, La II, Ce II, Nd II, Sm II, and Gd II in our continuum-normalized spectra by fitting Gaussian profiles with the splot task in IRAF. We use the debblend task to disentangle absorption lines from adjacent spectral features whenever necessary. We measure an equivalent width for every absorption line in our line list that could be recognized, taking into consideration the quality of a spectrum in the vicinity of a line and the availability of alternative transitions of the same species. If possible we avoid lines blue than 4500 Å, as the signal-to-noise ratios (S/Ns) in our spectra blueward of 4500 Å are poor. Blueward of 5000 Å in MIKE’s blue arm we were able to measure equivalent widths of lines with equivalent widths greater than 10 mA. Redward of 5000 Å in MIKE’s red arm, we were able to measure equivalent widths of lines with equivalent widths greater than 5 mA. These limiting S/Ns applied even to our lower-S/N stars. In a few cases we measured lines with smaller EWs for species without other available lines. Whenever possible, we avoid saturated lines like Mg I b as well. We consider hyperfine splitting in our abundance inferences for Mn I, Co I, and Y II. We account for isotopic splitting in barium using data from McWilliam (1998) for the three Ba II lines at 5853, 6141, and 6496 Å that we use for our barium abundance inferences. We use the 1D plane-parallel $\alpha$-enhanced ATLAS9 model atmospheres and the 2019 version of MOOG to infer elemental abundances based on each equivalent width measurement. We use spectral synthesis to infer the abundance of Eu II, mostly from its 6645 Å line. Although this line is not usually strong, it is clearly measurable in 10 of the 13 giants in our sample. For the most europium-poor star in our sample, 2MASS J05141665–6454310, we used the Eu II line at 4129 Å for our abundance inference.

We report our input atomic data, measured equivalent widths, and the abundances and associated uncertainties we derive in Table 2. We present in Table 5 our adopted mean elemental abundances and associated uncertainties defined as the quadrature sum of the line-by-line abundance dispersions and the uncertainties that result from our photospheric stellar parameter uncertainties. We indicate typical uncertainties in each panel of Figures 2–4. Our iterative use of both isochrones and the classical excitation/ionization balance approach to stellar parameter inference produced very precise stellar parameters, and that precision is reflected in the abundance uncertainties we report in Table 5.

As we described in Section 3, we have not accounted for the possibility of systematic uncertainties in our stellar parameter inferences. To quantify the effect of possible systematic uncertainties in our stellar parameter inferences on our abundance inferences, we recalculated our abundances assuming $T_{\text{eff}}$ and $\log g$ uncertainties $\Delta T_{\text{eff}} = 100$ K and
### Table 5
Mean Elemental Abundances

| Species | $n$ | log($c_e$) | [X/Fe] | $\sigma_{[X/Fe]}$ | $n$ | log($c_e$) | [X/Fe] | $\sigma_{[X/Fe]}$ | $n$ | log($c_e$) | [X/Fe] | $\sigma_{[X/Fe]}$ |
|---------|----|------------|--------|------------------|----|------------|--------|------------------|----|------------|--------|------------------|
| Na I    | 2  | 4.187      | 0.300  | 0.264            | 3  | 3.974      | -0.222 | 0.210           | 2  | 4.168      | 0.550  | 0.264           |
| Na I     | 2  | 4.072      | 0.166  | ...              | 3  | 3.877      | -0.339 | ...             | 2  | 3.916      | 0.278  | ...             |
| Mg I    | 2  | 5.710      | 0.493  | 0.287            | 2  | 5.662      | 0.136  | 0.211           | 1  | 5.523      | 0.573  | 0.125           |
| Si I    | 3  | 5.864      | 0.687  | 0.174            | 4  | 6.027      | 0.541  | 0.023           | 4  | 6.204      | 1.296  | 0.090           |
| K I     | 1  | 3.569      | 0.832  | 0.192            | 1  | 3.237      | 0.191  | 0.151           | 5  | 3.679      | 1.211  | 0.174           |
| K I     | 1  | 2.854      | 0.157  | ...              | 1  | 2.932      | -0.074 | ...             | 1  | 2.711      | -0.054 | ...             |
| Ca I    | 14 | 4.581      | 0.614  | 0.132            | 9  | 4.383      | 0.107  | 0.150           | 8  | 4.547      | 0.849  | 0.096           |
| Sc II   | 5  | 0.736      | -0.071 | 0.079            | 4  | 0.870      | -0.246 | 0.138           | 4  | 0.899      | 0.361  | 0.069           |
| Ti I    | 13 | 3.265      | 0.628  | 0.164            | 9  | 3.199      | 0.253  | 0.165           | 10 | 3.363      | 0.995  | 0.176           |
| Ti II   | 5  | 3.307      | 0.670  | 0.125            | 6  | 3.313      | 0.367  | 0.203           | 5  | 3.178      | 0.810  | 0.169           |
| Cr I    | 6  | 3.632      | 0.345  | 0.289            | 5  | 3.262      | -0.334 | 0.241           | 2  | 3.178      | 0.160  | 0.141           |
| Mn I    | 2  | 3.032      | -0.055 | 0.143            | 4  | 2.809      | -0.587 | 0.212           | 3  | 2.865      | 0.047  | 0.144           |
| Fe I    | 31 | 5.294      | ...    | ...              | 26 | 5.222      | ...    | ...             | 27 | 5.190      | ...    | ...             |
| Fe II   | 24 | 5.163      | ...    | ...              | 20 | 5.464      | ...    | ...             | 14 | 4.898      | ...    | ...             |
| Co I    | 3  | 3.321      | 0.714  | 0.214            | 2  | 3.081      | 0.165  | 0.214           | 2  | 2.920      | 0.582  | 0.162           |
| Ni I    | 14 | 4.172      | 0.305  | 0.144            | 7  | 3.882      | -0.294 | 0.117           | 9  | 4.043      | 0.445  | 0.119           |
| Cu I    | 1  | 2.073      | 0.146  | 0.144            | ... | ...        | ...    | ...             | 1  | 1.785      | -0.130 | 0.068           |
| Zn I    | ... | ...        | ...    | ...              | ... | ...        | ...    | ...             | ... | ...        | ...    | ...             |
| Y II    | 2  | -0.215     | -0.092 | 0.205            | 3  | 0.599      | 0.413  | 0.404           | 3  | 0.221      | 0.613  | 0.182           |
| Ba II   | 3  | -0.205     | -0.142 | 0.264            | 2  | 0.508      | 0.262  | 0.292           | 3  | -0.428     | -0.096 | 0.201           |
| La II   | ... | ...        | ...    | ...              | ... | ...        | ...    | ...             | ... | ...        | ...    | ...             |
| Ce II   | 2  | -0.664     | 0.089  | 0.062            | 3  | 1.305      | 1.749  | 1.619           | 2  | -0.355     | 0.667  | 0.280           |
| Nd II   | 2  | -1.009     | -0.096 | 0.188            | 5  | -0.166     | 0.438  | 0.196           | 3  | -0.602     | 0.580  | 0.198           |
| Sm II   | 1  | -0.865     | 0.518  | 0.056            | 2  | -0.409     | 0.665  | 0.275           | ... | ...        | ...    | ...             |
| Gd II   | 1  | 0.005      | 1.258  | 0.133            | 2  | -0.132     | 0.812  | 0.266           | 1  | -0.382     | 1.140  | 0.045           |
| Eu II   | 1  | -0.963     | 0.853  | 0.300            | 1  | -0.500     | 1.004  | 0.300           | ... | ...        | ...    | ...             |

| Species | $n$ | log($c_e$) | [X/Fe] | $\sigma_{[X/Fe]}$ |
|---------|----|------------|--------|------------------|
| Na I    | 3  | 4.209      | 0.144  | 0.167            |
| Na I     | 3  | 4.100      | 0.015  | ...              |
| Mg I    | 4  | 5.868      | 0.473  | 0.230            |
| Si I    | 4  | 6.187      | 0.832  | 0.081            |
| K I     | 1  | 3.333      | 0.423  | 0.200            |
| Ti I    | 9  | 3.265      | 0.470  | 0.204            |
| Cr I    | 13 | 3.589      | 0.124  | 0.279            |
| Mn I    | 5  | 2.965      | -0.300 | 0.244            |
| Fe I    | 79 | 5.222      | ...    | ...              |
| Fe II   | 28 | 5.340      | ...    | ...              |
| Co I    | 5  | 3.216      | 0.431  | 0.223            |
| Ni I    | 16 | 4.105      | 0.060  | 0.177            |
### Table 5
(Continued)

| Species | \( n \) | \( \log(X) \) | [X/Fe] | \( \sigma_{\log(X)} \) | [X/Fe] | \( \sigma_{\log(X)} \) | [X/Fe] | \( \sigma_{\log(X)} \) | [X/Fe] | \( \sigma_{\log(X)} \) |
|---------|-------|-------------|--------|-----------------|--------|-----------------|--------|-----------------|--------|-----------------|
| Cu I    | 1     | 2.348       | 0.323  | 0.247           | ...    | ...             | ...    | ...             | ...    | ...             |
| Zn I    | 2     | 2.591       | 0.186  | 0.064           | 2      | 2.498           | 0.358  | 0.144           | 2      | 3.022           |
| Y II    | 4     | -0.168      | -0.223 | 0.135           | 5      | -0.010          | 0.200  | 0.287           | 3      | -0.362          |
| Ba II   | 3     | -0.055      | -0.170 | 0.342           | 3      | -0.477          | -0.327 | 0.170           | 3      | 0.837           |
| La II   | 2     | -1.020      | 0.025  | 0.252           | 2      | -0.532          | 0.778  | 0.141           | 3      | 0.059           |
| Ce II   | 5     | -0.602      | -0.027 | 0.287           | 2      | -0.706          | 0.134  | 0.308           | 4      | 0.148           |
| Nd II   | 6     | -0.491      | 0.244  | 0.133           | 5      | -0.828          | 0.172  | 0.138           | 5      | 0.077           |
| Sm II   | 1     | -0.449      | 0.756  | 0.090           | 1      | -1.124          | 0.346  | 0.062           | 1      | 0.316           |
| Gd II   | 2     | -0.562      | 0.513  | 0.157           | 3      | -0.363          | 0.977  | 0.249           | 2      | -0.043          |
| Eu II   | 1     | -0.980      | 0.655  | 0.150           | 2      | -1.500          | 0.400  | 0.300           | 1      | -0.230          |

| Na I    | 2     | 3.922       | -0.154 | 0.317           | 2      | 4.172           | -0.051 | 0.406           | 2      | 4.290           |
| Mg I    | 6     | 5.625       | 0.219  | 0.164           | 4      | 5.993           | 0.440  | 0.185           | 4      | 5.850           |
| Si I    | 4     | 5.748       | 0.382  | 0.088           | 6      | 5.902           | 0.389  | 0.088           | 6      | 5.153           |
| K I     | 1     | 2.634       | -0.430 | 0.123           | 1      | 5.660           | 1.257  | 0.221           | 1      | 3.325           |
| Na I LTE| 2     | 3.383       | -0.670 | ...             | 2      | 3.664           | -0.560 | ...             | 2      | 4.275           |
| Mg I LTE| 6     | 5.625       | 0.219  | 0.164           | 4      | 5.993           | 0.440  | 0.185           | 4      | 5.850           |
| Si I LTE| 4     | 5.748       | 0.382  | 0.088           | 6      | 5.902           | 0.389  | 0.088           | 6      | 5.153           |
| Ca II   | 19    | 4.337       | 0.181  | 0.129           | 19     | 4.576           | 0.273  | 0.135           | 19     | 4.535           |
| Ti II   | 5     | 1.025       | 0.029  | 0.124           | 5      | 1.142           | -0.001 | 0.121           | 5      | 1.531           |
| Ti II LTE| 33   | 3.035       | 0.209  | 0.105           | 33     | 3.171           | 0.198  | 0.149           | 42     | 3.552           |
| Cr II   | 14    | 3.331       | -0.145 | 0.183           | 11     | 3.614           | -0.009 | 0.187           | 14     | 3.477           |
| Mn II   | 5     | 3.082       | -0.192 | 0.184           | 4      | 2.657           | -0.766 | 0.130           | 5      | 3.291           |
| Fe I    | 81    | 5.119       | ...    | 78               | 5.430  | ...             | ...    | 34               | 5.451  | ...             |
| Fe II   | 26    | 5.306       | ...    | 26               | 5.453  | ...             | ...    | 25               | 5.954  | ...             |
| Co I    | 3     | 3.158       | 0.362  | 0.195           | 3      | 3.401           | 0.458  | 0.147           | 5      | 3.278           |
| Ni I    | 15    | 4.073       | 0.017  | 0.160           | 11     | 4.452           | 0.249  | 0.203           | 22     | 4.329           |
| Cu I    | ...   | ...         | ...    | ...             | ...    | ...             | ...    | ...             | 1      | 1.975           |
| Zn I    | 2     | 2.569       | 0.153  | 0.143           | 2      | 2.730           | 0.167  | 0.131           | 2      | 2.671           |
| Y II    | 5     | 0.229       | 0.163  | 0.117           | 2      | 0.207           | -0.006 | 0.177           | 3      | 0.285           |
| Ba II   | 3     | 0.359       | 0.233  | 0.251           | 3      | -0.031          | -0.304 | 0.220           | 3      | 0.049           |
| La II   | 3     | 0.113       | 1.147  | 0.100           | 3      | -0.412          | 0.475  | 0.216           | 2      | -0.478          |
| Ce II   | 5     | -0.106      | 0.458  | 0.227           | 2      | 0.433           | 0.850  | 0.256           | 2      | 0.084           |
| Nd II   | 6     | 0.419       | 1.143  | 0.246           | 5      | -0.052          | 0.525  | 0.147           | 3      | 0.198           |
| Sm II   | 2     | 0.055       | 1.249  | 0.162           | 2      | -0.421          | 0.626  | 0.125           | 2      | -0.394          |
| Gd II   | 3     | 0.394       | 1.458  | 0.202           | 1      | -0.106          | 0.811  | 0.093           | 1      | 0.044           |
| Eu II   | 1     | -0.410      | 1.214  | 0.150           | 1      | -0.990          | 0.487  | 0.300           | 1      | -0.520          |
\[ \Delta \log g = 0.1 \text{ dex}. \] However, the effect of these inflated stellar parameter uncertainties is small because our abundance uncertainties are dominated by our metallicity uncertainties.

To present a more complete view of the Magellanic Clouds’ metal-poor stellar populations, we also plot in Figures 2–4 the abundances of stars in LMC inner disk/bar fields (Pompéia et al. 2008; Van der Swaelmen et al. 2013), as well as the abundances of stars in both the LMC and SMC observed by SDSS-IV/APOGEE-2 made available as part of SDSS DR16 (e.g., Nidever et al. 2020). For the latter sample, to focus on LMC and SMC members, we use the heliocentric radial velocity and proper-motion cuts proposed by Nidever et al. (2020) using the APOGEE spectra themselves and Gaia DR2 astrometry (Gaia Collaboration et al. 2016, 2018; Salgado et al. 2017; Arenou et al. 2018; Lindegren et al. 2018; Luri et al. 2018).\footnote{We note that we did not repeat the careful membership selection described in Nidever et al. (2020), as in this case we only use the SDSS DR16 Magellanic Clouds sample to compare with the more metal-poor stars in our sample.}

We do not segregate the SDSS DR16 Magellanic Clouds sample into individual LMC/SMC samples, as Nidever et al. (2020) suggested that both galaxies have similarly delayed chemical evolution histories (especially at metallicities below [Fe/H] \( \sim -2 \)).

4.1. \( \alpha \)-elements

Magnesium, silicon, calcium, and titanium are often referred to as \( \alpha \)-elements. While magnesium and calcium are indeed synthesized by the fusion of existing nuclei and \( \alpha \)-particles, silicon is formed during both hydrostatic and explosive oxygen burning. Likewise, titanium is a product of both explosive oxygen and silicon burning. Silicon and titanium are still usually included as \( \alpha \)-elements, though, because the chemical evolutions of [Si/Fe] and [Ti/Fe] as functions of [Fe/H] are similar to those of magnesium and calcium (e.g., Nomoto et al. 2006; Clayton 2007; Wongwathanarat et al. 2017).

We plot in Figure 2 our inferred LTE [\( \alpha /Fe \)] abundances as a function of [Fe/H]. We find that our inferred magnesium, calcium, and titanium abundances are consistent with the \( \alpha \)-enhanced abundances observed in metal-poor Milky Way stars. This is true for both our LMC and SMC samples. As we argue below, among the \( \alpha \)-elements we studied, our magnesium abundance inferences are likely to be least affected by departures from the assumptions of LTE. In the Fe II-based metallicity range spanned by our Magellanic Clouds sample -- 2.6 \( \lesssim [Fe/H] \lesssim -1.5 \), the 16th, 50th, and 84th percentiles of our [Mg/Fe] distribution are [Mg/Fe] = 0.10, 0.37, and 0.53, respectively. For the 113 Milky Way halo stars from Roederer et al. (2014) in the same Fe II-based metallicity range, the 16th, 50th, and 84th percentiles of the [Mg/Fe] distribution are [Mg/Fe] = 0.10, 0.26, and 0.41, respectively. In other words, the 1\( \sigma \) ranges of the two distributions are consistent. While our sample size is too small to apply the two-sided Kolmogorov–Smirnov test often used to assess whether or not there is reason to believe that two samples were produced by the same parent distribution, we nevertheless performed the calculation and found a \( p \)-value = 0.895. This result gives us no reason to believe that the Magellanic Clouds [Mg/Fe] distribution is distinct from that of the Milky Way in the same metallicity range. Applying these same steps to calcium and titanium produces the same result and gives us no reason to believe that their distributions are distinct from that of the Milky Way in the same metallicity range. The high abundances of magnesium and calcium we infer are also in agreement with the increase in [\( \alpha /Fe \)] with decreasing [Fe/H] observed in the Magellanic Clouds comparison sample at higher metallicities.

For the two stars in common between our sample and SDSS2 DR16, we compared our \( \alpha \)-element abundances with those produced by ASPCAP with no bad data or warning flags. For [Mg/Fe] and [Ca/Fe], both sets of abundances are consistent within the uncertainties. For [Si/Fe], our abundances are higher than the ASPCAP abundances.
Figure 3. Abundances of light odd-Z elements sodium and scandium plus iron-peak elements chromium, manganese, cobalt, and nickel. We plot as dark-green stars our nine LMC giants and as orange stars our four SMC giants. We plot as light-green squares LMC inner disk giants from Pompéia et al. (2008) and as light-green triangles LMC bar giants from Van der Swaelmen et al. (2013). We plot as gray circles LMC and SMC giants observed by SDSS-IV/APOGEE-2 that are part of SDSS-IV/DR16 (e.g., Nidever et al. 2020). The point with error bars in a corner of each panel corresponds to the mean uncertainty of our complete 13-star sample. Aside from elevated cobalt abundances that can be attributed to enrichment from hypernovae, the light odd-Z and iron-peak abundances we infer are as expected for metal-poor giants in the Milky Way and its dSph galaxies.

Figure 4. Abundances of neutron-capture elements yttrium, barium, and europium. We plot as dark-green stars our nine LMC giants and as blue stars our four SMC giants. We plot as light-green squares LMC inner disk giants from Pompéia et al. (2008) and as light-green triangles LMC bar giants from Van der Swaelmen et al. (2013). We plot as gray circles metal-poor Milky Way giants from Barklem et al. (2005) and Jacobson et al. (2015) selected for high-resolution follow-up observations without regard to their r-process abundances. The point with error bars in a corner of each panel corresponds to the mean uncertainty of our complete 13-star sample. In the metallicity range $-2.6 \lesssim [Fe/H] \lesssim -1.5$, relative to the Milky Way the $[\text{Eu}/Fe]$ abundances of the giants stars in our Magellanic Clouds sample are uniformly high with an increased occurrence of r-II stars with $[\text{Eu}/Fe] > 1.0$ and $[\text{Eu}/\text{Ba}] > 0$. The stars consistently have $[\text{Eu}/\text{Ba}]$ abundances indicative of r-process nucleosynthesis.
Our inferred magnesium and calcium abundances are unlikely to be significantly affected by departures from the assumptions of LTE. Non-LTE corrections for LTE magnesium abundances from the INSPECT project\textsuperscript{20} based on the results of Osorio & Barklem (2016) are about $-0.03 \text{dex}$ for the magnesium lines we used and the photospheric stellar parameters of the stars in our sample. These corrections are too small to affect any of our conclusions based on magnesium abundances. Non-LTE corrections for LTE silicon abundances $[\text{Si/Fe}] \lesssim 0.8$ based on the Amarsi & Asplund (2017) correction grid are about $-0.02 \text{dex}$. For stars with abundances $[\text{Si/Fe}] \gtrsim 0.8 \text{dex}$, non-LTE corrections can be as large as $-0.2 \text{dex}$. Correcting for departures from LTE would therefore decrease the dispersion in $[\text{Si/Fe}]$ for our sample. Non-LTE corrections for LTE calcium abundances based on the Amarsi et al. (2020) correction grid are about $-0.1$ for metal-poor giants. Non-LTE corrections for titanium can be as large as $+0.2 \text{dex}$ (e.g., Bergemann 2011), but grids of corrections for titanium are not currently available. Overall, we argue that magnesium is the $\alpha$-element in our sample least affected by possible departures from the LTE assumption.

\subsection*{4.2. Light Odd-Z and Iron-peak Elements}

While sodium is mostly produced in core-collapse supernovae, sodium yields are dependent on metallicity, and consequently its chemical evolution is not as easily interpreted as the chemical evolution of the $\alpha$-elements. Both the exact nucleosynthetic origin and chemical evolution of scandium and potassium are likewise hard to identify and interpret (e.g., Clayton 2007). We plot in the top panels of Figure 3 our measured $[\text{Na/Fe}]$ and $[\text{Sc/Fe}]$ abundances as a function of $[\text{Fe/H}]$. The dispersions in our inferred $[\text{Na/Fe}]$ abundances are considerably higher than the $\alpha$-element dispersion depicted in Figure 2. This is a common occurrence in studies of metal-poor stars and is also observed at higher metallicities in the Pompéia et al. (2008), Van der Swaelmen et al. (2013), and SDSS DR16 comparison samples. Our scandium abundance inferences have a dispersion comparable to the $\alpha$-element dispersion depicted in Figure 2. For the two stars in common between our sample and SDSS DR16, we compared our light odd-Z abundances with those produced by ASPCAP with no bad data or warning flags. For $[\text{Cr/Fe}]$ and $[\text{Ni/Fe}]$, both sets of abundances are consistent within the uncertainties.

Our inferred iron-peak abundances are unlikely to be significantly affected by departures from the assumptions of LTE. While chromium abundances can be strongly affected by departures from the assumptions of LTE with non-LTE corrections as large as $+0.5 \text{dex}$ for metal-poor giants (e.g., Bergemann & Cescutti 2010), our chromium abundances are consistent with our comparison samples. Non-LTE manganese corrections for metal-poor giants are about $+0.2 \text{dex}$ (e.g., Amarsi et al. 2020), comparable to our inferred manganese uncertainties.

\subsection*{4.3. Neutron-capture Elements}

Elements with atomic numbers beyond zinc are mostly produced by neutron-capture processes either “slow” or “rapid” relative to $\beta$ decay timescales. The relative contributions of these $s$- and $r$-processes to the nucleosynthesis of each neutron-capture element are functions of metallicity. Some elements like yttrium and barium\textsuperscript{21} are commonly used as tracers of the $s$-process, while europium is the most easily observed element thought to be produced exclusively in the $r$-process (e.g., Cescutti et al. 2006; Jacobson & Friel 2013; Ji et al. 2016a).

We plot in Figure 4 our inferred neutron-capture element abundances as a function of $[\text{Fe/H}]$. The abundances of the $s$-process elements yttrium and barium inferred from Y II and Ba II lines are normal. $[\text{Y/Fe}]$ abundances clustered near the solar value are commonly observed in metal-poor Milky Way giants. Likewise, subsolar $[\text{Ba/Fe}]$ abundances are not

\textsuperscript{20}http://inspect-stars.com/

\textsuperscript{21}Even though barium is usually used as a tracer of the $s$-process, there can be important contributions from $r$-process nucleosynthesis at lower metallicities (e.g., Casey & Schlaufman 2017; Mashonkina & Belyaev 2019).
Figure 5. Spectra for two LMC giants in our sample 2MASS J05133509−7109322 ([Eu/Fe] ≈ 0.6) and 2MASS J05224088−6951471 ([Eu/Fe] ≈ 1.5) plus the well-studied metal-poor giant HD 122563 ([Eu/Fe] ≲ 0). All three stars have similar similar photospheric stellar parameters, and 2MASS J05133509−7109322 and 2MASS J05224088−6951471 span our S/N range. Top left: spectra in the blue in the wavelength range 4100 Å ≤ λ ≤ 4120 Å. Top right: spectra in the green in the wavelength range 5320 Å ≤ λ ≤ 5340 Å. Bottom left: spectra in the red in the wavelength range 6640 Å ≤ λ ≤ 6650 Å. Bottom right: close-up view of the Eu II line at 6645 Å.

5. Discussion

In both the Large and Small Magellanic Clouds, in the metallicity interval −2.6 ≤ [Fe/H] ≤ −2.0 we observe high average values of [Eu/Fe], increased occurrences of r-process-enhanced stars relative to the Milky Way, and α-element enhancements. To quantify the significance of these first two observations, we compare our results with the distribution of Milky Way halo [Eu/Fe] abundances observed by Barklem et al. (2005) and Jacobson et al. (2015) in the same range of metallicity. Since our sample was selected independently of [Eu/Fe], it should provide an unbiased view of the Magellanic Clouds’ [Eu/Fe] distribution in the metallicity range −2.6 ≤ [Fe/H] ≤ −1.5. Likewise, the stars observed by Barklem et al. (2005) and Jacobson et al. (2015) were selected without regard to their [Eu/Fe] abundances, so the union of the Barklem et al. (2005) and Jacobson et al. (2015) catalogs provides an unbiased view of the distribution of [Eu/Fe] in Milky Way halo stars in the metallicity range −2.6 ≤ [Fe/H] ≤ −1.5. Because all of the stars in our Magellanic Clouds sample have [Eu/Ba] ≥ 0 as expected from r-process nucleosynthesis, we first remove all stars from the Barklem et al. (2005) and Jacobson et al. (2015) catalogs with [Eu/Ba] < 0. From here, we refer to this sample as our control sample.

For each of the nine stars in our LMC sample, we calculate the probability $p_i$ that a randomly selected star from the control sample with $[\text{Fe/H}]_{\text{MC}} - [\text{Fe/H}]_{\text{control}} < \sigma(\text{Fe/H})$ has $[\text{Eu/Fe}]_{\text{control}} > [\text{Eu/Fe}]_{\text{MC}}$. We then use these individual probabilities to calculate the probability $9$ $p_i \\sum_{i=1}^{9}$ that a nine-star sample from the control sample has a more extreme uncommon and are frequently observed in metal-poor Milky Way stars in both the halo and bulge (e.g., Reggiani et al. 2017, 2020; Prantzos et al. 2018; Kobayashi et al. 2020). Our inferred abundances of the r-process element europium in metal-poor Magellanic Cloud giants are remarkable. Most extraordinary are the [Eu/Fe] ≈ 1.5 abundances observed in the stars 2MASS J05121686−6517147 and 2MASS J05224088−6951471. In Figure 5 we show europium lines at 6645 Å to illustrate their large equivalent widths and therefore the large abundances of europium in our sample. The occurrence of so-called r-II stars is very high in our sample of metal-poor Magellanic Cloud giants. Indeed, three of our nine metal-poor LMC giants are significantly enhanced in europium according to the classical definition of r-II stars (i.e., [Eu/Fe] ≳ 1.0 and [Eu/Ba] ≥ 0) from Beers & Christlieb (2005). If instead we adopt the new empirical r-II classification (i.e., [Eu/Fe] ≳ 0.7) proposed by Holmbeck et al. (2020), then six out of our nine metal-poor LMC giants are r-II stars (with two more at [Eu/Fe] = 0.65 and [Eu/Fe] = 0.50 very close to the defined limit). Regardless of which classification we adopt, all nine of our LMC giants are considered r-II stars (i.e., [Eu/Fe] ≥ 0.3) and therefore r-process enhanced. While we were only able to infer europium abundances for two of our four metal-poor SMC giants, one is an r-II star according to Beers & Christlieb (2005), while both are r-II stars according to Holmbeck et al. (2020). While we see elevated Eu abundances in the metallicity range −2.6 ≤ [Fe/H] ≤ −1.8, at higher metallicities [Eu/Fe] levels off close to the values observed in the Milky Way at similar metallicities (e.g., Van der Swaelmen et al. 2013; Kobayashi et al. 2020).

Among the neutron-capture abundances we inferred, grids of non-LTE corrections are only readily available for barium. Non-LTE barium corrections for metal-poor giants are about −0.1 dex (e.g., Amarsi et al. 2020).
[Eu/Fe] distribution than what we observe in the LMC. We find that random sampling from the control [Eu/Fe] distribution has only a 1 in 20,600 chance of producing the extreme [Eu/Fe] we observe in the LMC, equivalent to a 3.9σ offset. A similar calculation for the two SMC stars for which we were able to infer [Eu/Fe] indicates that random sampling from the control [Eu/Fe] distribution has only a 1 in 279 chance of producing the extreme [Eu/Fe] distribution we observe in the SMC, equivalent to a 2.69σ offset. Overall, we find that random sampling from the control [Eu/Fe] distribution has only a 1 in 2.88 × 10^6 chance of producing the extreme [Eu/Fe] distribution we observe in the metal-poor Magellanic Clouds sample, equivalent to a 4.96σ offset.

All 11 metal-poor Magellanic Cloud giants for which we could infer a europium abundance would be classified as r-I or r-II stars according to the criteria proposed by Beers & Christlieb (2005). We find that three of nine metal-poor LMC giants would be classified as r-II stars according to Beers & Christlieb (2005); six would be classified as r-II stars according to Holmbeck et al. (2020). Both metal-poor SMC giants for which we could infer europium abundances would be considered r-II stars according to Holmbeck et al. (2020); only one would be considered an r-II star according to Beers & Christlieb (2005). If we model the occurrence of r-process-enhanced stars with a binomial distribution and use an uninformative Beta(1,1) prior in a Bayesian analysis, then the posterior on occurrence will have a Beta distribution as well. We thereby find in the metallicity range −2.6 ≤ [Fe/H] ≤ −1.5 r-I occurrence rates in the LMC, SMC, and complete Magellanic Cloud samples of 93.9% ± 10%, 79.4% ± 25%, and 94% ± 9%, respectively. According to the Beers & Christlieb (2005) definition, we find in the same metallicity range r-II occurrence rates in the LMC, SMC, and complete Magellanic Cloud samples of 36% ± 15%, 50% ± 25%, and 38% ± 14%, respectively. According to the Holmbeck et al. (2020) definition, we find in the same metallicity range r-II occurrence rates in the LMC, SMC, and complete Magellanic Cloud samples of 64% ± 14%, 79% ± 25%, and 70% ± 12%, respectively.

The occurrence rates of r-process-enhanced stars we observe in the Magellanic Clouds are significantly higher than in the halo of the Milky Way or most ultrafaint dSph galaxies. Barklem et al. (2005) found that 14% ± 3% of metal-poor Milky Way halo stars are classified as r-I/r-II according to the Beers & Christlieb (2005) definitions. More recent estimates by the r-process Alliance have found similar occurrences (e.g., Hansen et al. 2018; Sakari et al. 2018). We note that while Ezzeddine et al. (2020) report somewhat higher rates of r-process enhancement, even their possibly biased input sample still produces significantly lower occurrences of both r-I and r-II stars than what we observe in the Magellanic Clouds. The ultrafaint dSph galaxies Reticulum II and Tucana III are the only environments in which similar occurrences of r-process-enhanced stars have been found (e.g., Ji et al. 2016a, 2016b; Roederer et al. 2016; Hansen et al. 2017; Marshall et al. 2019).

In addition to their enhancements in [Eu/Fe], in the metallicity range −2.6 ≤ [Fe/H] ≤ −2.0 all of our metal-poor giants in the LMC and SMC giants are also enhanced in the α-elements. These elevated [α/Fe] abundances are indicative of formation by a time at which thermonuclear supernovae had not yet started contributing significantly to the Magellanic Clouds’ stellar populations’ chemical evolution (e.g., Tinsley 1979). The implication is that the metal-poor LMC and SMC giants in our sample formed after the Magellanic Clouds’ first core-collapse supernovae but before thermonuclear supernovae could contribute significantly to the Magellanic Clouds’ chemical evolution. The copious iron-peak nucleosynthesis produced in thermonuclear supernovae causes [α/Fe] to decline, and the metallicity at which [α/Fe] transitions from a high and constant value to a linearly decreasing function of metallicity is often called the “knee” in the [Fe/H]–[α/Fe] plane.

While the scenario outlined above is likely too simplistic and the metallicity at which [α/Fe] declines depends on stellar and supernova feedback, outflows, and inflows, [α/Fe] tends to begin its decline at higher metallicities in more massive galaxies (e.g., Suda et al. 2017; Nidever et al. 2020). The Magellanic Clouds appear to be an outlier in this regard, as it has been argued that in the Magellanic Clouds [α/Fe] begins its decline below [Fe/H] ≈ −2.2 (Nidever et al. 2020). These upper limits are below the metallicities at which [α/Fe] begins to decline in less massive galaxies like Sagittarius, Fornax, and Sculptor, though we acknowledge that the α-abundance plateaus in these galaxies are not as clearly defined as in the Milky Way (e.g., Kirby et al. 2011b). Indeed, if the Magellanic Clouds followed the trends with mass observed in Sagittarius, Fornax, and Sculptor, then [α/Fe] would start to decline in the Magellanic Clouds at [Fe/H] ≈ −1.2 (e.g., Nidever et al. 2020).

Our stars extend to lower metallicities than most of the Magellanic Cloud stars studied by Nidever et al. (2020), and we therefore attempted to locate the metallicity at which [α/Fe] begins to decline in the Magellanic Clouds. To algorithmically search for the knee in the Magellanic Clouds’ [Fe/H]–[α/Fe] distribution, we use the segmented (Muggeo 2003) package in R (R Core Team 2020) to fit a segmented piecewise linear model to the [Fe/H] and [Mg/Fe] values presented in Figure 2. For our point estimates, the best-fit piecewise linear model features a declining [Mg/Fe] trend in the [Fe/H]–[Mg/Fe] plane, even at [Fe/H] ≈ −2.6. We were unable to identify a plateau at constant [Mg/Fe] at low metallicity using the combination of our observations and SDSS DR16 data, so it is difficult to interpret this result according to the Tinsley (1979) paradigm. We also used a Monte Carlo simulation to investigate the impact of our [Fe/H] and [Mg/Fe] uncertainties on our inferences about the knee. On each iteration of our Monte Carlo simulation, we sampled values of [Fe/H] and [Mg/Fe] from normal distributions assuming the uncertainties given in Table 5. We then fit a segmented piecewise linear model to the [Fe/H] and [Mg/Fe] values produced in each iteration and saved the result. While our [Fe/H] and [Mg/Fe] uncertainties limit our ability to precisely infer segment slopes and end points, we never observed a plateau at constant [Mg/Fe] at low metallicity. We plot the results of these calculations in Figure 6.

We now propose a scenario that explains the ubiquitous r-process enhancement of the Magellanic Clouds’ α-enhanced metal-poor stars and accommodates what is known about the Magellanic Clouds’ other properties. In accord with our estimates of their ages, the α- and r-process-enhanced metal-poor giants we observe in both the LMC and SMC formed in each galaxy’s initial burst of metal-poor star formation more than 10 Gyr in the past (e.g., Harris & Zaritsky 2004, 2009). Relative to the onset of this initial burst of star formation, they must have formed after a few Myr but before a few tens to
100 Myr to explain our observation of their $[\alpha/Fe] \approx 0.4$. While the Milky Way was able to produce stars with $[Fe/H] \approx -1.0$ and $[\alpha/Fe] \approx 0.4$, the chemical evolution of the Magellanic Clouds moved more slowly such that even stars with $[Fe/H] \lesssim -2$ show a decline in $[\alpha/Fe]$ with increasing $[Fe/H]$ (e.g., Figure 6 and Nidever et al. 2020).

We propose two reasons for this apparently slow chemical evolution. The first was the Magellanic Clouds’ ongoing accretion of unenriched gas from the cosmic web, extending the duration of their metal-poor star formation, as the supply of unenriched gas was sufficient to keep $[Fe/H] \lesssim -2$. Unlike most of the Milky Way’s satellite galaxy population, the Magellanic Clouds’ long history of evolution in isolation protected them from ram pressure stripping and strangulation, consequently ensuring a consistent supply of unenriched gas from the cosmic web. The second reason for the Magellanic Clouds’ extended era of metal-poor star formation was that they could not be quenched by either stellar and supernova feedback (because of their relatively high masses compared to the classical and ultrafaint dwarf galaxies) or AGN feedback (because of their low masses compared to the Milky Way and M31).

The Magellanic Clouds’ extended durations of metal-poor star formation, combined with their high star formation rates (relative to the Milky Way’s classical and ultrafaint dSph galaxies), ensured that even nucleosynthesis that occurs in uncommon astrophysical events would contribute to their chemical evolution. In particular, the ubiquitous $r$-process enhancement of the Magellanic Clouds’ $\alpha$-enhanced stars we observe was the result of (1) rare nucleosynthetic events that (2) have characteristic timescale longer than the core-collapse supernova timescale but shorter than or comparable to the thermonuclear supernova timescale. The former fact is necessary to accommodate the rarity of $r$-process-enhanced ultrafaint dSph galaxies, while the latter fact is necessary to accommodate the relative rarity of $r$-process-enhanced stars in the halo of the Milky Way. Because rare classes of core-collapse supernovae like collapsars or magnetorotationally driven supernovae would occur quickly, our observations favor compact object mergers involving a neutron star as the origin of the $r$-process elements observed in $r$-process-enhanced stars at low metallicities in the Milky Way, the Magellanic Clouds, and Reticulum II.

We argue that our observation of the Magellanic Clouds’ $[\alpha/Fe]$ and $[Eu/Fe]$ distributions in the metallicity interval $-2.6 \lesssim [Fe/H] \lesssim -2.0$ favors the nucleosynthesis of $r$-process elements with a delay between a few Myr and a few tens to 100 Myr after the onset of star formation. In accord with our results for the Magellanic Clods, Matsuno et al. (2021) used simple chemical evolution models to suggest that the progenitor Gaia-Enceladus supports the idea of delayed $r$-process enrichment with a timescale shorter than the characteristic thermonuclear supernovae delay time. Likewise, our upper limit on the delay time is in agreement with the conclusions of Skuladóttir & Salvadori (2020). Based on the relationship between the $r$-process abundances and the star formation histories of classical dSph galaxies and the Milky Way’s solar neighborhood, those authors proposed the existence of two different $r$-process sources: a quick source that occurs less than 100 Myr after the onset of star formation and a delayed source that occurs more than 4 Gyr after the onset of star formation. In contrast with their results, as we plot in Figure 7, the $[Eu/Mg]$ ratios of the Magellanic Clouds are constant at supersolar values throughout the entire metallicity range we examined. We argue that this trend is consistent with a constant ratio of the nucleosynthesis of magnesium in core-collapse supernovae.
and europium in compact object mergers involving a neutron star at times in excess of 100 Myr after the onset of star formation. Although the Magellanic Clouds’ [Eu/Mg] abundances are flat, we show in Figure 7 that there is a clear declining trend in [Eu/Ba] abundances with increasing metallicity that we attribute to the increasing importance of s-process barium produced in low-mass asymptotic giant branch (AGB) stars.

We predict that future observations of galaxies that resemble the Magellanic Clouds in two key properties will also display metal-poor stellar populations with ubiquitous r-process enhancement. The first key property is evolution substantially in isolation that allows a galaxy to accrete unenriched gas from the cosmic web and avoid ram pressure stripping/strangulation inside the virial radius of a more massive halo. The second key property is an intermediate mass that is high enough to be robust against stellar and supernova feedback but low enough not to be significantly affected by AGN feedback or accretion shocks.

6. Conclusion
We observed with high-resolution Magellan/MIKE spectroscopy nine LMC and four SMC stars selected using the mid-infrared metal-poor star selection of Schlaufman & Casey (2014) and archival data. These stars are the most metal-poor Magellanic Cloud stars yet subject to a comprehensive abundance analysis. We find that in the interval $-2.6 \leq [\text{Fe/H}] \leq -1.5$ these stars are similar to Milky Way halo stars in their α, light odd-Z, iron-peak, and s-process neutron-capture element abundances, including their enhancement in α-elements magnesium, calcium, and titanium. We discover
that both the Large and Small Magellanic Clouds are ubiquitously enhanced in the $r$-process element europium relative to the Milky Way’s halo. The probabilities that the large [Eu/Fe] abundances we observe in the LMC, the SMC, and our complete Magellanic Clouds sample could be explained by random sampling from an [Eu/Fe] distribution like the Milky Way’s are less than 1 in 20,600, 1 in 279, and 1 in $2.88 \times 10^5$, respectively. These probabilities would be equivalent to $3.90\sigma$, $2.69\sigma$, and $4.96\sigma$ in a Gaussian distribution. Even though we studied the Magellanic Clouds’ [α/Fe]–[Fe/H] distribution to unprecedentedly low metallicities, we could not to identify a plateau in the [α/Fe]–[Fe/H] distribution and therefore were unable to identify the [Fe/H] value at which [α/Fe] begins to decrease (i.e., the “knee”).

We argue that the ubiquitous α and europium enhancements observed in the Magellanic Clouds are a product of their isolated chemical evolution and long history of accretion from the cosmic web that extended the era of metal-poor star formation for a much longer time in the Magellanic Clouds than in the Milky Way or M31. This extended duration of star formation allowed time for $r$-process nucleosynthesis in events that began to occur somewhere between the core-collapse supernova timescale (a few Myr after the onset of star formation) and the thermonuclear supernova timescale (a few tens to 100 Myr after the onset of star formation). These events that produced the europium enhancements we observe in the Magellanic Clouds must have been rare; otherwise, $r$-process-enhanced stars would be ubiquitous in the Milky Way’s ultrafaint dSphs. Compact object mergers involving a neutron star are the best candidate for a rare event that produces $r$-process nucleosynthesis on a timescale longer than the core-collapse supernova timescale. Our observations provide strong support for compact object mergers involving a neutron star occurring after core-collapse supernova but before thermonuclear supernova as the site of the $r$-process nucleosynthesis responsible for the ubiquitous europium enhancement we observe in the Magellanic Clouds in the interval $-2.6 \lesssim [\text{Fe}/\text{H}] \lesssim -1.5$. We predict that metal-poor stars in intermediate-mass galaxies that evolved substantially in isolation will also be enhanced in $r$-process elements.
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